CIS 5636 Ad Hoc Networks (Part I)

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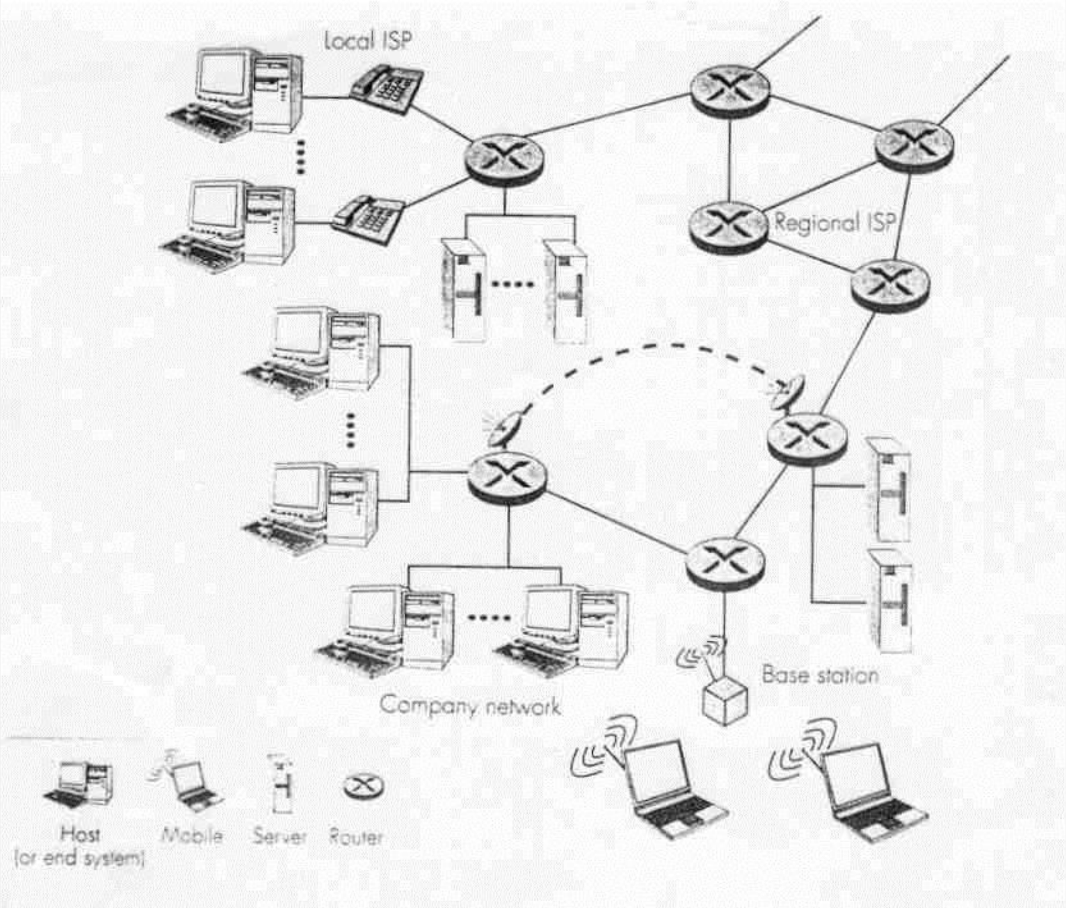
Classification of Communication Networks

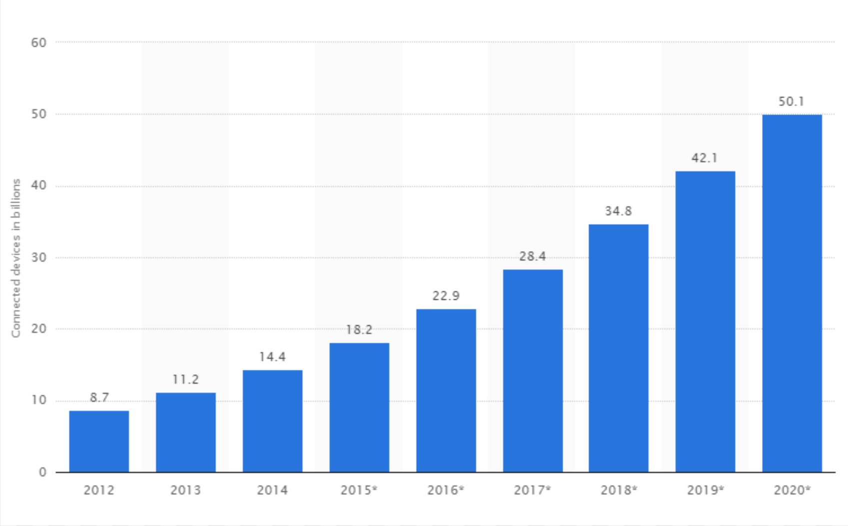
- Scale
  - LAN, MAN, WAN, Internet
- Transmission technology
  - broadcast
  - point-to-point
- Service
  - single service
  - integrated service
- Transmission medium
  - wired networks
  - wireless networks

Wired/Wireless Networks



Wireless Networks to IoTs

- 1.4 billion smartphone purchased in 2015, 52% Android.
- By 2017, 2.6 billion in total, 1/3 of population; ¼ in China, ½ of population.
- Internet of Things (IoTs): projection on connected devices 02-20
- Manytime, manywhere
- Anytime, anywhere



Advanced Wireless Research Initiative, 2016

- 4G/LTE coverage for 98% of U.S. citizen
- $400 million, 4 city-scale testing platforms
- NSF, FCC (open up more spectrum), and industry

> *Twenty-first century businesses need 21st century infrastructure—modern ports, and stronger bridges, faster trains and the fastest Internet...I intend to protect a free and open Internet, extend its reach to every classroom, and every community, and help folks build the fastest networks so that the next generation of digital innovators and entrepreneurs have the platform to keep reshaping our world.*
>
> - President Obama, 2015 State of the Union

Wireless Comm. Characteristics

- Higher interference (low reliability)
- Low bandwidth and transmission rates
- High variable conditions (loss rate, disconnection, channel changes)
- Limited computing, transmission, and energy resources
- Limited service coverage
- Weaker security

Samples

- Portable phones (home cordless, cellular, PCS)
- Paging (one-way service)
- Personal digital assistants (PDAs)
- Wireless LANs (small service area with high-bit-rate services)
- Smartphones (PDAs, calendar, media player, video games, GPS, camera, apps,…)

Samples (Cont'd.)

- Satellites (ubiquitous coverage with low-bit-rate services)
  - Two-way comm. between satellites and vehicles (and ships)
  - One-way comm. Global Positioning Systems (GPS)
- Wireless loops (local or metropolitan)
- Wireless ATM
- Mobile IP

Wireless Network Applications

- Positioning method using Cell-id
  - Local weather forecast
  - Nearest vacant parking garage
  - Events today in the city
- Personalized service: M-business
  - E-mail
  - Mobile gaming
  - Mobile advertising
- Social networks applications

Wireless Channels

- Path Loss
  - Ratio of the power of transmitter (t) and receiver (r)
  - $P_t/P_r \sim d^4$ (free space) or $\sim d^2$ (two paths)
- Interference
  - Cochannel
  - Adjacent channel
- Fading (fluctuations)
  - Time variation of received signal power caused by changes in transmission
- Doppler shift
  - Frequency change/shift due to mobility of t or r
  - Doppler shift: v/λ

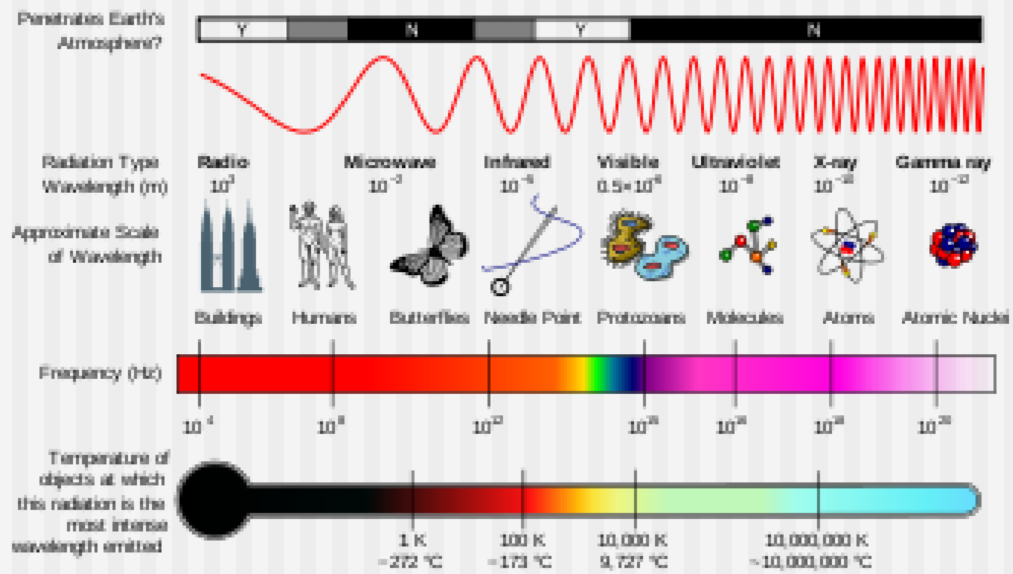
    (v: speed between t and r)

Wireless Comm. Basics

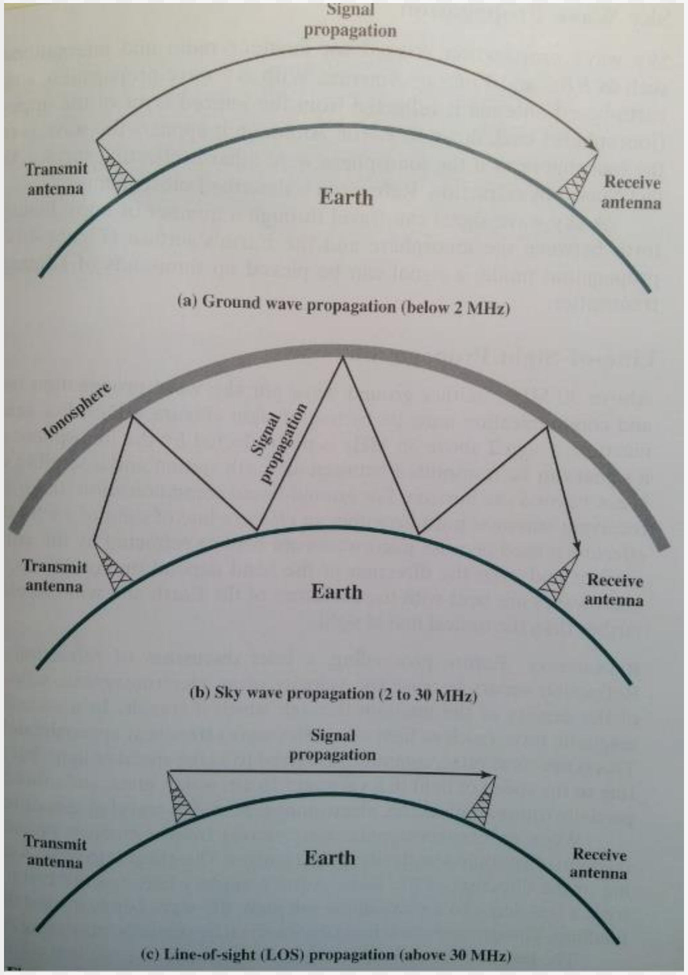
- Electromagnetic spectrum: $v = \lambda * f$
  - Special v: c: speed of light: 3×10^8
  - λ: wavelength in meters
    - Sine and square wave
  - f: frequency in Hertz (cycles per second)

e.g. 900 MHz has 0.33 m wavelength

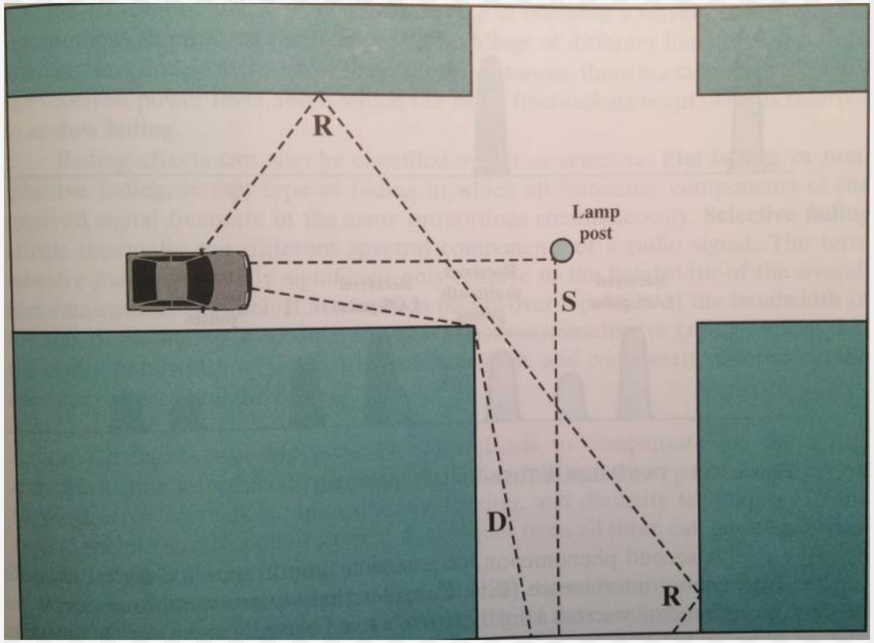
- Radio propagation
  - Line-of-sight (straight)
  - Reflection (large object)
  - Diffraction (corner)
  - Scattering (small object)



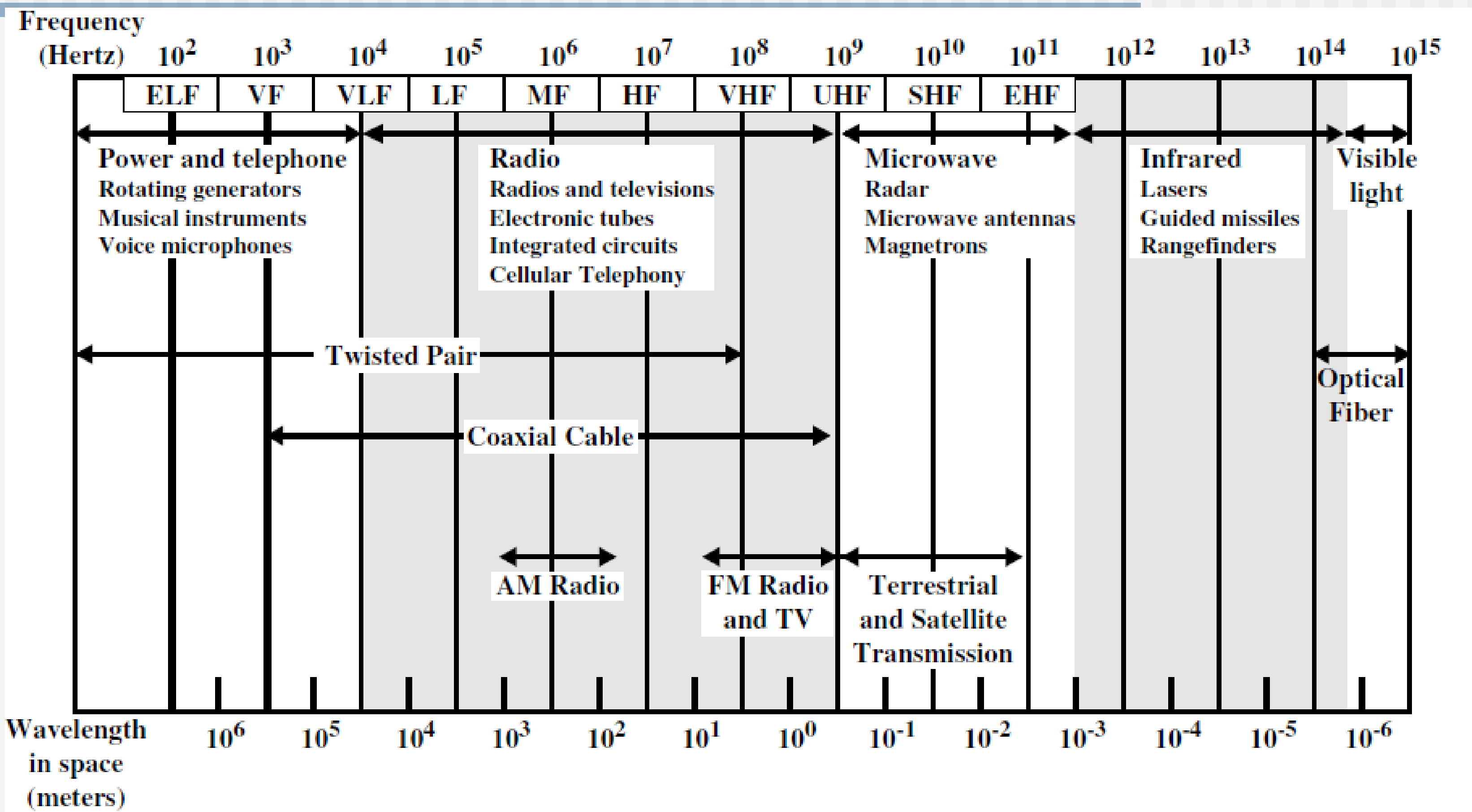
Wireless Comm. Basics



- Reflection (R)
- Diffraction (D)
- Scattering (S)



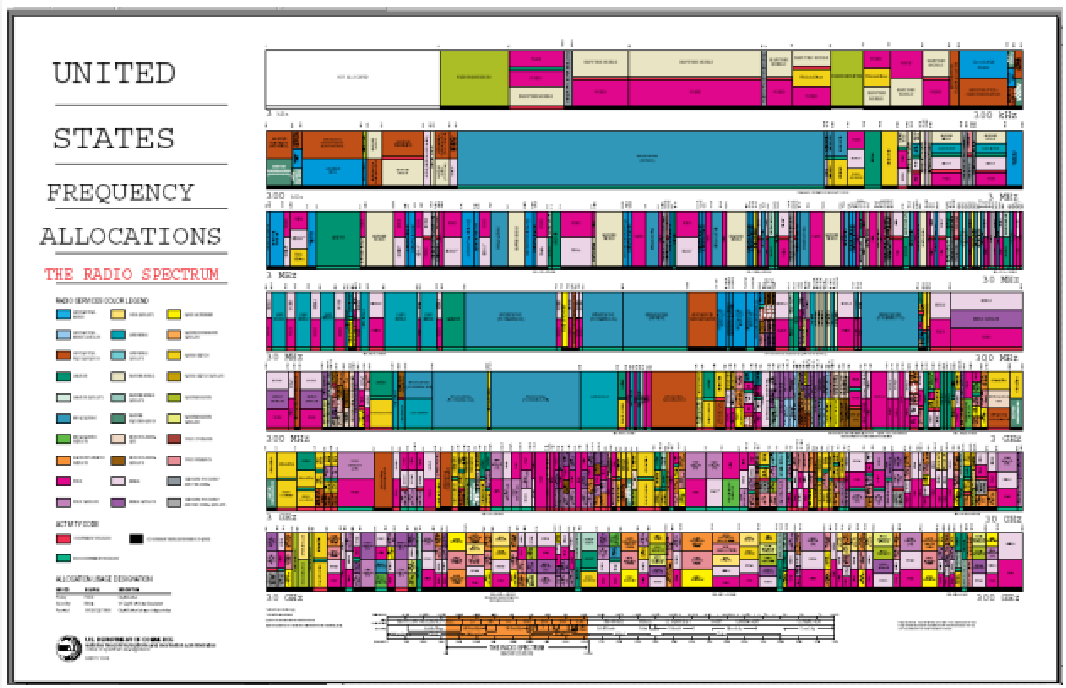
Electromagnetic Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

Cognitive Radios

- Cognitive radios
  - Sensing (spectrums)
  - Cognition (primary users)
  - Adaptability (best use unused spectrum)
- Adaptive Channel Allocation
  - Spectrum sharing (primary and secondary)
  - Graph and game theory



Spectrum Observer

Channel Capacity

- Nyquist's Theorem

  $C = 2 \times B \times \log_2 L$

  - C: capacity
  - B: Bandwidth
  - L: number of signal levels
  - Binary: L =2

- Shannon's Theorem

  $C = B \times \log_2 (1 + S/N)$

  - S: signal power
  - N: noise power
  - SNR (signal-noise-ratio): $10 \log_{10}(S/N)$ (in decibels: db)

Example

- Suppose spectrum is 3 MHz and 4 MHz with SNR: 24 db

  B = 4-3 = 1 Mhz

  SNR = 24 db = 10 $\log_{10}(S/R)$

  Using Shannon's formula,

  $C = 10^6 \times \log_2(1+251)$

  $= 10^6 \times 8 = 8$ Mbps

- No. of levels needed to achieve the capacity based on Nyquist's formula

  $C = 2B \log_2 L$

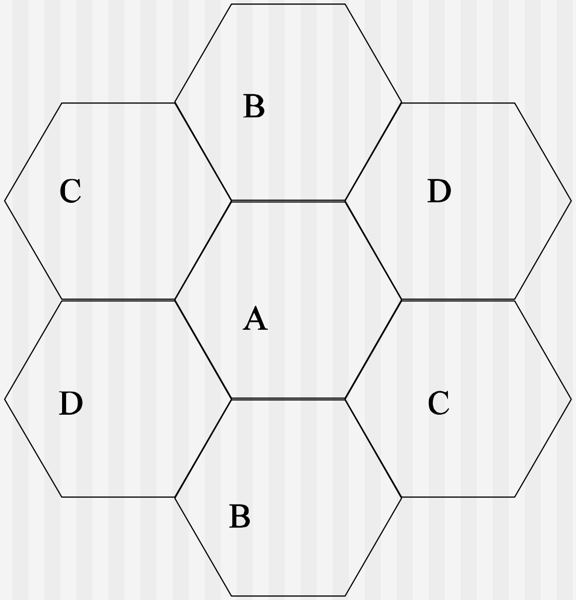
  $8 \times 10^6 = 2 \times 10^6 \times \log_2 L$

  $4 = \log_2 L$

  $L = 16$

Infrastructured Networks

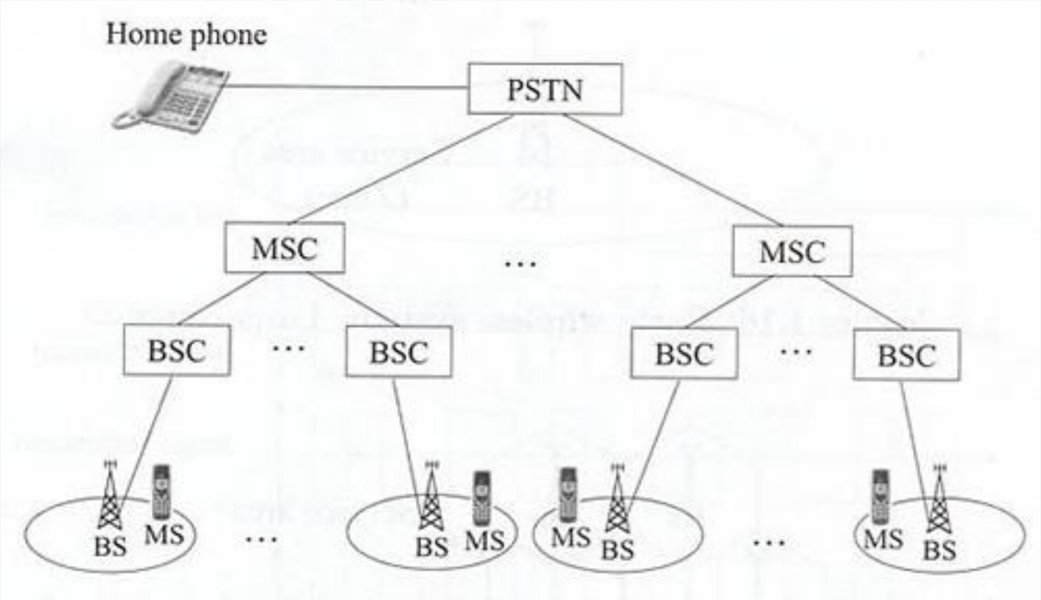
- Cellular architecture
- Base station



Infrastructured Networks

- Cell (hexagon with 2-10 km radius)
- Cellular System Infrastructure
  - *MS* (mobile system)
  - *BS* (base station)
  - BSC (base station controller)
  - MSC (mobile switching center)
  - PSTN (public switched telephone network)

Infrastructured Networks

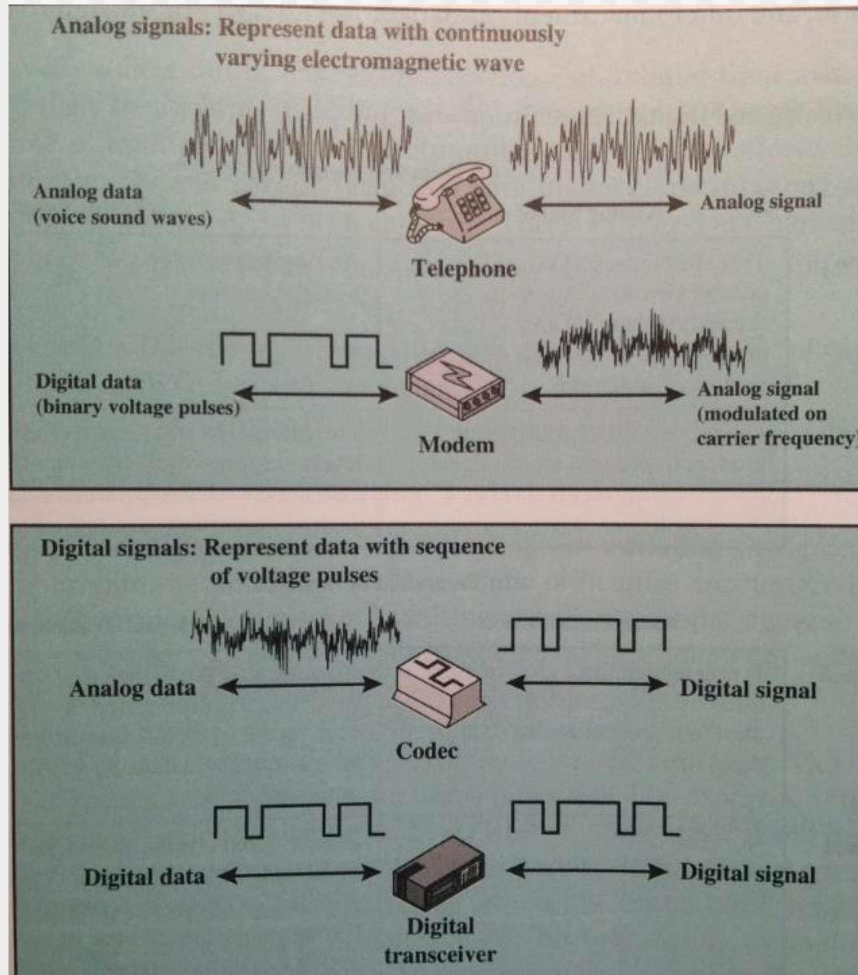


Infrastructured Networks

- Different generations
  - 1G (analog): 1980s
  - 2G (digital): 1990s
  - 2.5G (digital): Late 1990s
  - 3G (cdma2000 in US and W-CDMA in Europe and Japan): 2000s
    - 128 Kbps (high speed), 384 Kbps (slow speed)
    - 2 Mbps (stationary)
  - 4G (WiMax and LTE): 2010s
    - 2 Mbps (high speed) and 1 Gbps (slow speed)
  - 5G: 2020s?
    - 100 Mbps to 10 Gbps

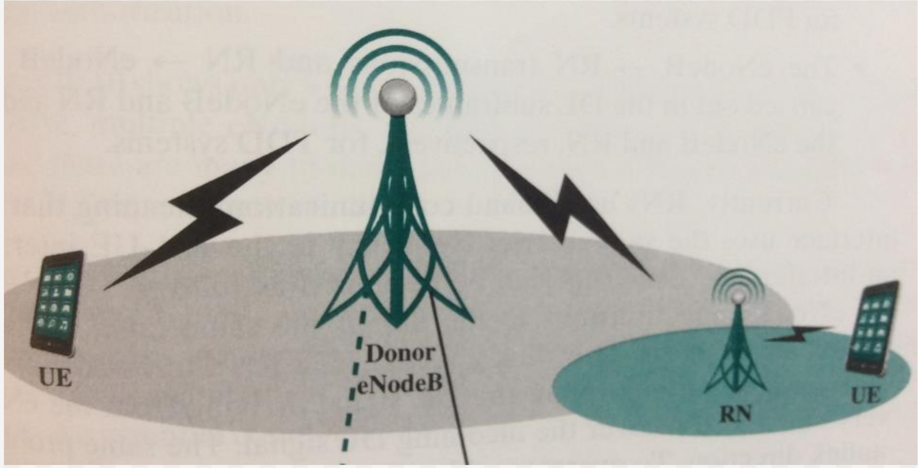
Infrastructured Networks

- Analog/digital conversion



Infrastructured Networks

- 4G
  - WiMax
  - LTE (long Term Evolution)
    - OFDMA (orthogonal FDMA)
    - BS: evolved NodeB
    - Relay node (RN)



System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	<50 ms
	Dormant to active	<50 ms	<10 ms
User plane delay		<5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350–500 km/h

Infrastructured Networks

- 5G wireless
  - Data rates of several tens or hundreds of Mbps should be supported for tens of thousands of users.
  - 1 to 10 Gbps to be offered, simultaneously to tens of workers on the same office floor.
  - Up to several 100,000's simultaneous connections to be supported for massive sensor deployments.
  - Spectral efficiency should be significantly enhanced compared to 4G.
  - Coverage and signaling efficiency should be improved.

Infrastructured Networks

- Issues to be covered
  - Cellular Concept
  - Mobility Management
    - Handoffs
    - Location Management
  - Channel Assignment

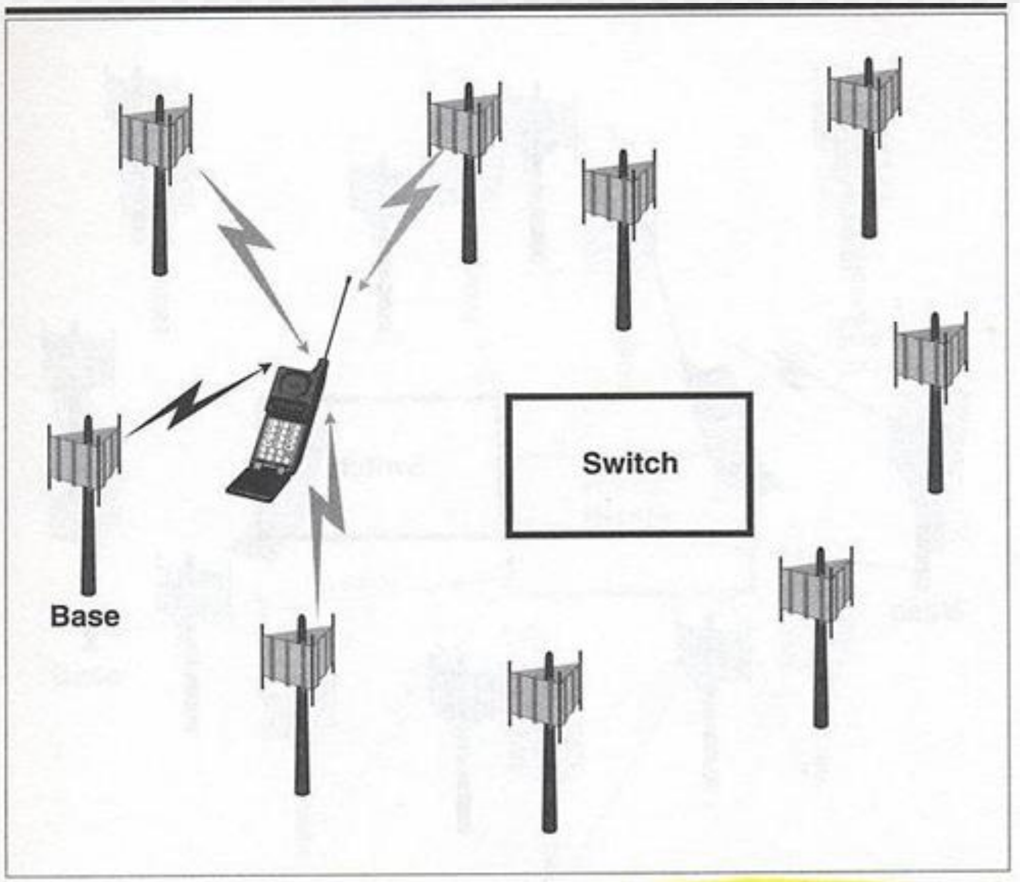
Celluar Call: a sample

- Susan’s telephone tunes to the strongest signal.
- Her request includes both her and Bill’s telephone numbers. BS relays the request to the switch.
- The switch commands several BS’s to transit paging messages containing Bill’s number.
- Bill’s phone responds to the paging message by informing the system of its location.

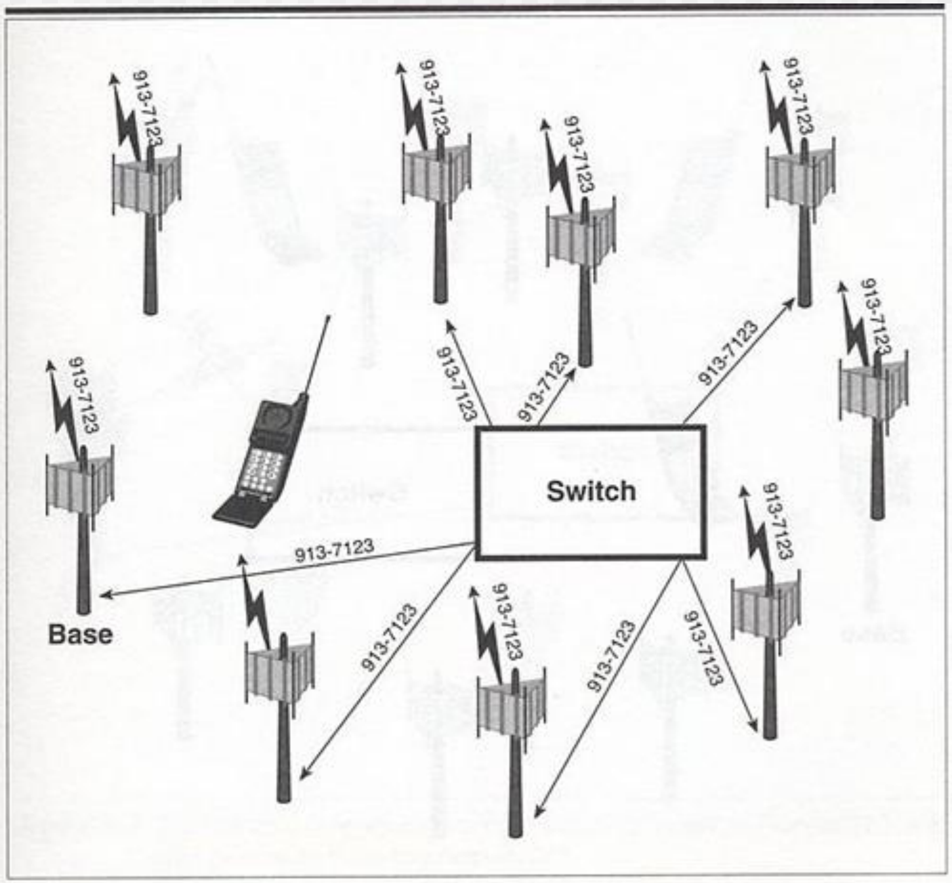
Cellular Call (Cont’d)

- The switch commands Susan’s phone to tune to channel X and Bill’s phone to channel Y.
- The cellular phone conversation starts.
- During the conversation, Bill moves to a new cell. The system rearranges itself to maintain the conversation.

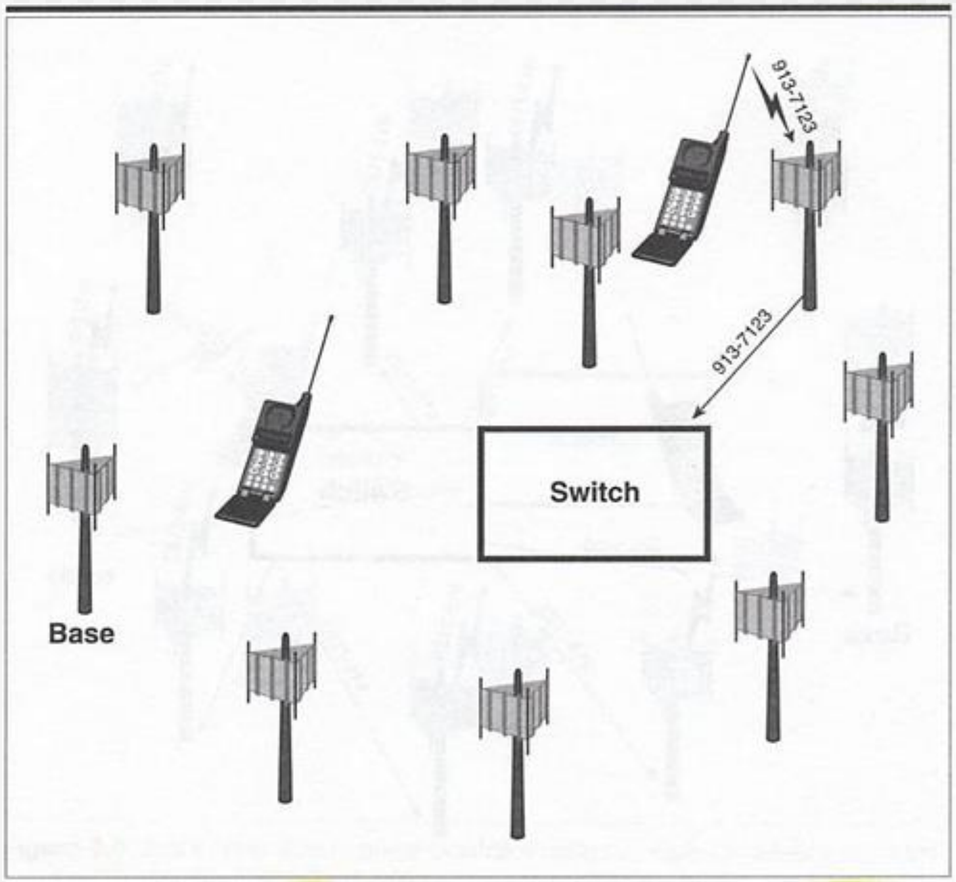
Cellular Call (Cont'd)



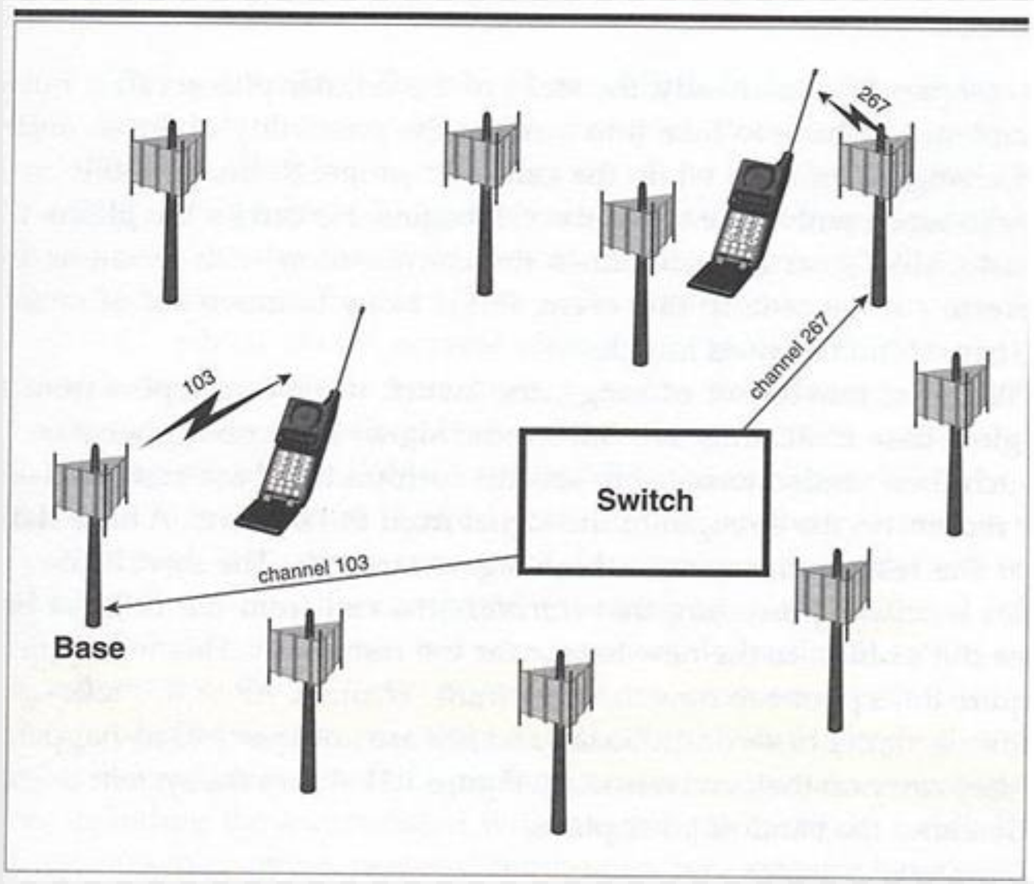
Cellular Call (Cont'd)



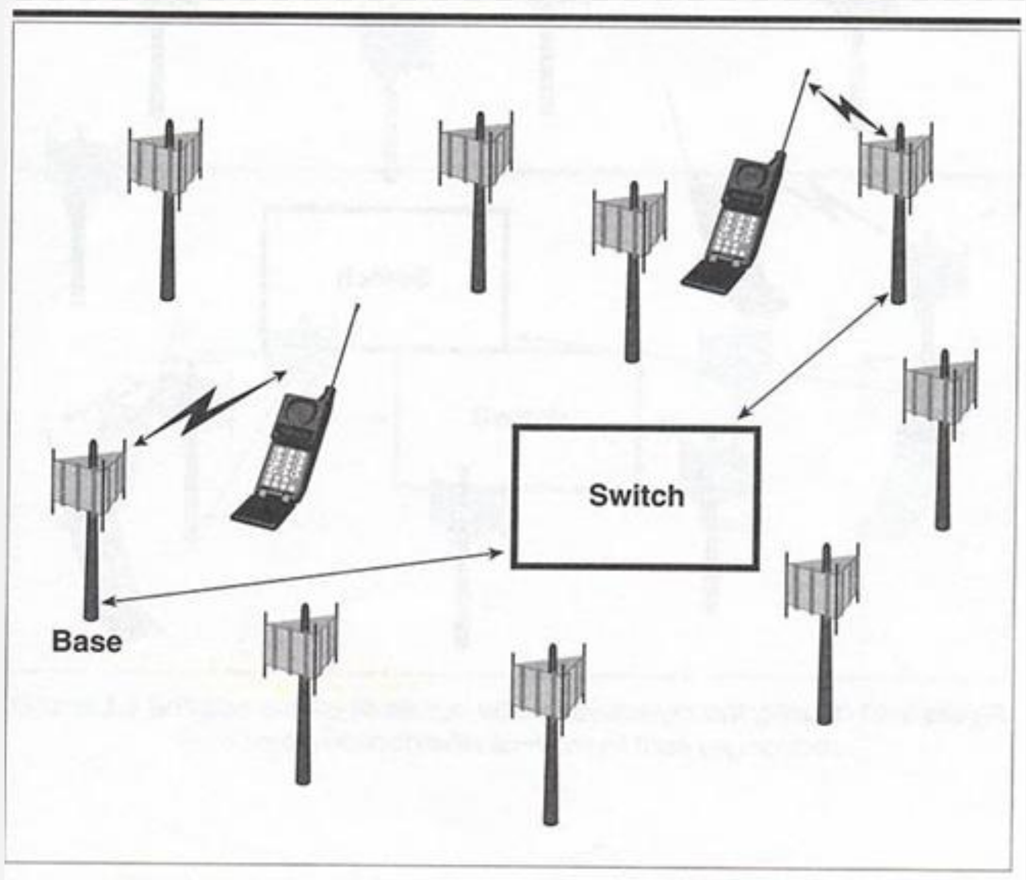
Cellular Call (Cont'd)



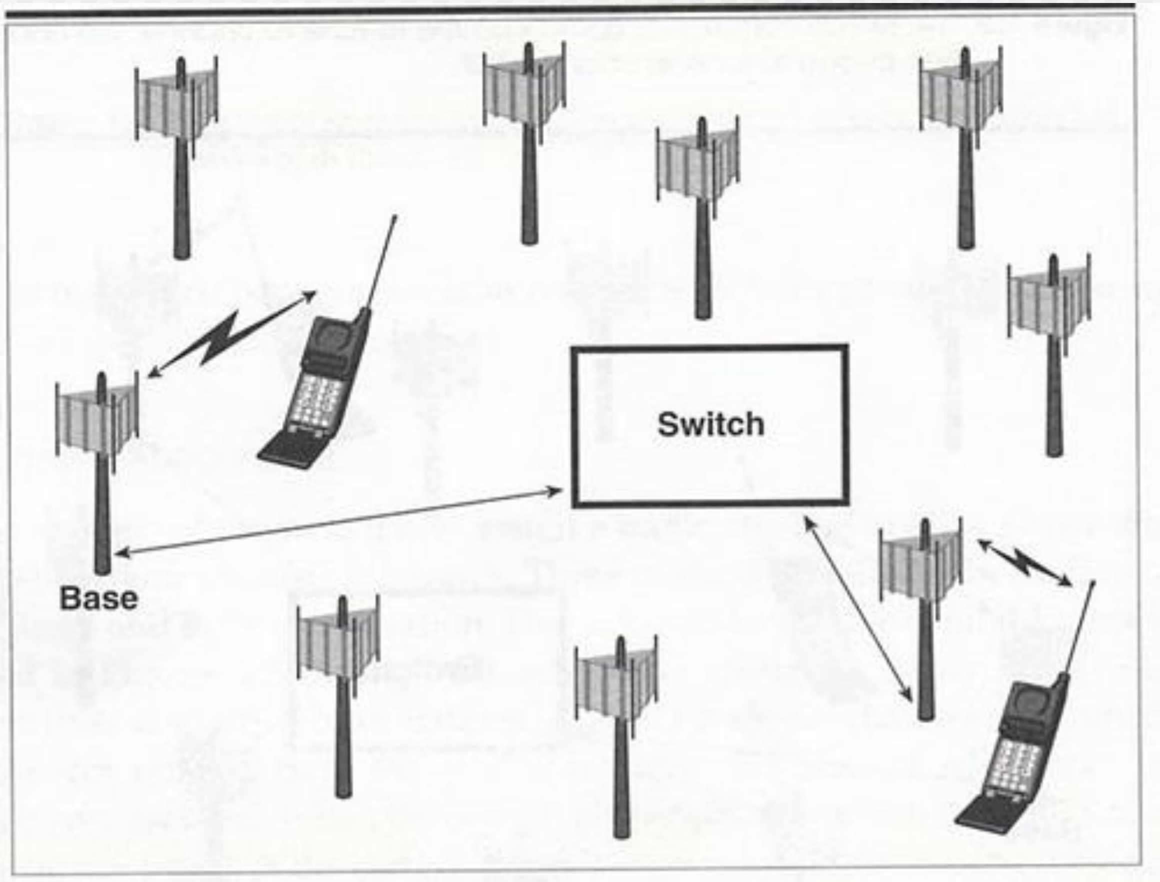
Cellular Call (Cont'd)



Cellular Call (Cont’d)

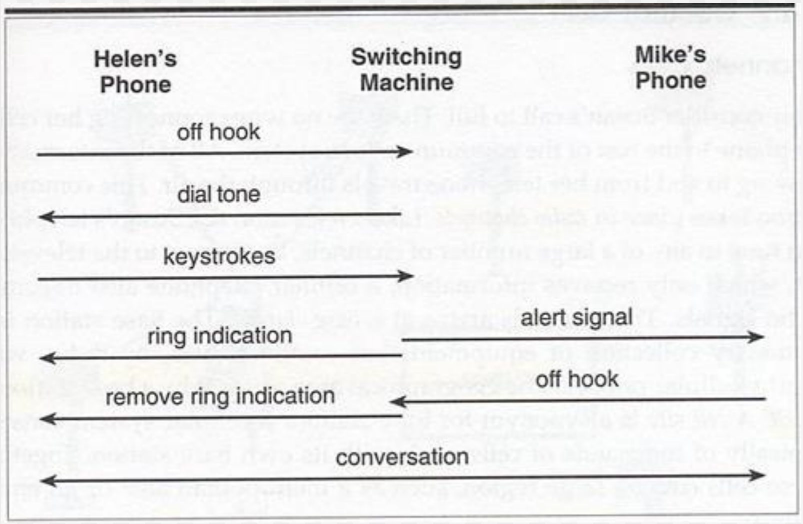


Cellular Call (Cont'd)



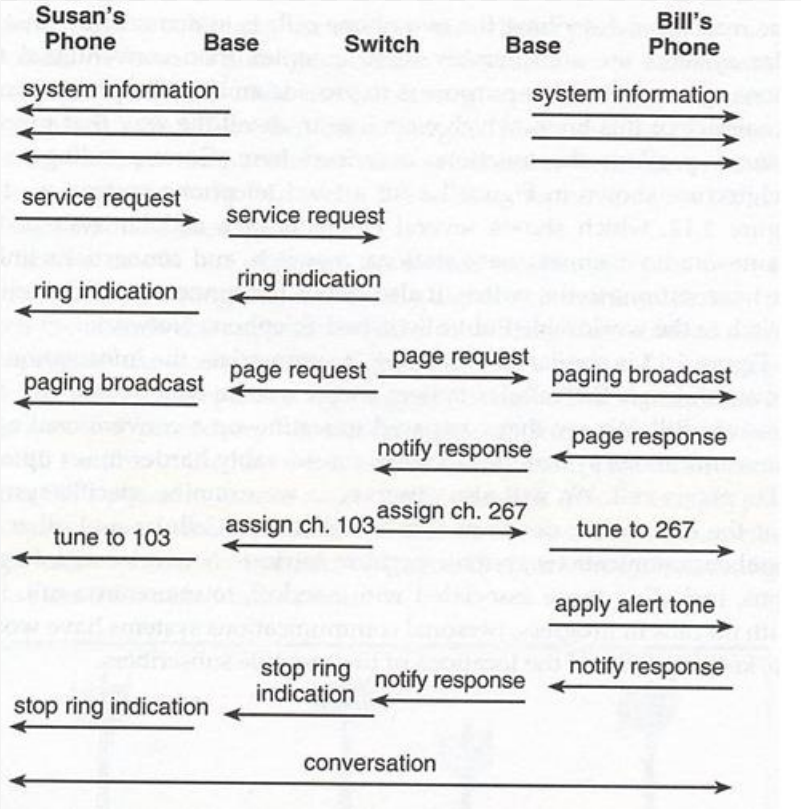
Cellular Call (Cont'd)

Information flow for conventional call



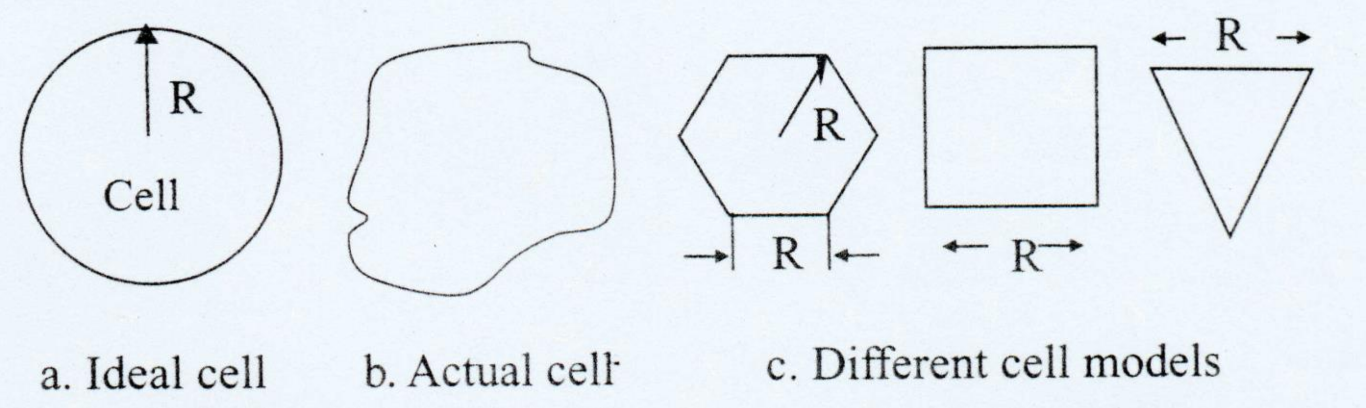
Cellular Call (Cont'd)

Information flow for cellular telephone call



Cellular Concept

- Cell: hexagon



MacDonald, “The Cellular Concept.” 1979

Cellular Concept

Shape of the Cell	Area	Boundary	Boundary Length/ Unit Area	Channels/Unit Area with N Channels/ Cells	Channels/Unit Area when Number of Channels Increases by a factor K	Channels/Unit Area when Size of Cell Is Reduced by a factor M
Square cell (side $= R$)	R^2	$4R$	$\frac{4}{R}$	$\frac{N}{R^2}$	$\frac{KN}{R^2}$	$\frac{K^2N}{R^2}$
Hexagonal cell (side$=$ R)	$\frac{3\sqrt{3}}{2}R^2$	$6R$	$\frac{4}{\sqrt{3}R}$	$\frac{N}{1.5\sqrt{3}R^2}$	$\frac{KN}{1.5\sqrt{3}R^2}$	$\frac{K^2N}{1.5\sqrt{3}R^2}$
Circular cell (radius $= R$)	πR^2	$2\pi R$	$\frac{2}{R}$	$\frac{N}{\pi R^2}$	$\frac{KN}{\pi R^2}$	$\frac{K^2N}{\pi R^2}$
Triangular cell (side $= R$)	$\frac{\sqrt{3}}{4}R^2$	$3R$	$\frac{4\sqrt{3}}{R}$	$\frac{4\sqrt{3}N}{3R^2}$	$\frac{4\sqrt{3}KN}{3R^2}$	$\frac{4\sqrt{3}K^2M^2N}{3R^2}$

Cellular Concept

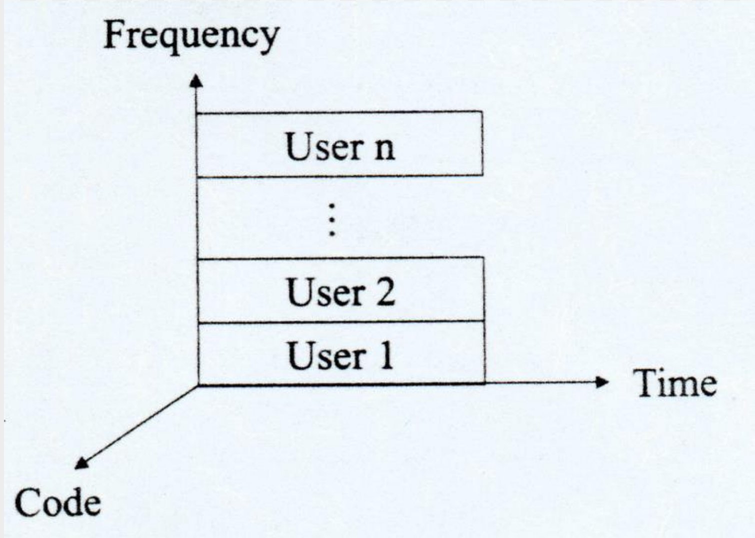
- Channels assigned to a cell
  - Forward (or downlink): channels used to carry traffic from the BS to MSs
  - Backward (or uplink): channels used to carry traffic from MSs to the BS
- Voice channel vs. control channel

Cellular Concept

- Multiple Radio Access
  - Contention-based: Aloha, CSMA
  - Conflict-free: FDMA, TDMA, CDMA,

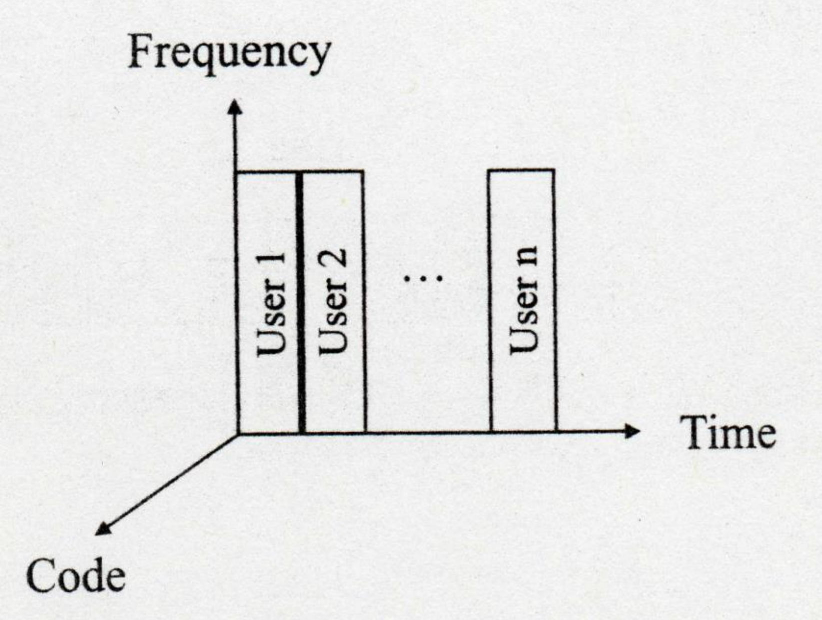
Cellular Concept

- Multiplexing techniques
  - FDMA (frequency division multiple access)



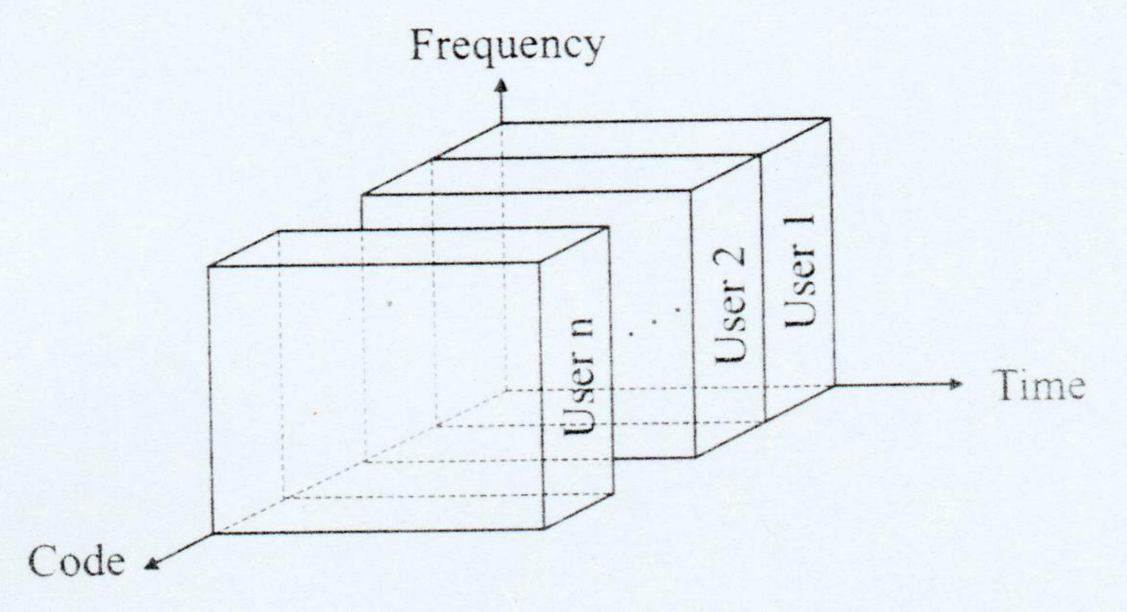
Cellular Concept

- Multiplexing techniques
  - TDMA (time division multiple access)
  - (GSM is based on TDMA)



Cellular Concept

- Multiplexing techniques
  - CDMA (code division multiple access)

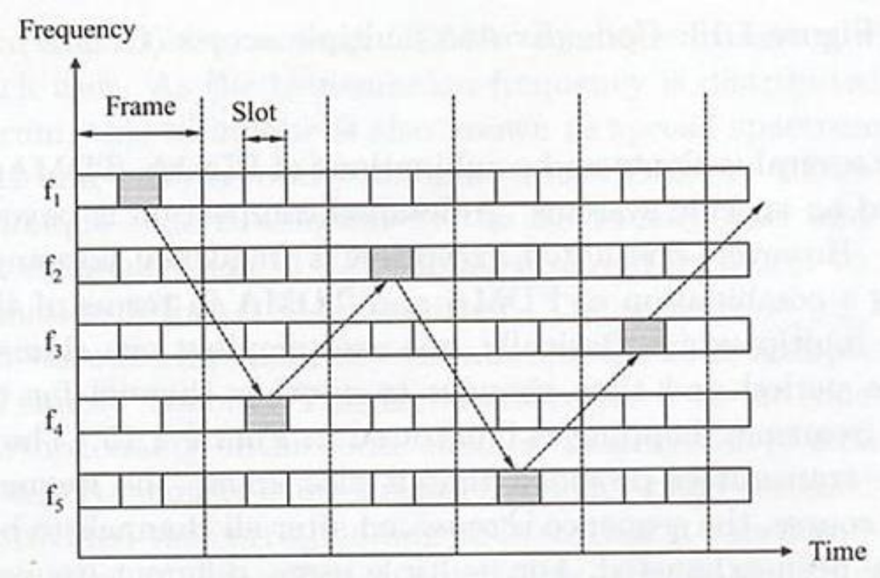


Cellular Concept

- Spread-spectrum technology
  - Make it less susceptible to the noise and interference by spreading over the bandwidth range of modulated signal
- Two methods used in CDMA
  - *Direct sequence*: one bit is represented by multiple bits in a spreading code.
  - *Frequency hopping:* a random sequence (also called hopping pattern) is used to change the signal frequency.

Cellular Concept

- Frequency hopping



Cellular Concept

- Cluster: a set of cells that you utilizes the entire available radio spectrum
- Channel Interference
  - Cochannel interference
  - Adjacent channel interference
  - Cosite channel interference

    (separated by k distance in frequency)

Cellular Concept

- Importance of Cellular Topology
  - U: # of users
  - W: available spectrum
  - B: bandwidth per user
  - N: frequency reuse factor (size of cluster)
  - M: # of cells required to cover an area

$$U = (M * W) / (N * B)$$

Cellular Concept

- Traffic Engineering
  - A cell is able to handle U simultaneous users that has L potential subscribers.
  - If $L \leq N$, the system is referred to as nonblocking, otherwise, it is blocking.
- Traffic intensity
  - $A=\lambda h$, where λ is the mean rate of calls attempted per unit time and h is the mean holding time per successful call.

Cellular Concept

- Cochannel reuse ratio

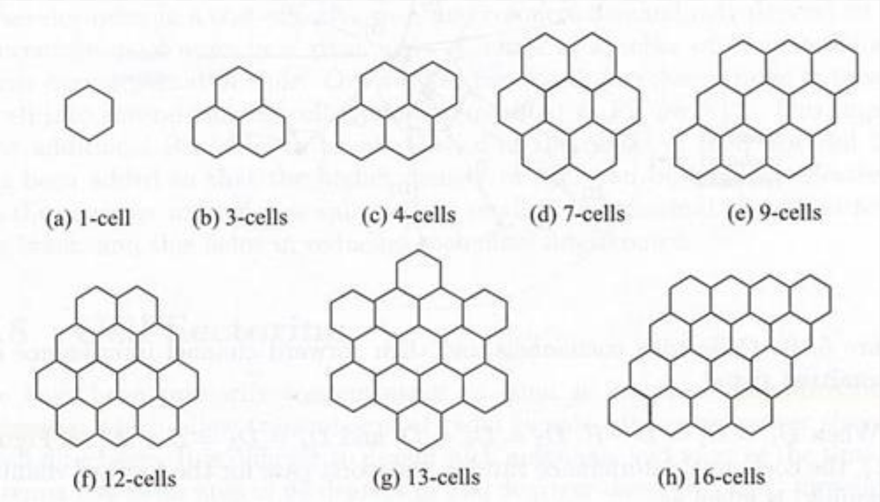
$$\frac{D}{R} = \sqrt{3N}$$

D: distance between cochannel cells
R: cell radius
N: cluster size

(N can only take on values of $I^2 + IJ + J^2$
for integers I and J)

Cellular Concept

- Cochannel reuse for N=1, 3, 4, 7, 9, 12, 13, 16



Cellular Concept

- Cochannel reuse for N=7

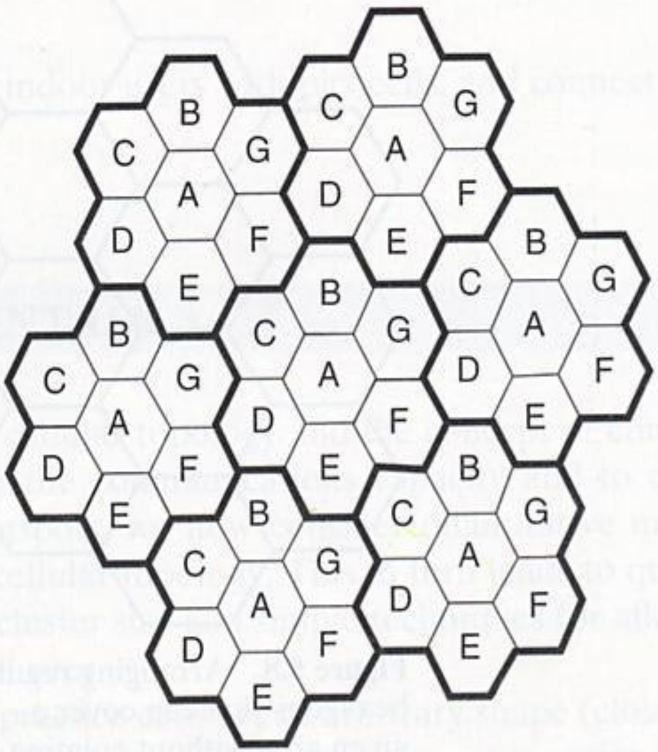


Figure 5.9 Hexagonal cellular architecture with a cluster size of $N = 7$.

Cellular Concept

- Carrier-to-Interference Ratio (CIR)

CIR = Pdesired / Pinterference

a: path-loss gradient (between 2 and 4)
signal strength: Pd^{-a}, where d1 is distance to signal and d2 is distance to interference

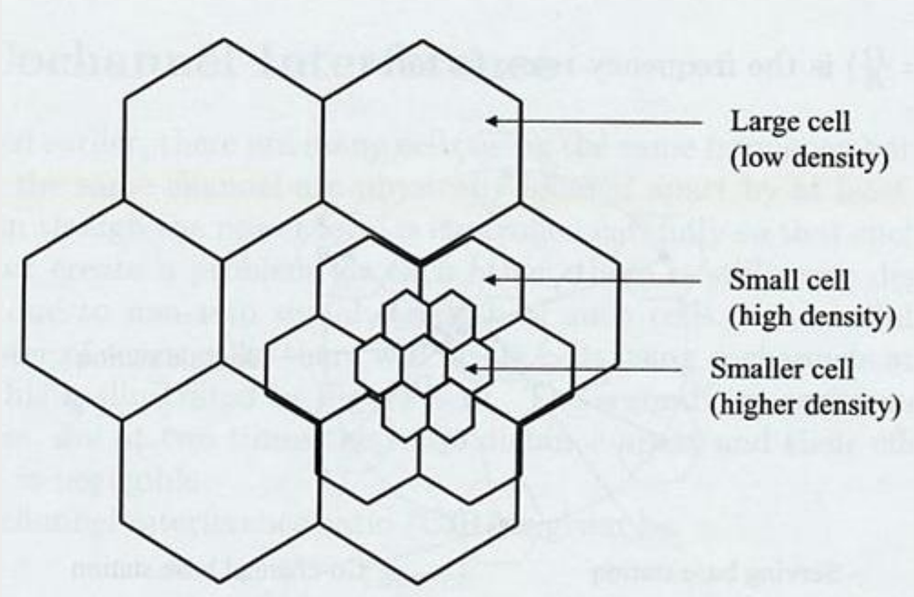
$$CIR = \frac{Pd_1^{-a}}{Pd_2^{-a}} = (\frac{d_2}{d_1})^a$$

Cellular Concept

- Capacity Expansion
  - Additional spectrum for new subscribers ($20 billion for PCS bands)
  - Change the cellular architecture: cell splitting and cell sectoring
  - Nonuniform distribution of the frequency bands
  - Change the modem and access technology

Cellular Concept

- Cell Splitting

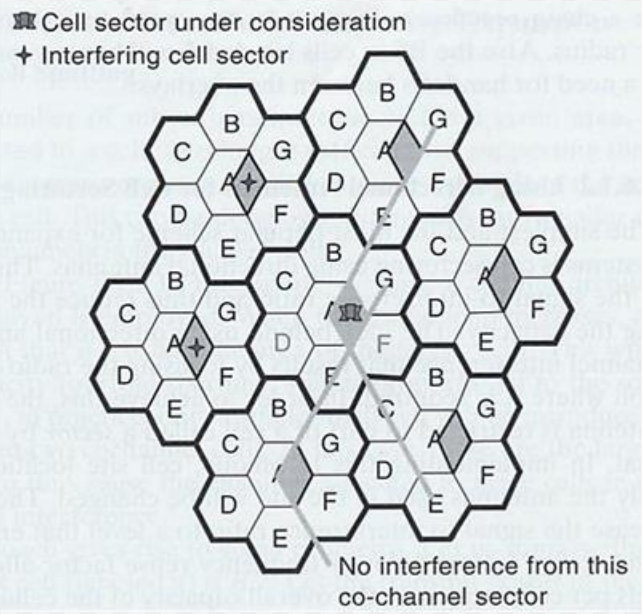


Cellular Concept

- Cellular Hierarchy
  - To extend the coverage area
  - To serve areas with higher density
- Picocells: local indoor
- Microcells: rooftops of buildings
- Macrocells: metropolitan areas
- Megacells: nationwide areas
- *Femtocells*: a special picocell but administered by end users

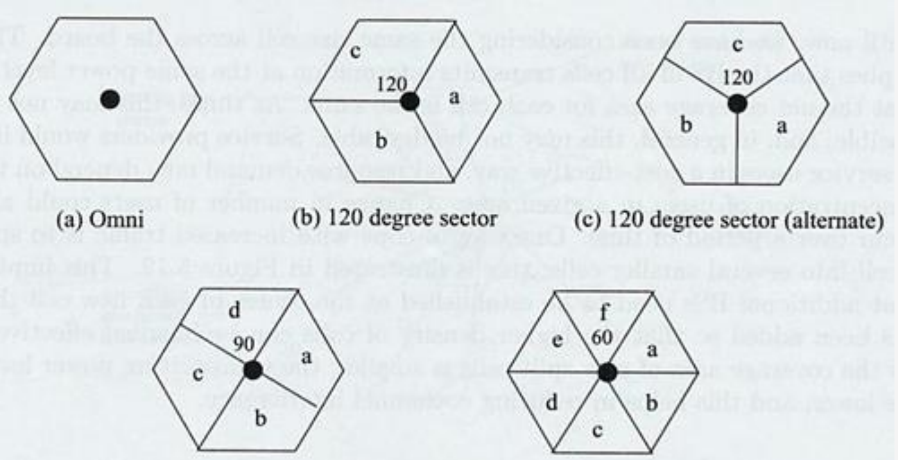
Cellular Concept

- Cell sectoring: Omnidirectional antennas vs directional antennas
- 120 degree directional antennas (3-sector cells)



Cellular Concept

- Different arrangements of directional antennas

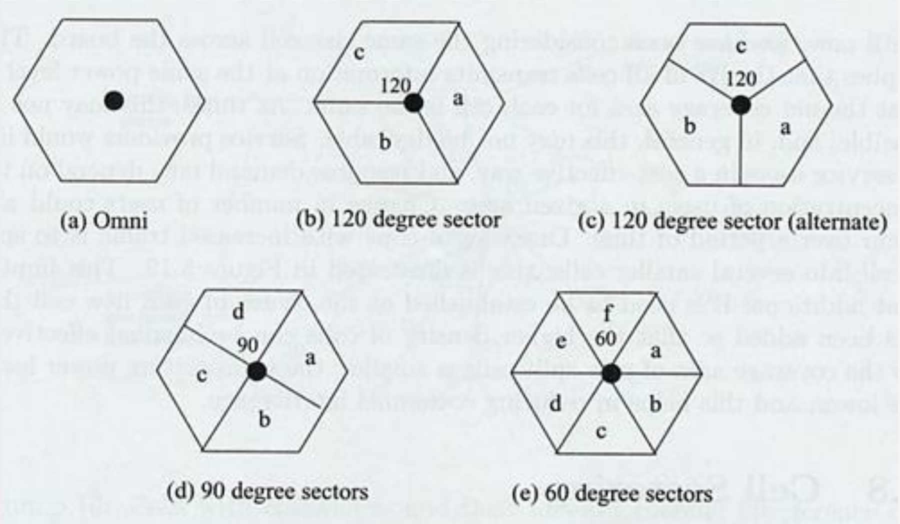


(a) Omni (b) 120 degree sector (c) 120 degree sector (alternate)

(d) 90 degree sectors (e) 60 degree sectors

Cellular Concept

- Different arrangements of directional antennas



Handoff

- Mobility Management
  - Handoff management
  - Location management

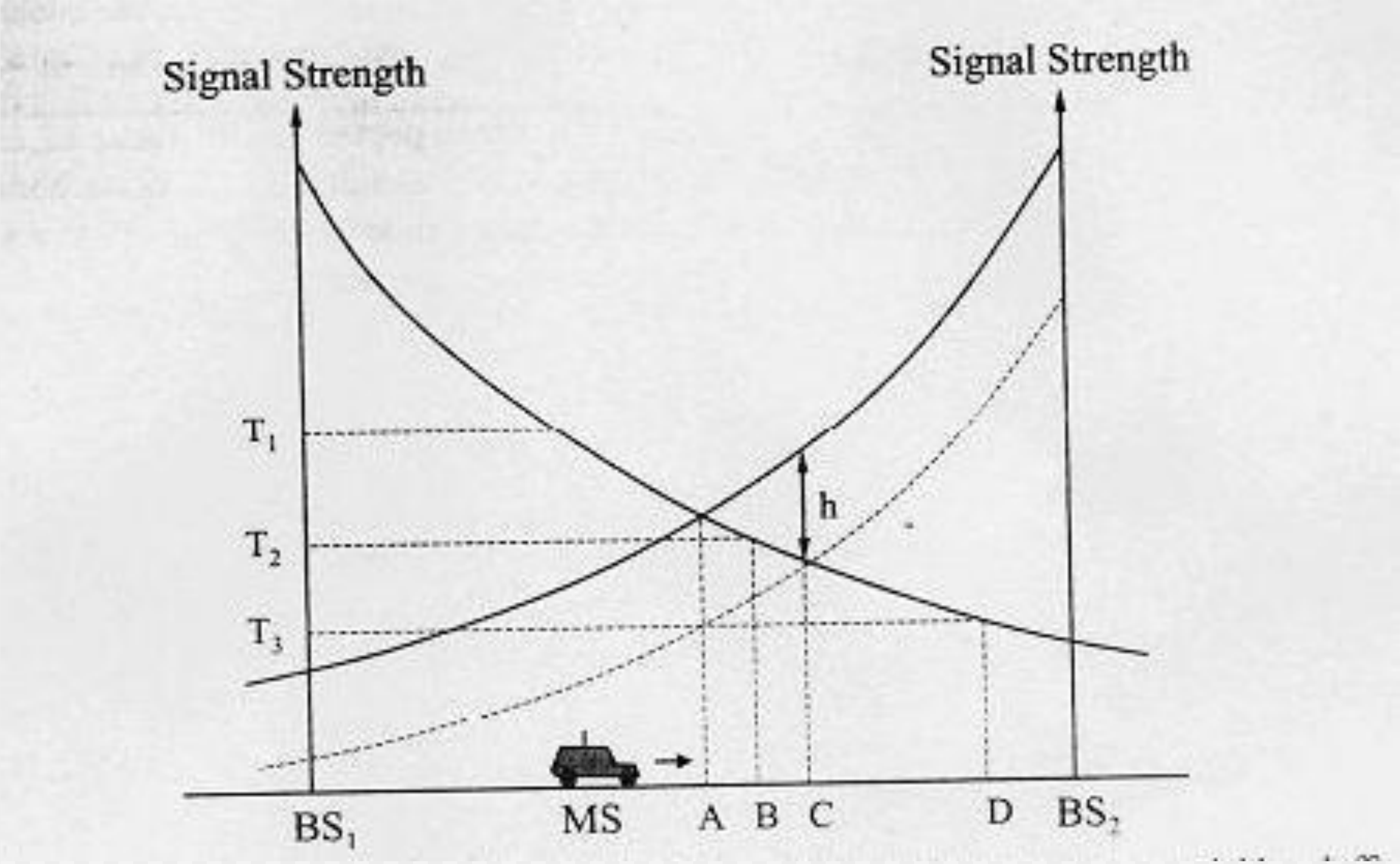
Handoff

- Handoff: provide continuous service by handover from one cell to another.
  - Hard handoff
    - break before make
    - TDMA and FDMA
  - Soft handoff
    - make before break
    - CDMA
- Signal strength contours (path loss)

Handoff

- Handoff Initiation
  - Relative signal strength (point A in the following figure)
  - Relative signal strength with hysteresis (point B): the value lags behind
  - Relative signal strength with threshold (point C): new BS is stronger by a margin H
  - Actual signal strength is below a given minimum strength (point D)

Handoff



Handoff

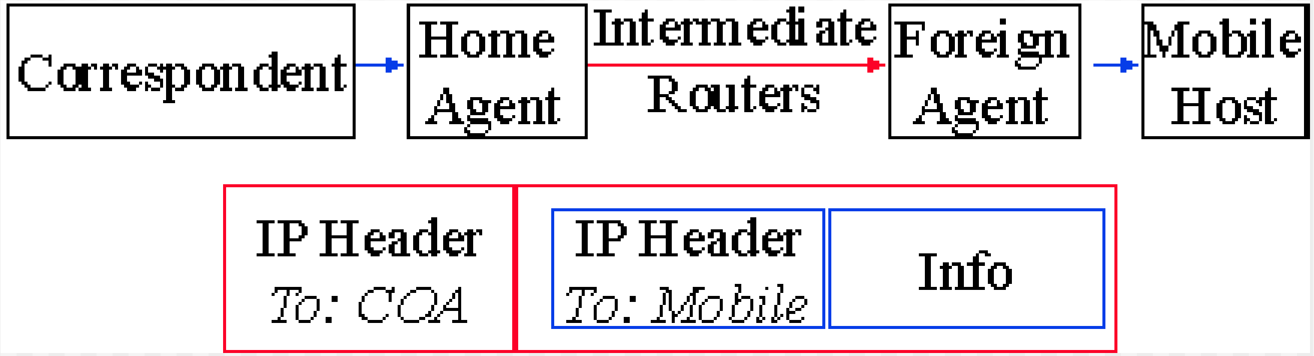
- Handoff Decision
  - Network-controlled handoff
    - Network makes a handoff decision and BSs collect measurements of MSs
  - Mobile-assisted handoff
    - MSs makes measurements and the network makes the decision
  - Mobile-controlled handoff
    - MS is completely in control of the handoff process

Internet and Wireless Internet

- Network Architecture
  - OSI reference model (7 layers)
    - Application, Presentation, Sessions, Transport, Network, Data Link, Physical
  - TCP/IP reference model (4 layers)
    - Application (Telnet, ftp, and http)
    - Transport (TCP and UDP)
    - Internet (IP)
    - Host-to-network (LAN: IEEE 802.11)
  - Others: ATM reference model

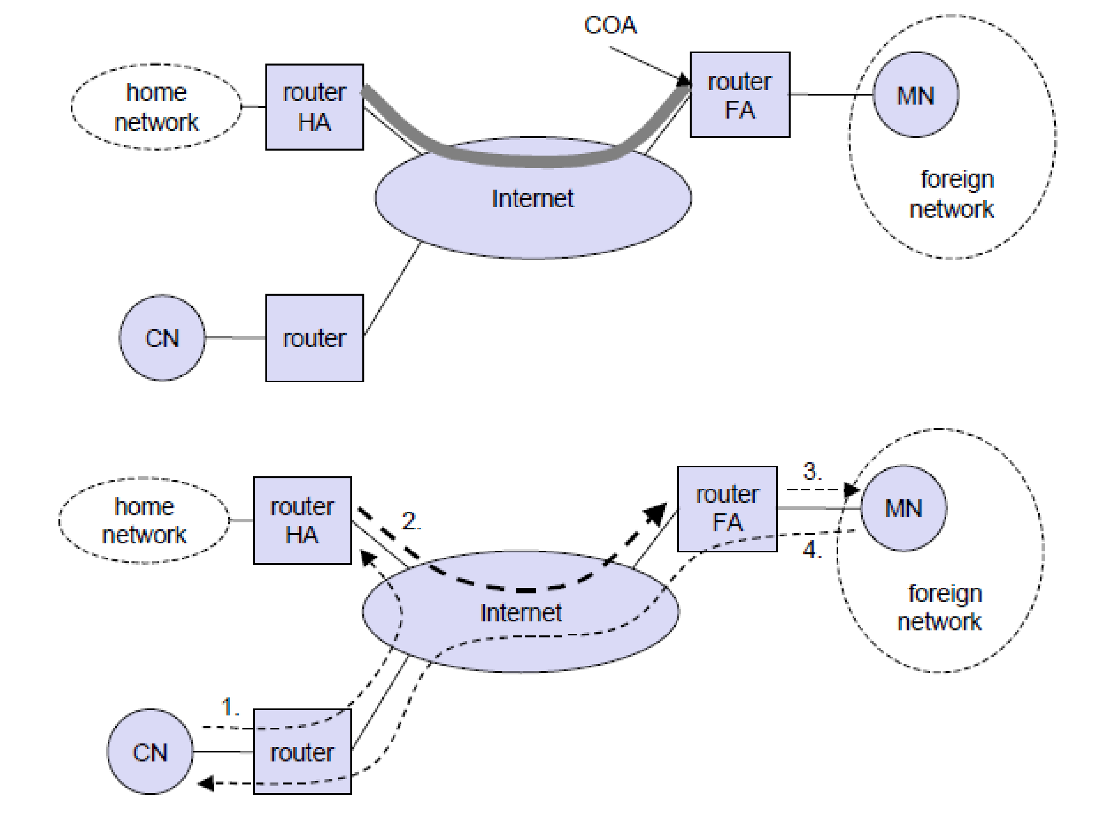
Mobile IP

- Compatibility, scalability, transparency.
- Concepts: Correspondent Node (CN), Foreign Agent (FA), Mobile Node (MN)
- Home Address (HA): Mobile's permanent IP address
- Care-of Address (COA): Address of the end-of-tunnel towards the MN.



Mobile IP

- Encapsulation and tunneling (to COA)
- Transfer to MN (1, 2, and 3) and from MN (4)



Transfer to MN

- Mobile IP (home agent, foreign agent, and care-of address): transfer to MN
  1. CN X transmits a message for mobile node A and the message is routed to A’s home network
  2. The home agent encapsulates the entire message inside a new message which has the A’s care-of address in the header and retransmits the message (called tunneling)
  3. The foreign agent strips off the outer IP header and delivers the original message to A

Wireless TCP

- Traditional TCP
  - Any loss is due to congestion
  - Current congestion window size is halved.
- Solutions
  - Snoop TCP (BS snoops traffic and keeps a backup)
  - Indirect TCP (BS acts as proxy between CN and MN)
  - Explicit loss notification (retransmit without congestion control mechanism)

Location Management

- Location management:

  Activities a wireless network should perform in order to keep track of where the MS is

  - Location updates
  - Paging
  - Location information dissemination

Location Management

- Location update

  Messages sent by the MS regarding its changing points of access to the fixed network

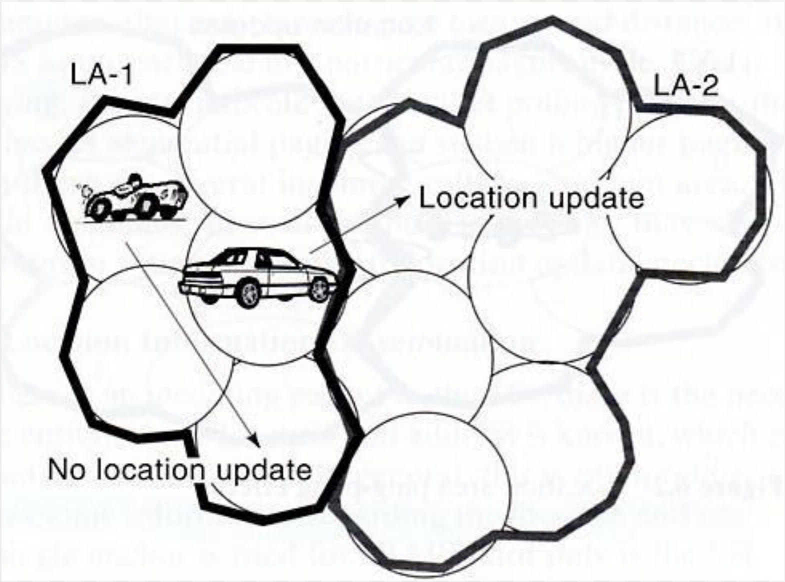
  - *Static location update*: the topology of the cellular network decides when the location update needs to be initiated
  - *Dynamic location update*: the mobility of the user, as well as the call patterns, is used in initiating location updates

Location Management

- Location Management Schemes
  - Location areas (LA)
    - Each LA consists of several contiguous cells
    - The BS of each cell broadcasts the ID of the LA to which the cell belong
  - Reporting center (RC)
    - A subset of cells is designated as RCs
    - The vicinity of a RC is the collection of all non-RCs that are reachable from the RC without crossing another RC
    - How to select of a set of RCs to minimize the total location management cost.

Location Management

- Location area (LA): a set of cells controlled by a MSC



Location Management

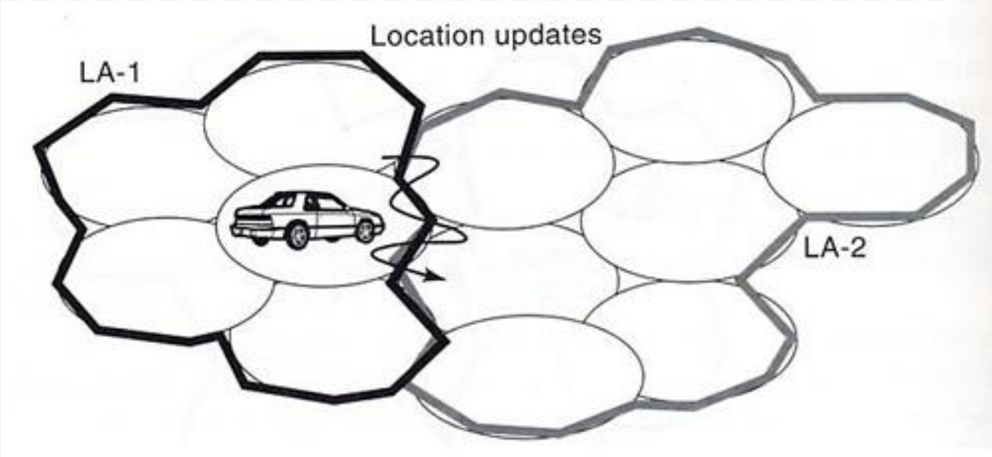
- Two types of database for tracking
  - Home location register (HLR)
  - Visitor location register (VLR)
- Location Registration
  - Register the MS as the new serving VLR
  - Update the HLR to record the ID of the new serving VLR
  - Deregister the MS at the old serving VLR

Location Management

- Location update
  - Each BS in the LA broadcasts its id number periodically
  - An MS is required to continually listen to the control channel for the LA id
  - When the id changes, the MS will make an update to the location by transmitting a message with the new id to the database containing the location information

Location Management

- Avoiding the ping-pong effect:



Location Management

- Update Strategies
  - Time-based
    - When a MS enters a new cell, it needs to find out the number of cells that will be paged if an incoming call arrive and the resulting cost for the network to page the mobile station.
    - The weighted paging cost is the paging cost multiplied by the call arrival probability.
    - A location update will be performed when the weighted paging cost exceeds the location update cost

Location Management

- Movement-based
  - Each MS keeps a count (init. 0) after each location update.
  - The count is increased by one when NS crosses the boundary between two cells.
  - When the count reaches a predefined threshold, the MS updates its location and resets the count to 0.

Location Management

- Distance-based
  - Each MS keeps track of distance between the current cell and the last reported cell.
  - The MS updates its location if the distance reaches a predefined threshold.
- Other tracking strategies
  - Profile-based
  - Topology-based
  - Load-sensitive-based

Location Management

- Location update vs. paging
  - Trade-off between the cost of the nature, number, and frequency of location updates, and the cost of paging
- Location information dissemination
  - The procedures that are required to store and distribute the location information relate to the MS’s
  - The use of HLR and VLR

Location Management

- Some optimization techniques
  - Multiple Ids
    - store the id’s of two most recently visited LAs
  - Maintaining cache of LA info
  - Pointer forwarding
    - Reporting can be eliminated by simply setting up a forwarding pointer from the old VLR to the new VLR
  - Local anchoring
    - A VLR close to the MS is selected as its local anchor
    - The HLR keeps a pointer to the local anchor

Location Management

- Call Delivery
  - Determining the serving VLR
  - Locating the visiting cell of the called MS (through paging)
- Paging: broadcasting a message in LA
  - Blanket paging with an LA (used in GSM)
  - Closest-cells first with ring search
  - Sequential paging

Location Management

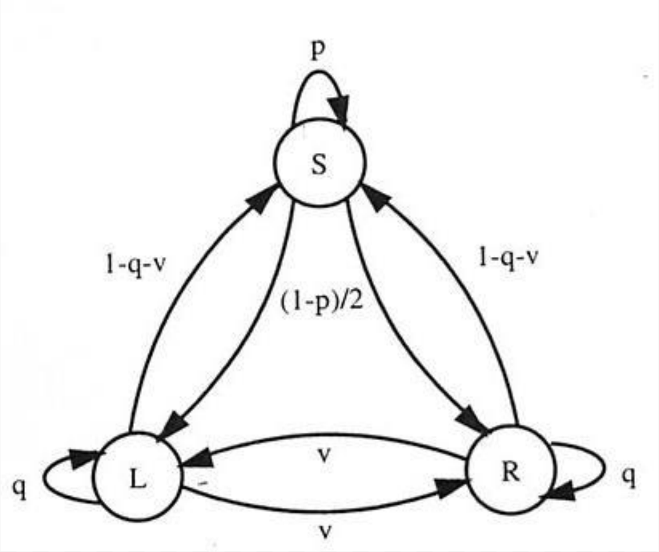
- Some Common Assumptions
  - Network topology
    - 1-D networks: linear array and ring
    - 2-D networks: hexagon and mesh
  - Call arrival probability
    - Known call arrival time (can update location just before the call arrival)
    - Poisson process

Location Management

- Mobility models
  - Fluid flow model: continuous movement with infrequent speed and direction changes
  - Random walk model: time is slotted. The probability that the subscriber remains in the current cell is *p* and to a neighbor is *(1-p)/n*, where n is the number of neighbors (memoryless)
  - Markov walk model: the current move is dependent on the previous move.
  - Normal walk model: The I th move, M(I), is obtained by rotating the (I-1) th move, M(I-1), counterclockwise for Θ(I) degrees, where Θ(I) is normally distributed with zero mean

Location Management

- A sample Markov walk model

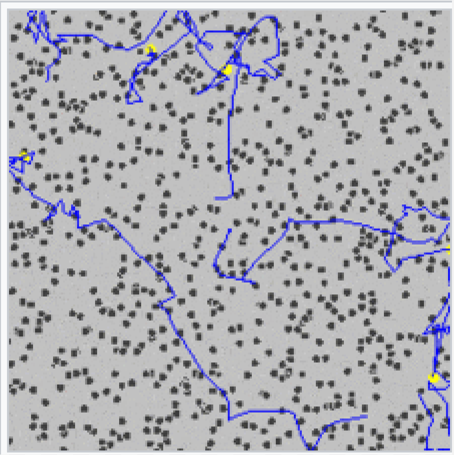


Entity Mobility Model with Bound

- Random walk model
  - Occurs in a time interval or a distance travelled, at the end of which a new direction and speed are calculated
  - Einstein: Brownian motion model

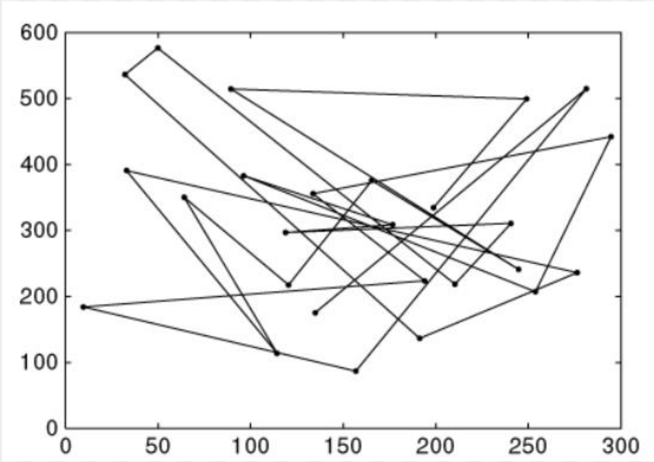
    Random motion of particles suspended in a fluid resulting from their collision with the fast-moving atoms or molecules in the liquid
  - Polya

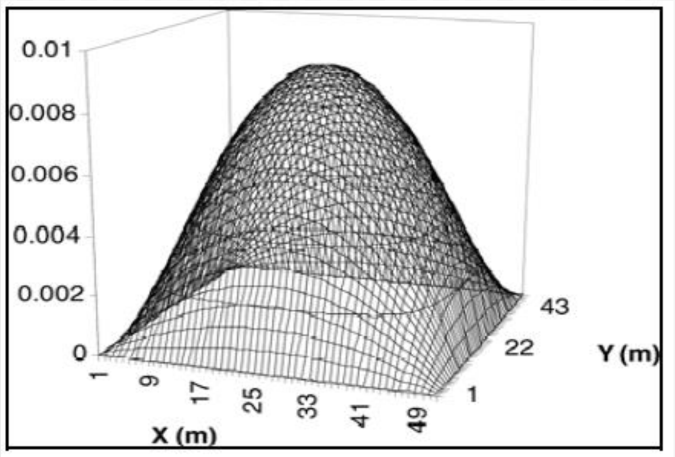
    A random walk on a 1-D or 2-D surface returns to the origin with complete certainty



Entity Mobility Model with Bound

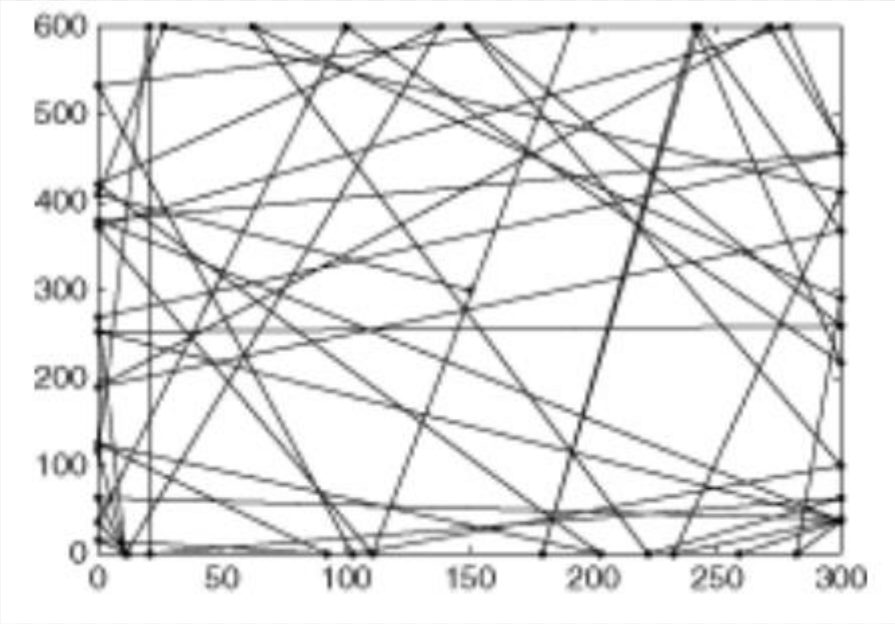
- Random waypoint model
  - Include pause times between changes in direction and/or speed, for a given location or time period
  - Issue: non-uniform spatial distribution
  - Solution: modified random waypoint or random direction





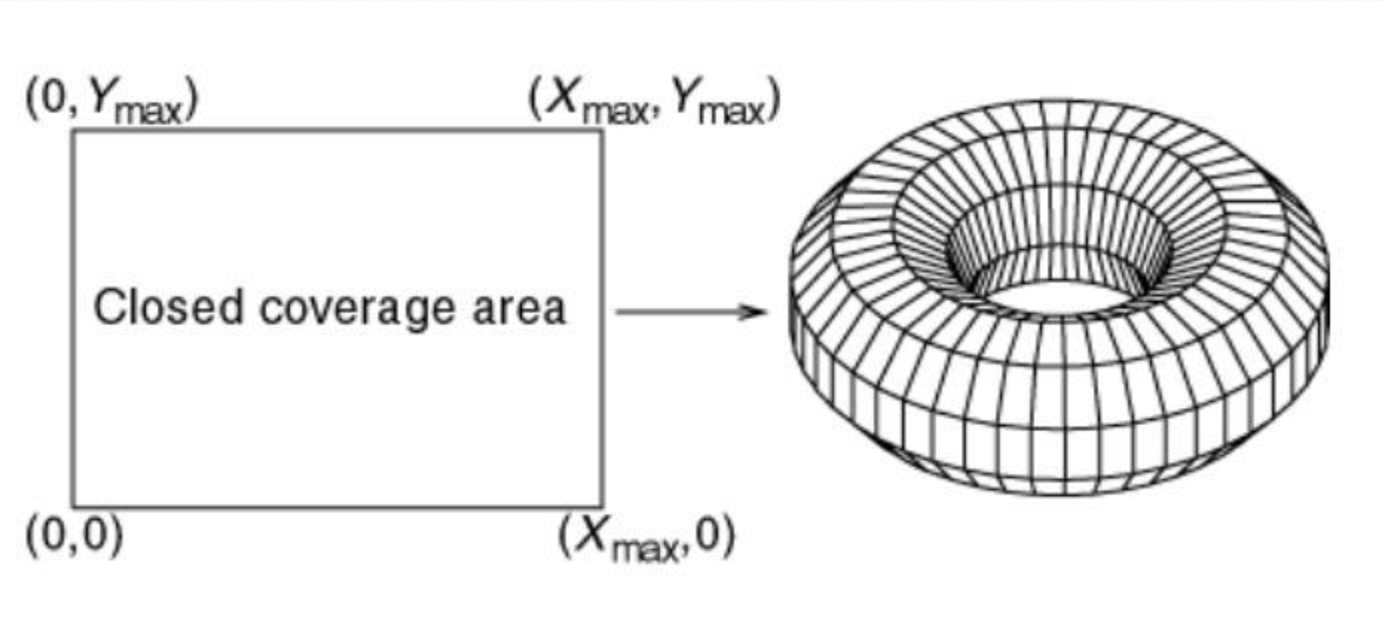
Entity Mobility Model with Bound

- Random direction model
  - Once the simulation boundary is reached, the mobile node pauses for a specified time, chooses another angular direction and continues the process.



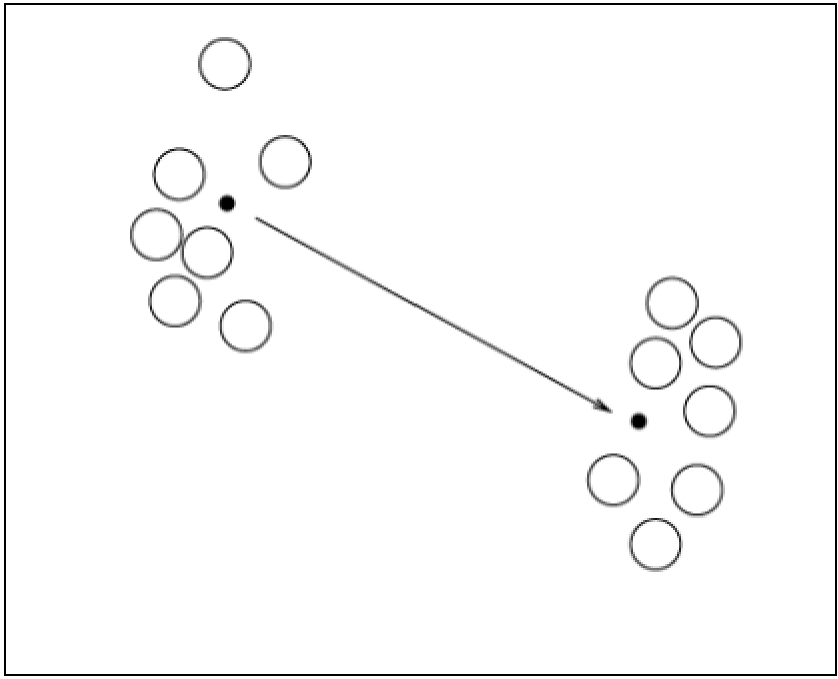
Entity Mobility Model without Bound

- Boundless simulation area
  - Mesh to Torus conversion



Group Mobility Model

- Column mobility
- Nomadic community mobility
- Pursue mobility
- Reference point group mobility



Camp, "A Survey of Mobility Models for Ad Hoc Network Research," WCMC, 2002.

Channel Assignment

Three constraints in channel assignment

- *Frequency constraints*: the number of available frequencies (channels) in the radio spectrum.
- *Traffic constraints*: the minimum number of frequencies required by each station.
- *Interference constraints*: the constraints on the placement of frequencies at different stations.

  (e.g. CIR in each co-channel is above the required minimum.)

Channel Assignment

Three types of interference constraints

- *Cochannel constraints*
- *Adjacent channel constraints*
- *Cosite constraints*: any pair of channels assigned to a radio cell must occupy a certain distance in the frequency domain.

Channel Assignment

- *Fixed channel assignment* (FCA): channels are nominally assigned to cells in advance according to the predetermined estimates traffic intensity.
- *Dynamic channel assignment* (DCA): channels are assigned dynamically as calls arrive.
- FCA works better in heavy traffic conditions

Channel Assignment

Other extensions and combinations:

- *Hybrid channel assignment* (HCA): channels are divided into two groups: one uses FCA and the other uses DCA.
- *Borrowing channel assignment* (BCA): channel assignment is still fixed, but each cell can borrow channels from its neighboring cells.

Channel Assignment

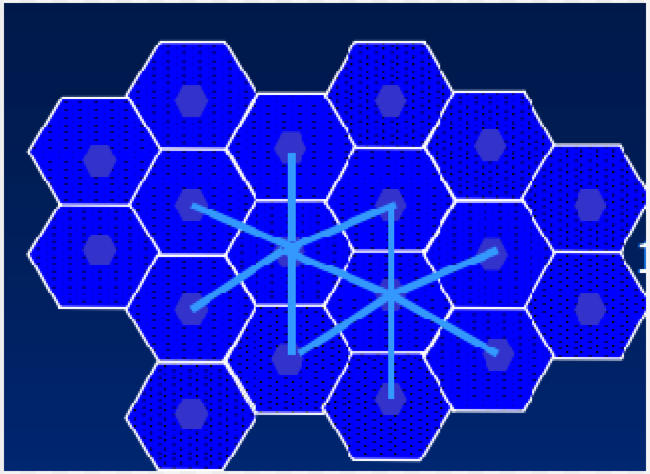
- Other approaches
  - With handoff: intracell and intercell
    - Direct some of the calls currently in process to attemp handoff to an adjacent cell
  - Power control: to achieve the desired CIR level
    - Reuse partition: each cell in the system is divided into two or more cocentric subcells (zones). The power required to achieve the desired CIR level is lower in inner zones.

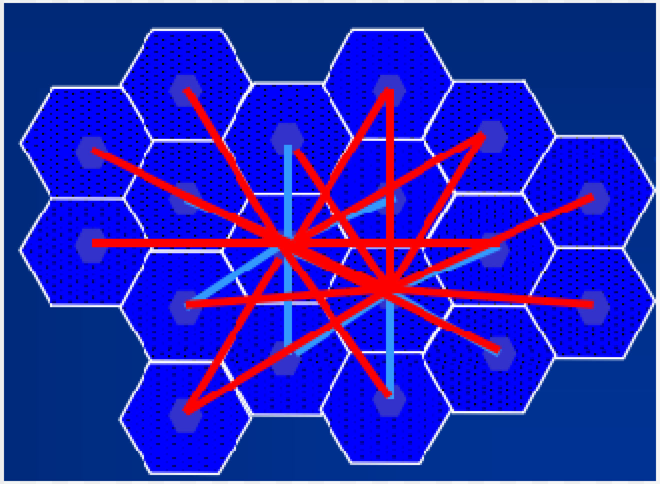
Channel Assignment

Models:

- Cellular network: graph G=(V, E) where V is the set of cells and E represents the set of adjacent cells.
- Weighted graph:
  - Weighted associated with links: separation of frequencies
  - Weighted associated with nodes: amount of frequencies

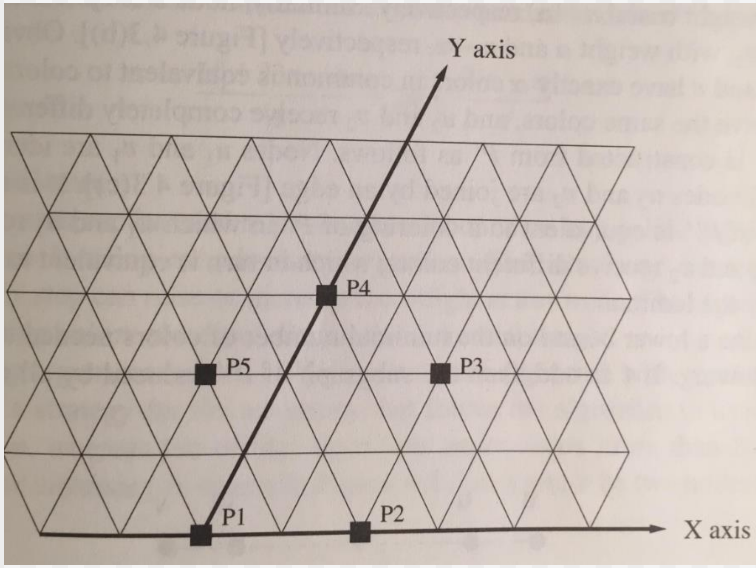
Cellular Network Graph





Cellular Coordinate

- Cell address



Cell:
ix+jy
x: (1, 0), y: (1/2, √3/2)

Six neighbors of cell (i, j):
(i±1, j), (i, j±1), (i+1, j-1), (i-1, j+1)

Example: P1: 0x+0y, P5: -1x+2y = (0, √3)
P4: 0x+3y = (3/2, 3 √3/2)

Channel Assignment

- Graph Labeling:
  - Constraint is a nonincreasing sequence of positive inter parameters c0, c1, …, ck.
  - Channels assigned to cells at graph distance i from each other must have a separation of at least ci.
- Recoloring (in a dynamic network):
  - Multicoloring as a sequence of weighted graphs {(G, w(t)): t >0}, where w(t)(u) is the number of calls to be served at node u at time t.
  - A challenge is to develop algorithms that do allow recoloring but only a limited amount.

Channel Assignment

Channel Assignment as a mapping problem:

- Optimization problem (NP-complete)
  - Sample combinatorial formulations
  - Heuristic techniques
- Graph coloring problem (with cochannel constraints only)
  - Graph models
  - Lower bounds

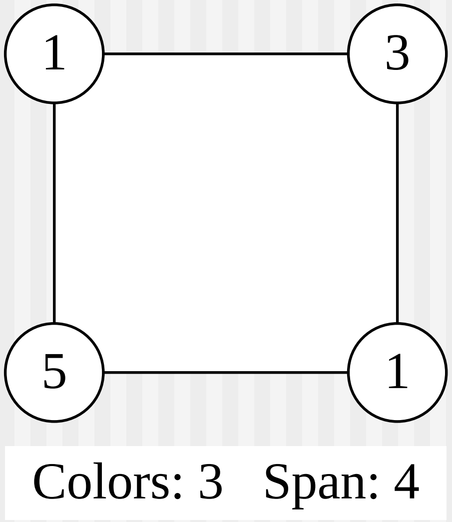
Channel Assignment

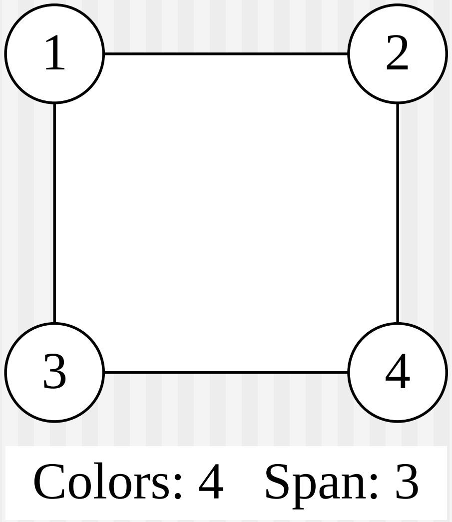
Frequency Assignment Problem (FAP):

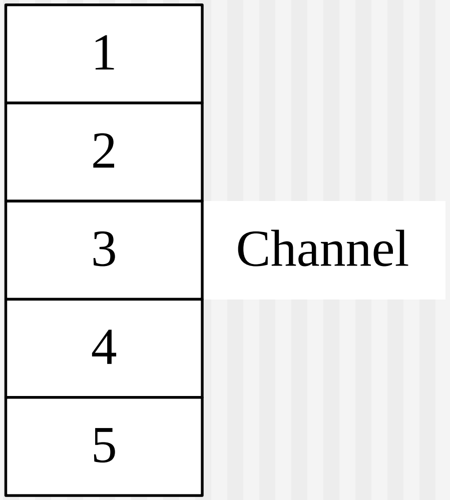
- *Minimum color FAP*: minimize the number of different frequencies used.
- *Minimum span FAP*: minimize the span (difference between max and min frequency used).
- *Minimum (total) interference FAP*: minimize the total sum of weighted interference.
- *Minimum blocking FAP*: minimize the overall blocking probability of the cellular networks.

Minimum Colors vs Span

Minimum colors and minimum span are different







Channel Assignment

Heuristic techniques:

- *Neural networks*
- *Evolutionary algorithms: Genetic algorithm*
- *Fuzzy logic*
- *Simulated annealing*
- *Tabu search*
- *Swarm intelligence* (collective behavior of animals)

Channel Assignment

A new heuristic is acceptable if:

- It can produce high-quality solutions more quickly than other methods,
- it identifies higher-quality solutions better than other approaches,
- it is easy to implement, or
- it has applications to a broad range of problems.

Channel Assignment

Graph model: multicoloring

- Weighted graph $(G=(V, E), w)$ and color set C
- Function f assigns each v in V a subset of $f(v)$ of C such that
  - For all $|f(v)|=w(v)$: each node gets $w(v)$ colors.
  - For all (u,v) in E, $f(u)$ and $f(v)$ have no common element: two neighboring nodes get disjoint sets of colors.
- Vertex coloring vs. edge coloring

Channel Assignment

Graph model: multicoloring with reuse distance of r.

- Define *G′=(V′, E′)* based on *G=(V, E)* such that
  - *V=V′* and $E = E \cup E^2 \cup \ldots \cup E^{r-1}$
  - Any pair of nodes at distance *d* < *r* in *G* is connected by an edge in *G′*.

Channel Assignment

Lower bounds:

- Clique: a complete subgraph.
- Weighted clique number: $\omega(G, w)$
  - Maximum weight of any maximal clique in the graph.
- Weighted clique number is a lower bound for the multicoloring problem.

Channel Assignment

Lower bounds:

- Minimum odd cycle: *n*
- Another lower bound: 2W/*(n-1)*,
  - *W* is the sum of weights of all nodes in the cycle
  - The maximum size of an independent set in an *n*-node odd cycle is (*n-1)/2*.