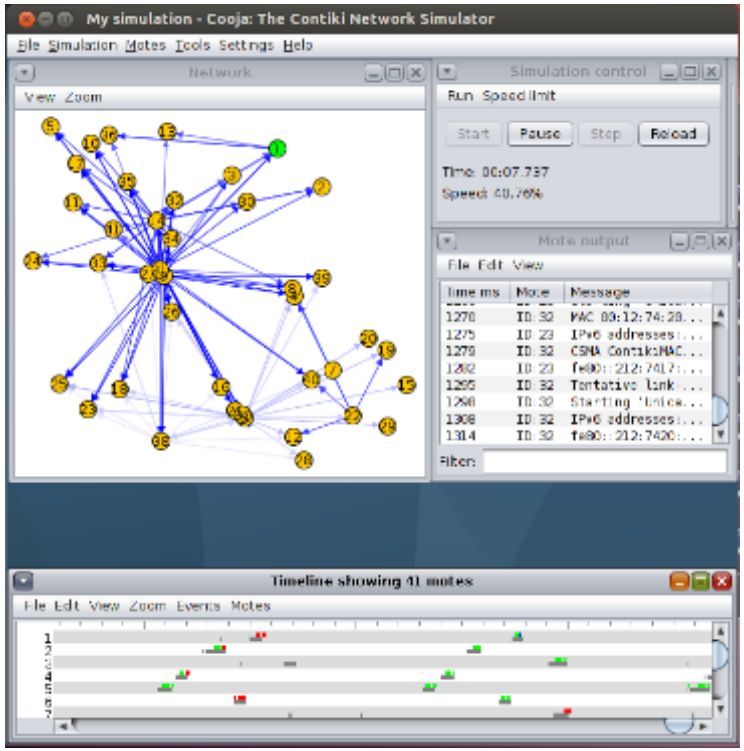
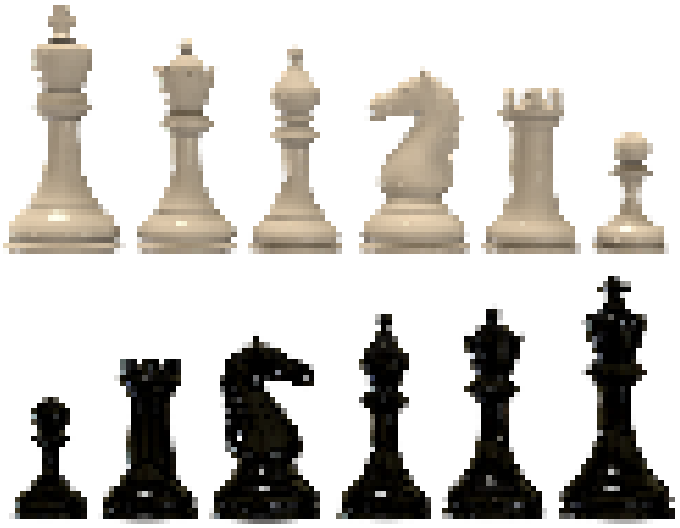
Cellular Wireless Networks





Chapter 13

13.1 Principles of Cellular Networks

13.2 First-Generation Analog

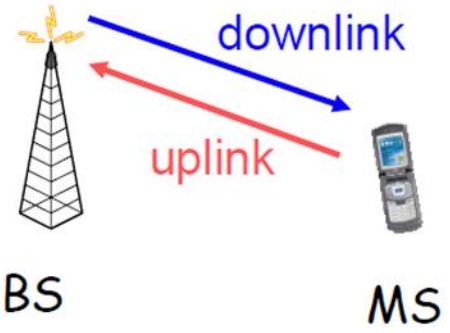
13.3 Second-Generation TDMA

13.4 Second-Generation CDMA

13.5 Third-Generation Systems

Terminologies

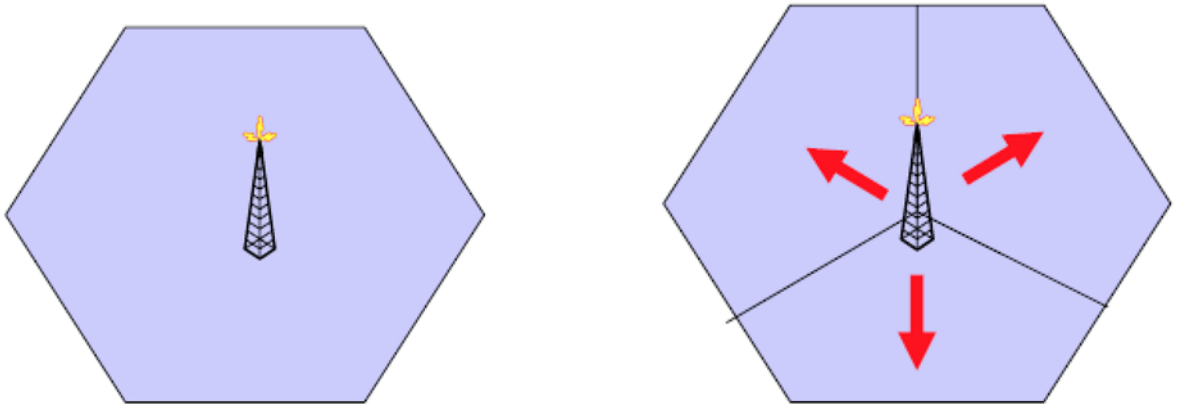
- Base station (BS)
- Node B, eNode B, gNode B, Access point (AP)
- Mobile station (MS)
- UE (User equipment), SS (Subscriber station), MT (mobile terminal), MN (mobile node)
- Downlink: BS → MS
- Forward link
- Uplink: MS → BS
- Reverse link



- Home location register (HLR)
- The HLR is a database used for storage and management of subscriptions.
- It stores permanent data about subscribers, including a subscriber's service profile, location information, and activity status.
- Visitor location register (VLR)
- The VLR is a database that contains temporary information about subscribers that is needed by the MSC in order to service visiting subscribers.

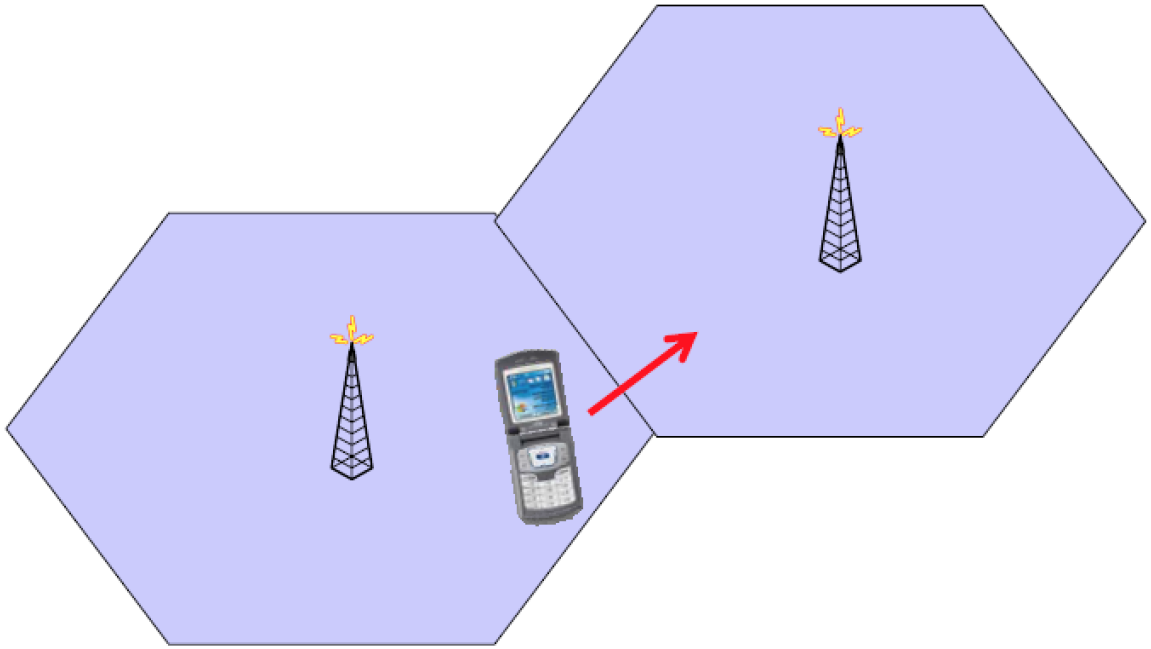
Cell and Sector

- Cell
  - Coverage area of a BS
- Sector
  - Partial area of a cell that is served by a directional antenna



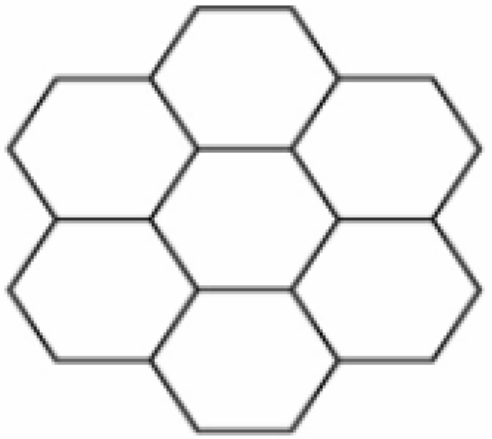
Handoff

- Handoff
  - MS changes serving BS due to movement or radio channel variation
  - handover



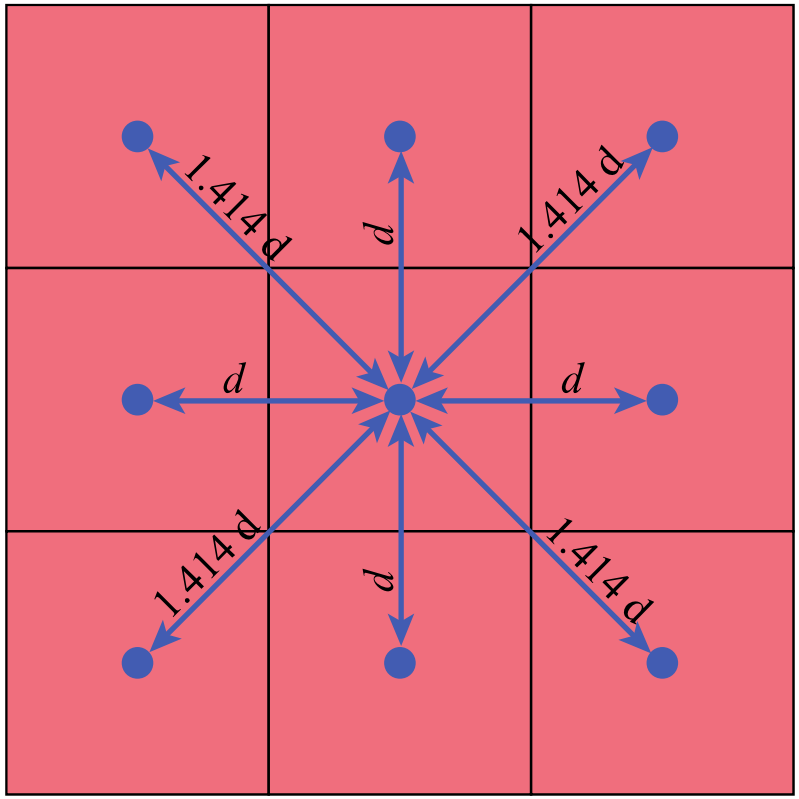
Basic Cellular Concept

- "Cell"
  - Typically, cells are hexagonal
  - In practice, it depends on available cell sites and radio propagation conditions
- Spectrum reuse
  - Reuse the same EM spectrum in other geographical location
  - Frequency reuse factor

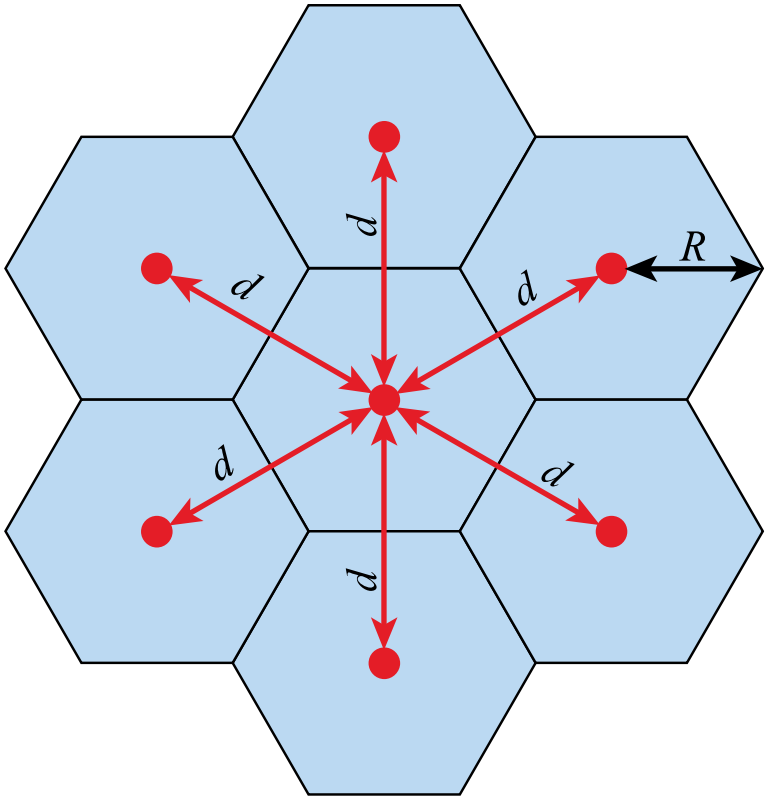


Cellular Network Organization

- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells
  - Each served by its own antenna
  - Served by base station consisting of transmitter, receiver, and control unit
  - Band of frequencies allocated
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)



(a) Square pattern

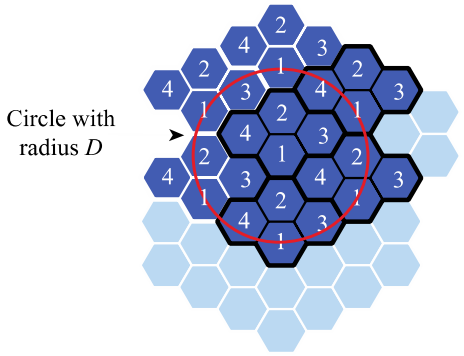


(b) Hexagonal pattern

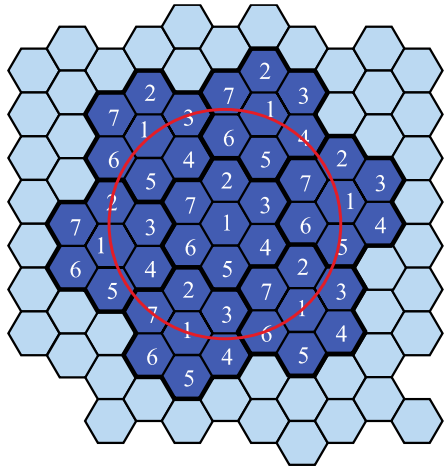
Cellular Geometries

Frequency Reuse

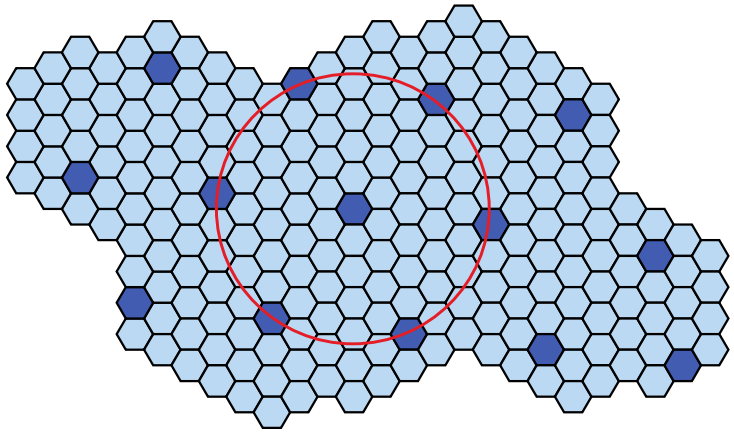
- Adjacent cells assigned different frequencies to avoid interference or crosstalk
- Objective is to reuse frequency in nearby cells
  - 10 to 50 frequencies assigned to each cell
  - Transmission power controlled to limit power at that frequency escaping to adjacent cells
  - The issue is to determine how many cells must intervene between two cells using the same frequency



(a) Frequency reuse pattern for $N = 4$



(b) Frequency reuse pattern for $N = 7$



(c) Black cells indicate a frequency reuse for $N = 19$

Frequency Reuse Patterns

Cluster

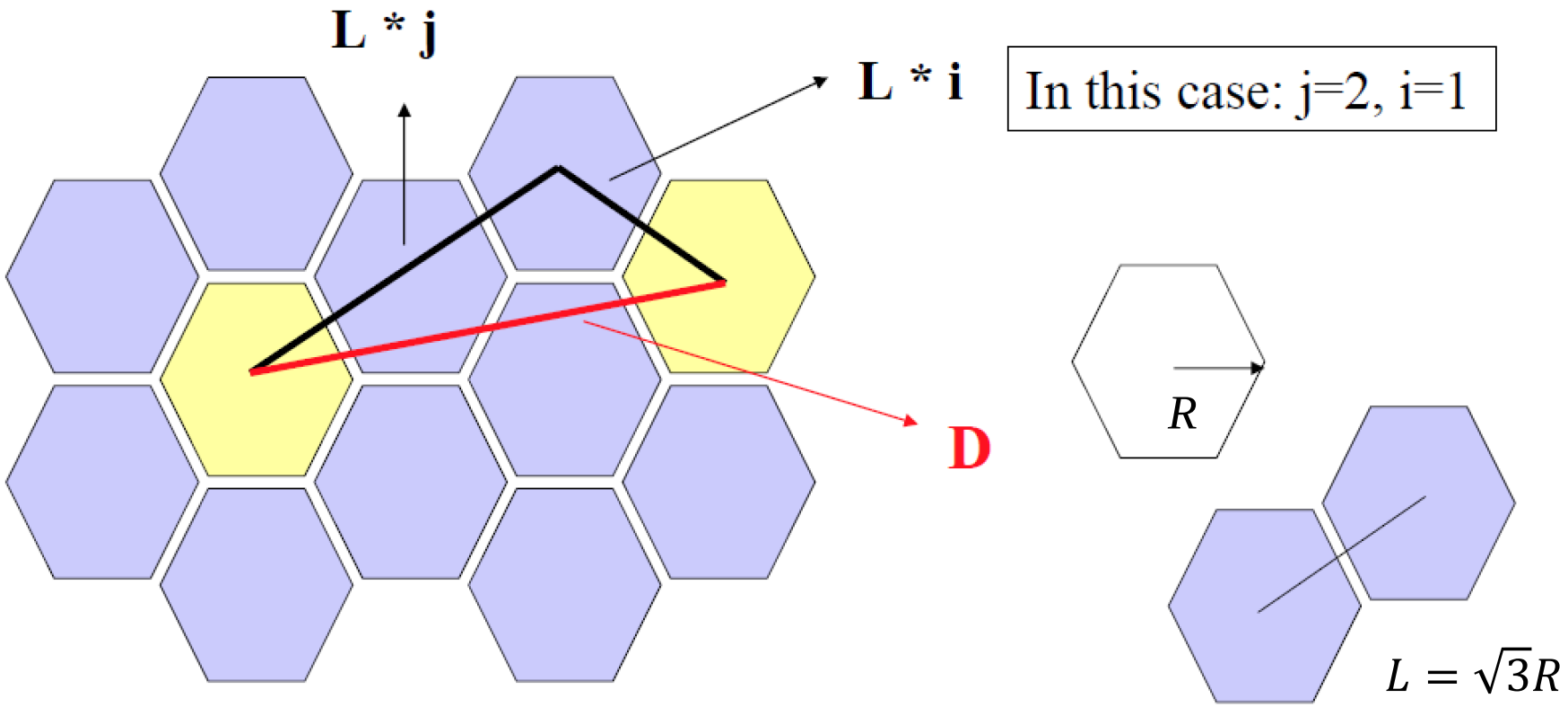
- Cluster: A group of cells
- Cluster size, *N*: the number of cells in a repetitious pattern
- Frequency reuse factor
  - (Total # of channels in a cluster) / (Total # of channels in a cell)
  - It is the rate at which the same frequency can be used in the network.
  - It is *1/K* where *K* is the number of cells which cannot use the same frequencies for transmission.
  - Common values for the frequency reuse factor are 1/3, 1/4, 1/7, 1/9 and 1/12 (or 3, 4, 7, 9 and 12 depending on notation)

Cluster Size

- Notations
  - *D* = Reuse distance, i.e., minimum distance between centers of cells that use the same frequency band (called cochannels)
  - *R* = Cell radius
  - *N* = Number of cells per cluster, e.g., cluster size
- In a hexagonal cell geometry, only the following values of *N* are possible: $N = I^2 + J^2 + (I \times J) \qquad I,\ J = 0, 1, 2, 3, \ldots$

  where *i*, *j* are positive integer.
- Hence, possible values of *N* are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on.

- The following relationship holds: $\frac{D}{R} = \sqrt{3N}$



$$D^2 = (L \cdot i)^2 + (L \cdot j)^2 - 2(L \cdot i)(L \cdot j)\cos(2\pi / 3)$$

$$D^2 = L^2 \cdot i^2 + L^2 \cdot j^2 - 2L^2 \cdot i \cdot j \cdot (-0.5)$$

$$D^2 = L^2 (i^2 + j^2 + ij)$$

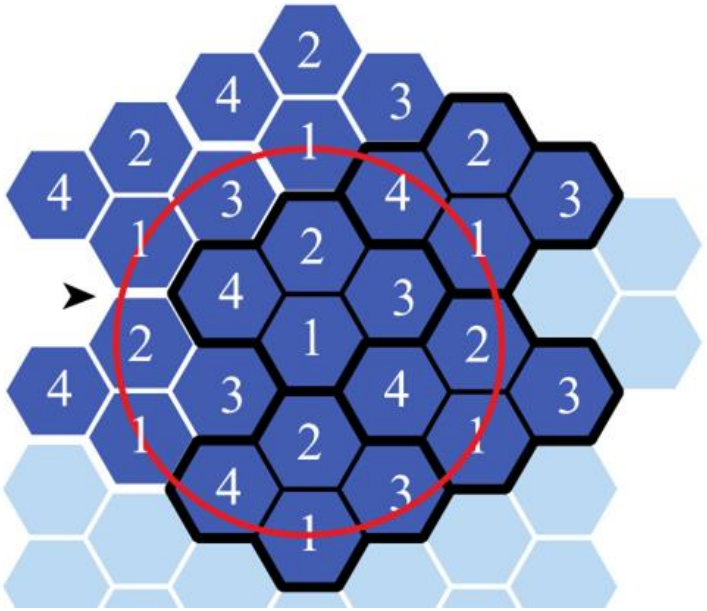
$$\frac{D}{R} = \sqrt{3(i^2 + j^2 + ij)} = \sqrt{3N}$$

Compute D based on "law of cosine"

Cluster Size - Proof

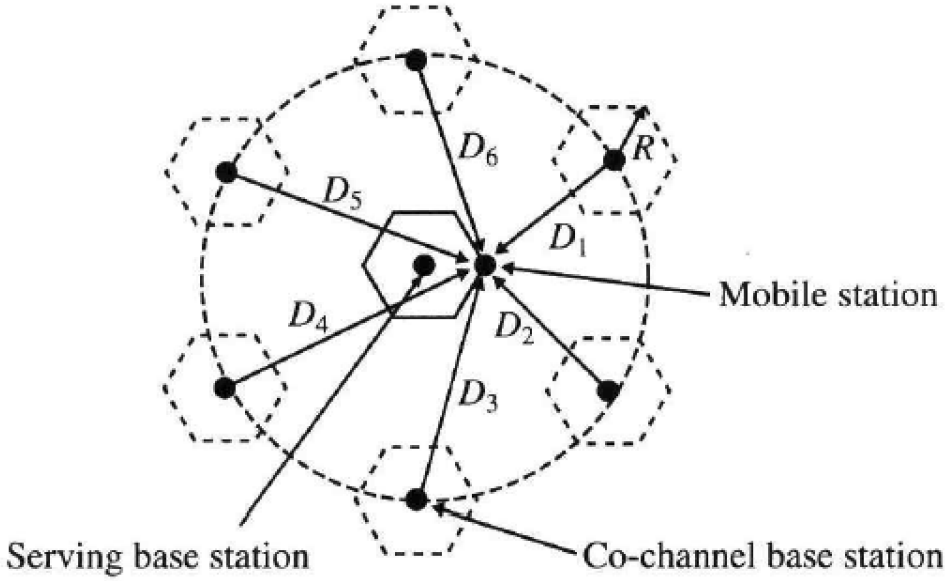
CIR (Carrier-to-Interference Ratio)

- Co-channel interference (CCI)
  - One of the major factors that limits cellular system capacity
  - CCI arises when the same carrier frequency is used in different cells.
- Worst-Case CIR on the Downlink (N=4) when the pass loss is give by $L = d^{\beta}$?



Worst-Case CCI (*N*=4)

- There are six first-tier, co-channel BSs, two each at (approximate) distances of D-R, D, and R+D and the worst case (average)
- CIR is

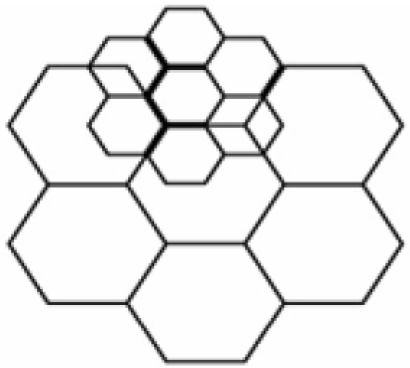


$$\frac{1}{2}\frac{R^{-\beta}}{(D-R)^{-\beta}+D^{-\beta}+(D+R)^{-\beta}}$$

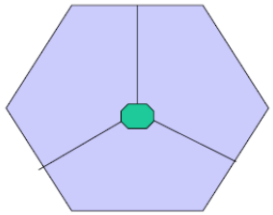
where $\frac{D}{R}=\sqrt{3N}$

Increasing Capacity

- Adding new channels: Typically, when a system is set up in a region, not all of the channels are used, and growth and expansion can be managed in an orderly fashion by adding new channels from the unused set.
- Frequency borrowing: frequencies are taken from adjacent cells by congested cells
- Cell splitting: cells in areas of high usage can be split into smaller cells
  - Smaller cells have greater system capacity: Better spatial reuse
  - As traffic load grows, larger cells could split into smaller cells



- **Cell sectoring:** cells are divided into a number of wedge-shaped sectors, each with their own set of channels
  - Use directional antenna reduces CCI (Co-channel interference)
  - 1 base station could apply several directional antennas to form several sectors
  - 3-sector cell



- **Small cells**: more cells and frequency reuse
  - Macrocell – large ourdoor cell
  - Microcell – antennas move to buildings, hills, and lamp posts
  - Picocell - useful on city streets in congested areas, along highways, and inside large public buildings.
  - Femtocell – inside buildings
- **Interference coordination:** tighter control of interference so frequencies can be reused closer to other base stations
  - Inter-cell interference coordination (ICIC)
  - Coordinated multipoint transmission (CoMP)

Example

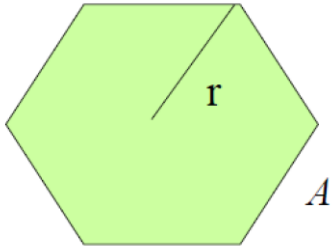
- When we have
  - Total coverage area = 100 mile^2 = 262.4 km^2
  - Total 1000 channels
  - Cell radius = 1km
- What is the total system capacity for frequency reuse factor N = 4 or 7?
  - Where the system capacity is defined as the number of users could be accommodated simultaneously.

Example

- When we have
  - Total coverage area = 100 mile^2 = 262.4 km^2
  - Total 1000 channels
  - Cell radius = 1km
- What is the total system capacity for frequency reuse factor N = 4 or 7?
  - Where the system capacity is defined as the number of users could be accommodated simultaneously.

Solution

- Area of the cell =
- # of cells = 262.4/2.6 = 100 cells
- # of channels/cell
  - S = # of channels / reuse factor
  - S_4 = 1000/4 = 250
  - S_7 = 1000/7 = 142
- System capacity
  - C = S * # of cells
  - C_4 = 250*100 = 250,000
  - C_7 = 142*100 = 14,200

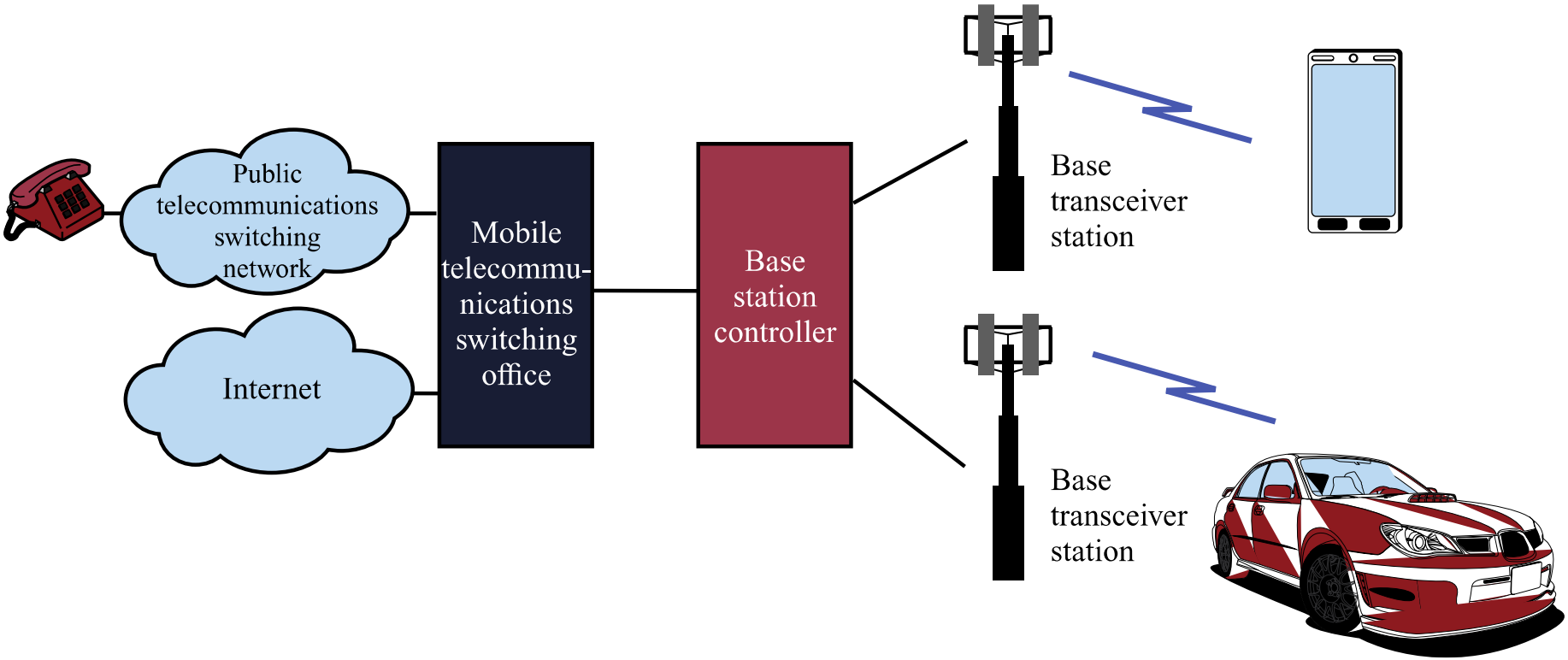


$$A = \frac{3\sqrt{3}}{2} r^2 = 2.6r^2$$

Note:
As *N* deceases, *C* increases but CCI also increases.

Cellular Systems Terms

- Base Station (BS) – includes an antenna, a controller, and a number of receivers
- Mobile telecommunications switching office (MTSO) – connects calls between mobile units
- Two types of channels available between mobile unit and BS
  - Control channels – used to exchange information having to do with setting up and maintaining calls
  - Traffic channels – carry voice or data connection between users

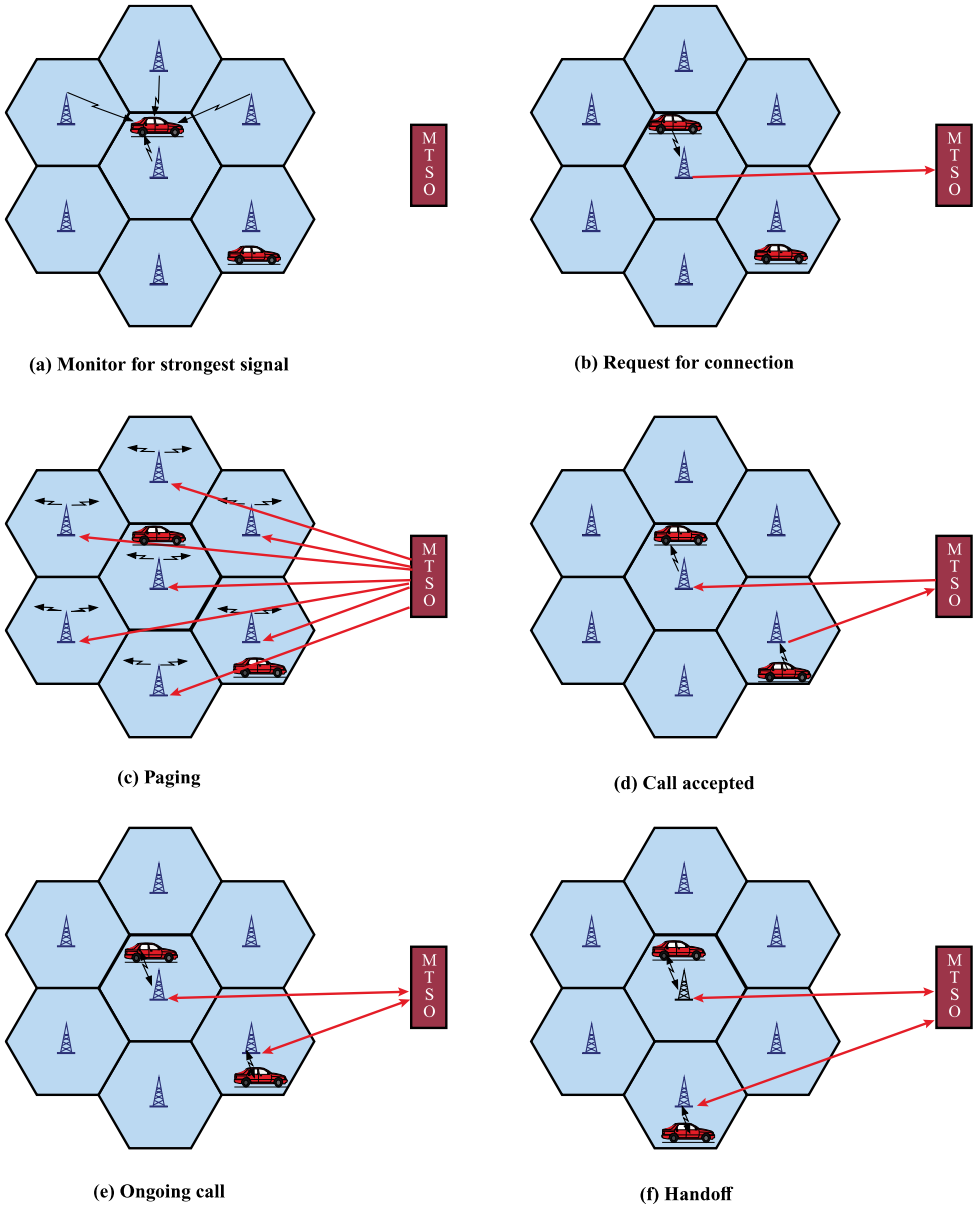


Overview of Cellular System

Steps in an MTSO Controlled Call between Mobile Users

- Mobile unit initialization
- Mobile-originated call
- Paging
- Call accepted
- Ongoing call
- Handoff

- **Mobile unit initialization**
  - When the mobile unit is turned on, it scans and selects the strongest setup control channel used for this system.
  - Then a handshake takes place between the mobile unit and the MTSO controlling this cell, through the BS in this cell. The handshake is used to identify the user and register its location.
- **Mobile-originated call**
  - A mobile unit originates a call by sending the number of the called unit on the preselected setup channel
- **Paging**
  - The MTSO sends a paging message to certain BSs to find the called mobile unit, depending on the called mobile unit number and the latest information on the unit's whereabouts
  - Each BS transmits the paging signal on its own assigned setup channel.
- **Call accepted**
  - The called mobile unit recognizes its number on the setup channel being monitored and responds to that BS,
- **Ongoing call**
  - While the connection is maintained, the two mobile units exchange voice or data signals
- **Handoff**
  - If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to the one assigned to the BS in the new cell

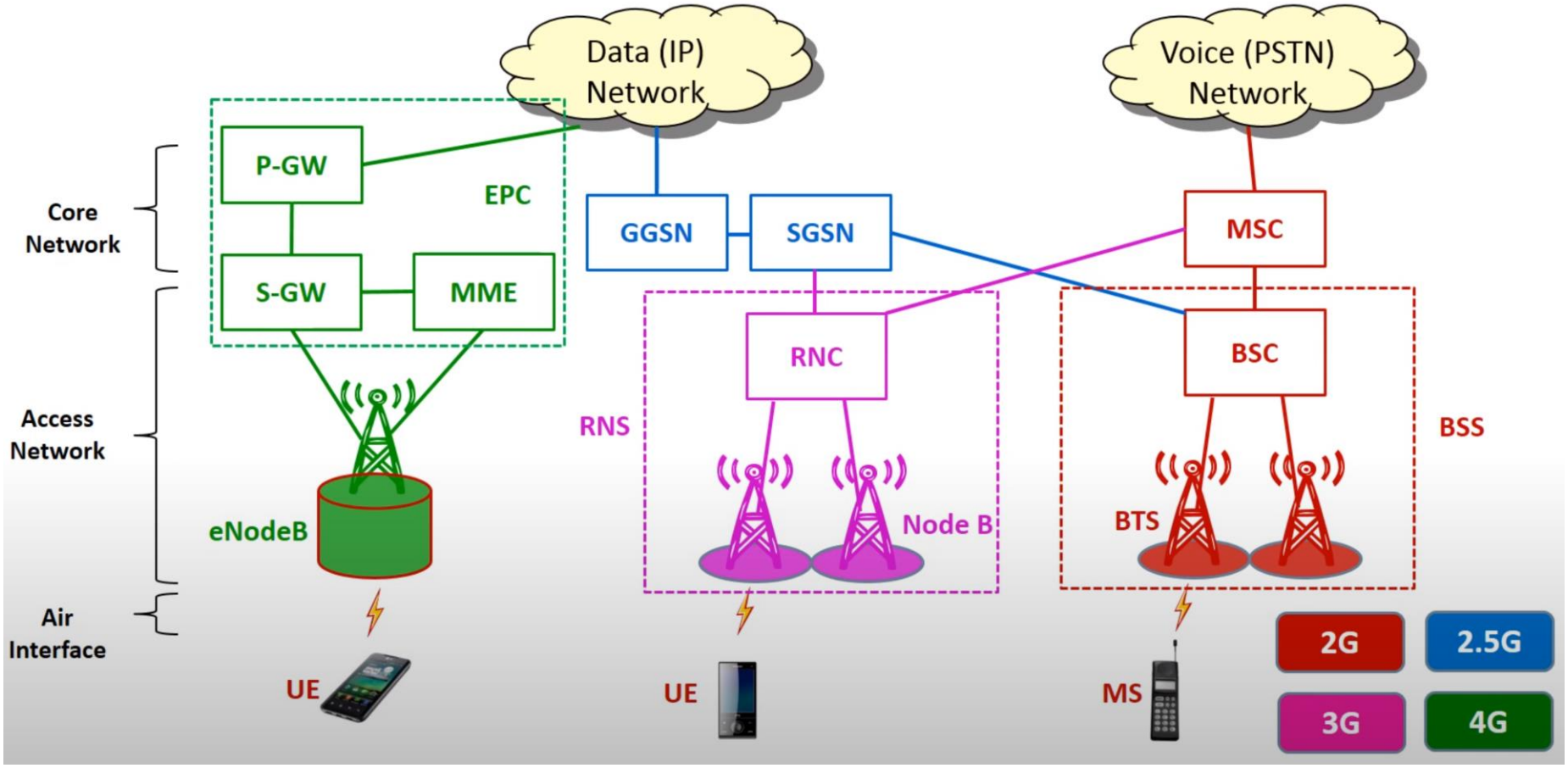


Example of Mobile Cellular Call

Additional Functions in an MTSO Controlled Call

- Call blocking
- Call termination
- Call drop
- Calls to/from fixed and remote mobile subscriber

- **Call blocking**: During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.
- **Call termination**: When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.
- **Call drop**: During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.
- **Calls to/from fixed and remote mobile subscriber**: The MTSO connects to the public switched telephone network. Thus, the MTSO can set up a connection between a mobile user in its area and a fixed subscriber via the telephone network.
- **Emergency call prioritization and queuing**: If a user identifies the all as an emergency call, calls that may experience blocking due to a busy BS may be queued and given first access when a channel becomes available.



2G/3G/4G Network Architecture

2G

- SIM: Subscriber Identity Module
- BTS: Base Transceiver Station
- BSC: Base Station Controller
- BSS: Base Station Subsystem
- MSC: Mobile Switching Centre
- HLR: Home Location Register
- VLR: Visitors Location Register

3G

- RNC: Radio Network Controller
- SGSN: Serving GPRS support node
  - MS 위치관리, Security function, Access control
- GGSN: Gateway GPRS support node
  - 외부 Packet Switched Network과의 interworking

4G

- S-GW: Serving Gateway
  - Intra-LTE mobility에서 anchor point 역할
- P-GW: PDN Packet Data Network Gateway
  - IP acllocation, Accounting
- MME: Mobility Management Entity
  - UE Autentication, Mobility Management

Mobile Radio Propagation Effects

- Signal strength
  - Must be strong enough between base station and mobile unit to maintain signal quality at the receiver
  - Must not be so strong as to create too much co-channel interference with channels in another cell using the same frequency band
- Fading
  - Signal propagation effects may disrupt the signal and cause errors

Handoff Performance Metrics

- **Cell blocking probability** – probability of a new call being blocked
- **Call dropping probability** – probability that a call is terminated due to a handoff
- **Call completion probability** – probability that an admitted call is not dropped before it terminates
- **Probability of unsuccessful handoff** – probability that a handoff is executed while the reception conditions are inadequate

Handoff Performance Metrics

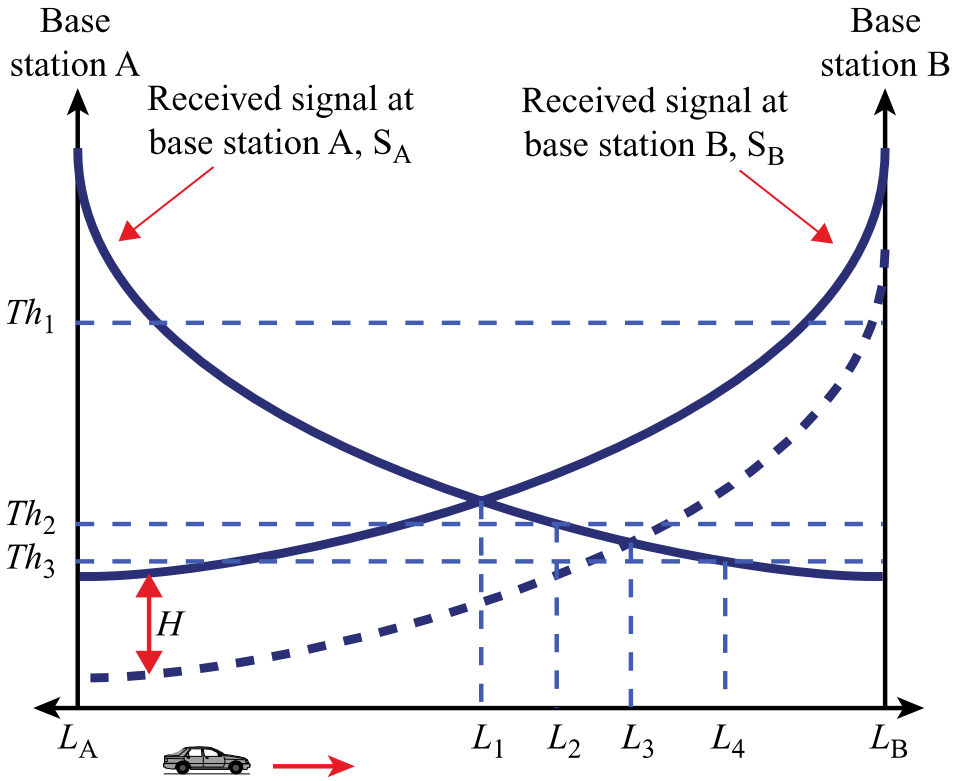
- **Handoff blocking probability** – probability that a handoff cannot be successfully completed
- **Handoff probability** – probability that a handoff occurs before call termination
- **Rate of handoff** – number of handoffs per unit time
- **Interruption duration** – duration of time during a handoff in which a mobile is not connected to either base station
- **Handoff delay** – distance the mobile moves from the point at which the handoff should occur to the point at which it does occur

Handoff Strategies Used to Determine Instant of Handoff

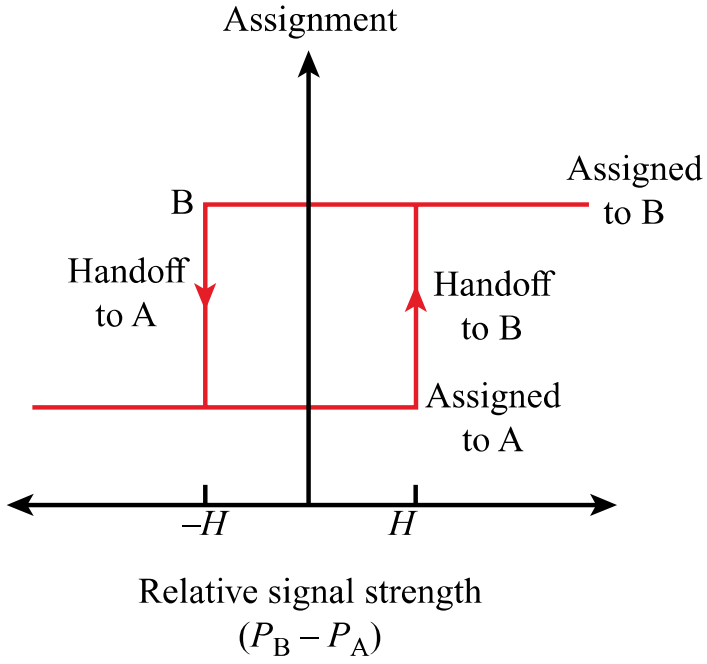
- Relative signal strength
- Relative signal strength with threshold
- Relative signal strength with hysteresis
- Relative signal strength with hysteresis and threshold
- Prediction techniques

Traditional Algorithms

- *Received Signal Strength*: The base station with the the largest strength is selected (choose BS B_{new} if $P_{new} > P_{old}$).
- *Received Signal Strength plus Threshold*: RSS of a new BS exceeds that of the old BS, RSS of old BS is below a threshold T (choose B_{new} if $P_{new} > P_{old}$ and $P_{old} < T$).
- *Received Signal Strength plus Hysteresis*: RSS of new BS is larger than that of the old BS by a hysteresis margin H (choose B_{new} if $P_{new} > P_{old} + H$).
- *Received Signal Strength, Hysteresis and Threshold*: RSS of a new BS exceeds that of the old BS by a hysteresis margin H, and RSS of old BS is below a threshold T (choose B_{new} if $P_{new} > P_{old} + H$ and $P_{old} < T$).
- *Algorithm plus Dwell Timer*: A timer is started at the instant when the condition in the algorithm is true. If the condition continues to be true till the timer expires, a handoff is performed.



(a) Handoff decision as a function of handoff scheme



(b) Hysteresis mechanism

Handoff Between Two Cells

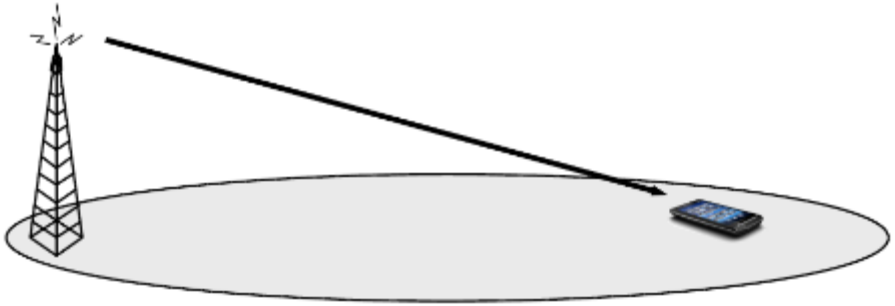
Ping-Pong Effect

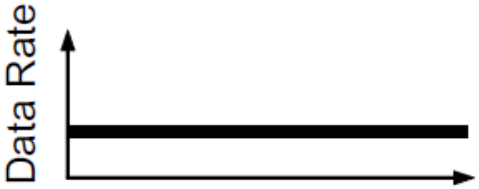
- Repeated handoffs back and forth between two base stations
  - Caused by not setting some parameters of handoffs like hysteresis and threshold wisely
  - Results in large system loads, multiple interruptions in voice transmissions and instability

Power Control

- Reasons to include dynamic power control in a cellular system
  - Received power must be sufficiently above the background noise for effective communication
  - Desirable to minimize power in the transmitted signal from the mobile
    - Reduce co-channel interference, alleviate health concerns, save battery power
  - In SS systems using CDMA, it's necessary to equalize the received power level from all mobile units at the BS

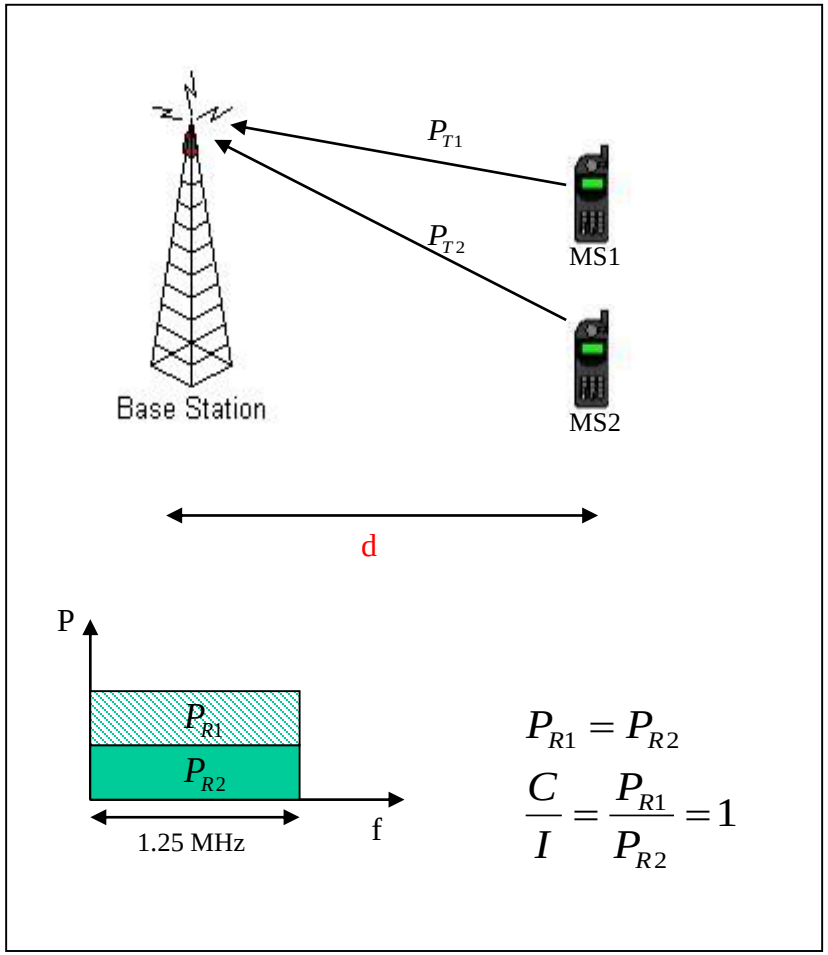
- Power control refers to the strategies or techniques required in order to adjust, correct and manage the power from the BS/MS in both directions (i.e. uplink and downlink) in an efficient manner.
- Advantages of PC
  - Maintain a satisfactory quality for users
  - Increase overall system capacity while meeting QoS requirements





Power control in the CDMA system

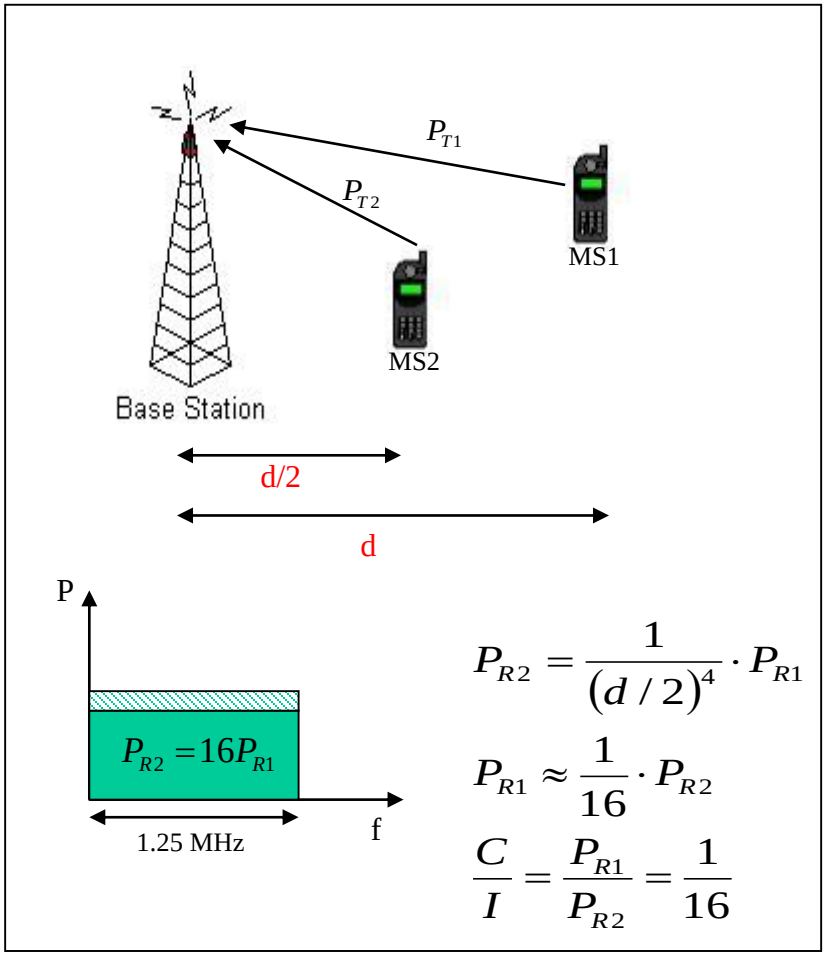
Ideal CDMA system



$$P_{R1} = P_{R2}$$

$$\frac{C}{I} = \frac{P_{R1}}{P_{R2}} = 1$$

Near-far effect



$$P_{R2} = \frac{1}{(d/2)^4} \cdot P_{R1}$$

$$P_{R1} \approx \frac{1}{16} \cdot P_{R2}$$

$$\frac{C}{I} = \frac{P_{R1}}{P_{R2}} = \frac{1}{16}$$

Types of Power Control

- Open-loop power control
  - Depends solely on mobile unit
  - No feedback from BS
  - Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
- Closed-loop power control
  - Adjusts signal strength in reverse channel based on metric of performance
  - BS makes power adjustment decision and communicates to mobile on control channel

Open Loop Power Control

BS

measuring received power

transmit

estimating path loss

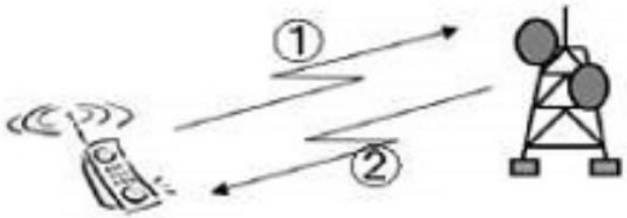
calculating transmission power

MS

transmit

receive

Closed Loop Power Control



BS

decide transmission power

②

power control command

about 1000 times per second

MS

transmit

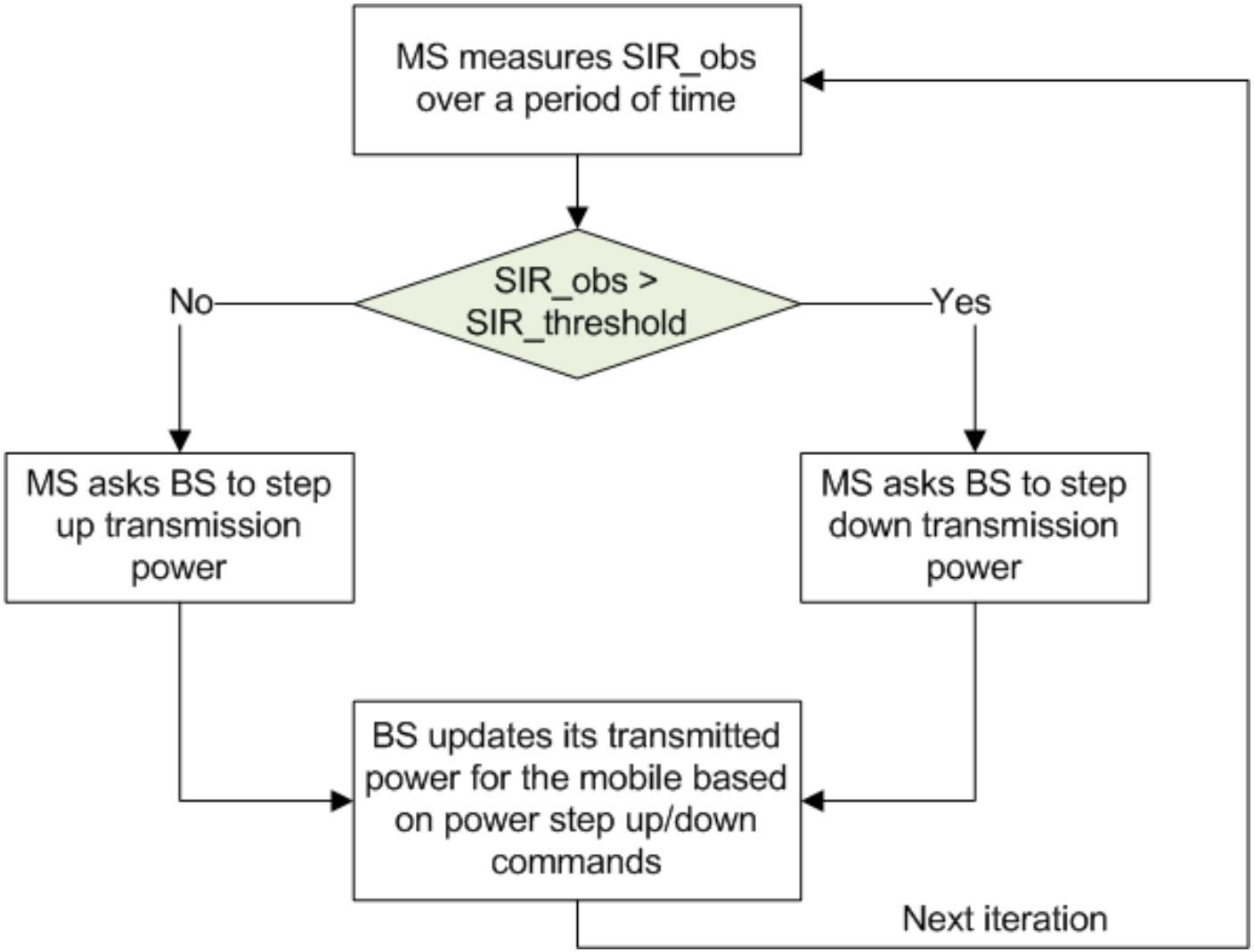
①

measuring received power

CDMA System

- Open-Loop Power Control
  - 이동단말과 기지국 간에 루프를 형성하지 않고 주로 이동단말에 의해 송신전력 조절
  - 순방향 및 역방향 경로손실이 같다는 가정 하에 전력제어 수행 (단순한 원리)
  - 동국이 기지국에서 오는 비콘신호세기에 따라 이동국 자체 만으로 전력제어
  - 상향,하향 링크 주파수대역이 분리되는 CDMA FDD 방식 등에서 단지 접속을 시도하는 초기 전력 결정과정에 만 이러한 제어방식이 사용됨

- Closed-Loop Power Control
  - 개방 루프 방식에서 오는 전력제어 오차를 수정 (다소 정교함)
  - 기지국이 일정 주기 마다(예, 1.25 ms 등) 수신 Eb/No와 요구 Eb/No를 비교하여 전력제어 비트를 결정하여 이동국에게 지시
  - 구분
    - Inner-loop 전력제어 방식 (내부루프) : 기지국과 이동단말 간에 수행
    - Outer-Loop 전력제어 방식 (외부루프) : 기지국 이외 외부센터에서 수행, 기지국 외부의 제어센터(RNC, Radio Network Controller)등이 전력제어 수행



Signal-to-interference ratio (SIR) based Power control algorithm

Traffic Engineering

- Ideally, available channels would equal number of subscribers active at one time
- In practice, not feasible to have capacity handle all possible load
- For *N* simultaneous user capacity and *L* subscribers
  - $L < N$ – nonblocking system
  - $L > N$ – blocking system

Blocking System Performance Questions

- Probability that call request is blocked?
- What capacity is needed to achieve a certain upper bound on probability of blocking?
- What is the average delay?
- What capacity is needed to achieve a certain average delay?

Traffic Intensity

- Load presented to a system:

$$A = \lambda h$$

  - λ = mean rate of calls attempted per unit time
  - h = mean holding time per successful call
  - A = average number of calls arriving during average holding period, for normalized λ