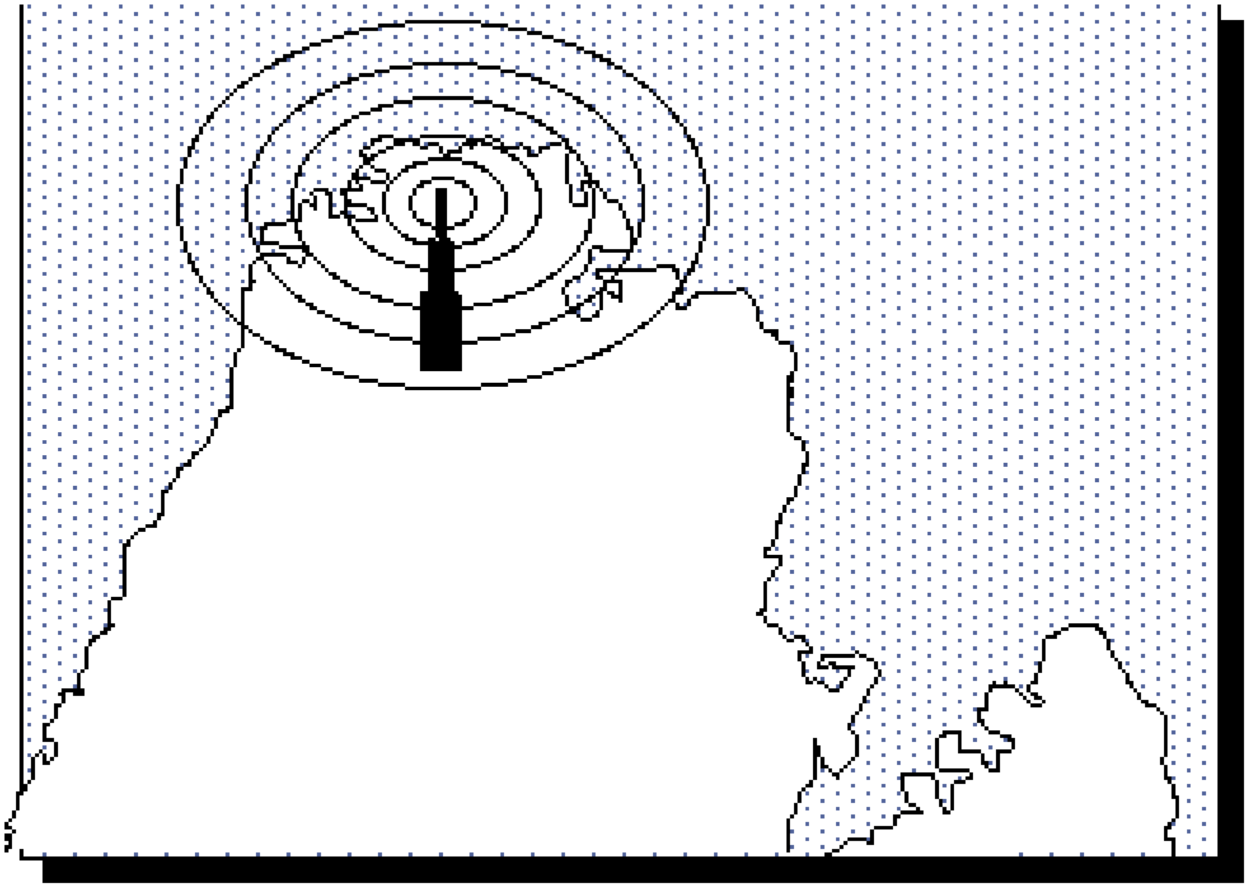
Cellular Wireless Networks

Early Mobile Networks

- Objectives of Early Mobile Radio Networks
  - Achieve large coverage area
  - Used single high power transmitter with an antenna mounted on a tall tower
  - Impossible to reuse frequency without interference
  - Bell Mobile Network in New York in 1970s could only support a maximum of 12 simultaneous calls over a 1000 sq. miles

Early Mobile System



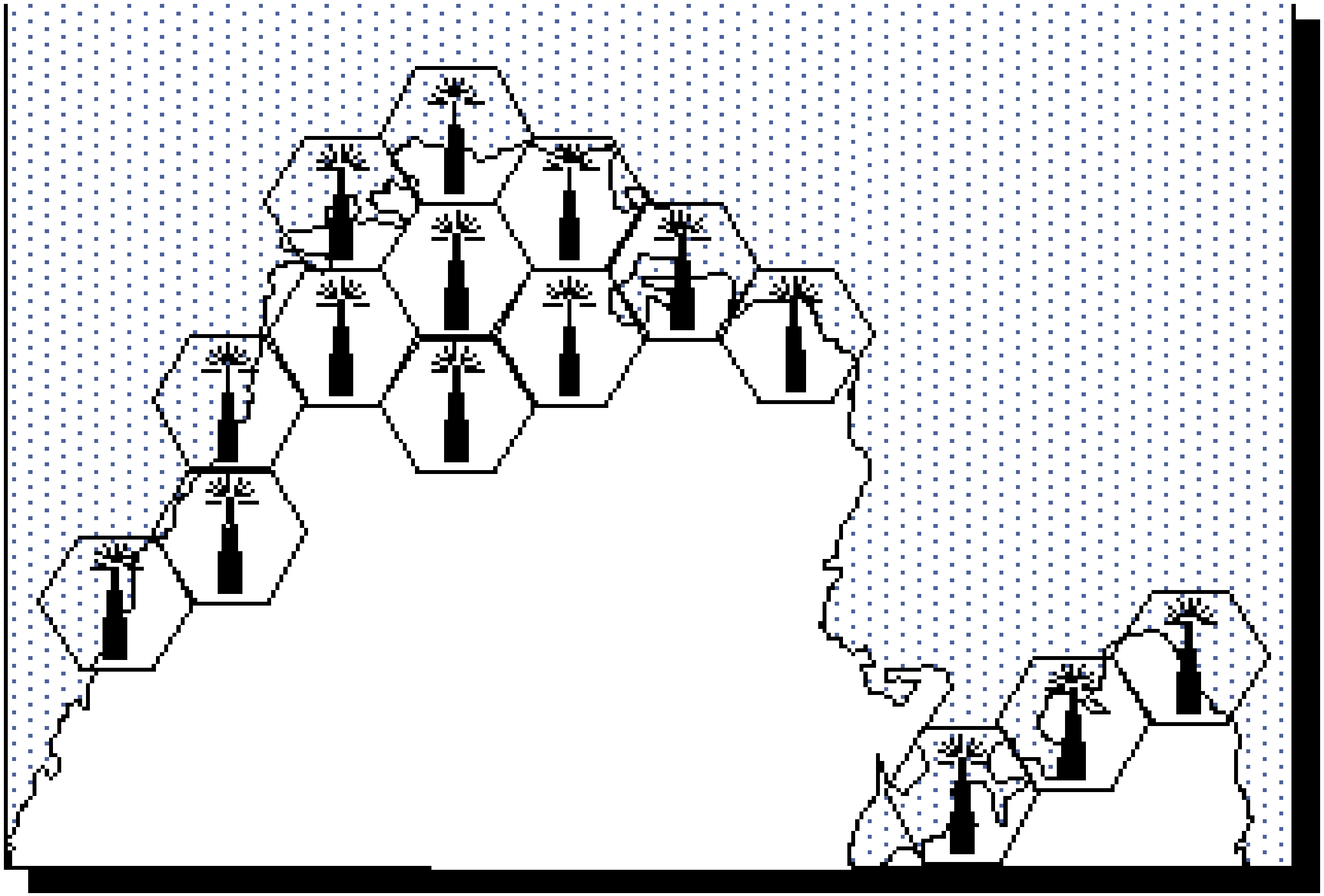
Birth of Cellular Concept

- Demand for Mobile Services kept on increasing
- Government Regulating Agencies could not make spectrum allocation in proportion to the demand
- It became imperative to restructure the radio telephone network - **cellular concept was invented**

Cellular concept

- Major breakthrough in solving the problem of spectral congestion & user capacity
- It offered very high capacity in a limited spectrum allocation without any major technological changes
- System Level idea where a single high power (large cell) transmitter is replaced with many low power transmitters (small cells)
- Each small cell providing coverage to only a small portion of service area
- This is the fundamental principle of modern wireless networks

Cellular System



Cellular Concept

- Each base station is allocated a portion of the total number of channels available to the entire system
- Nearby base stations are assigned different groups of channels
- All the available channels are assigned to a small number of neighbouring base stations
- Neighbouring base stations are assigned different groups of channels to minimize interference between base stations

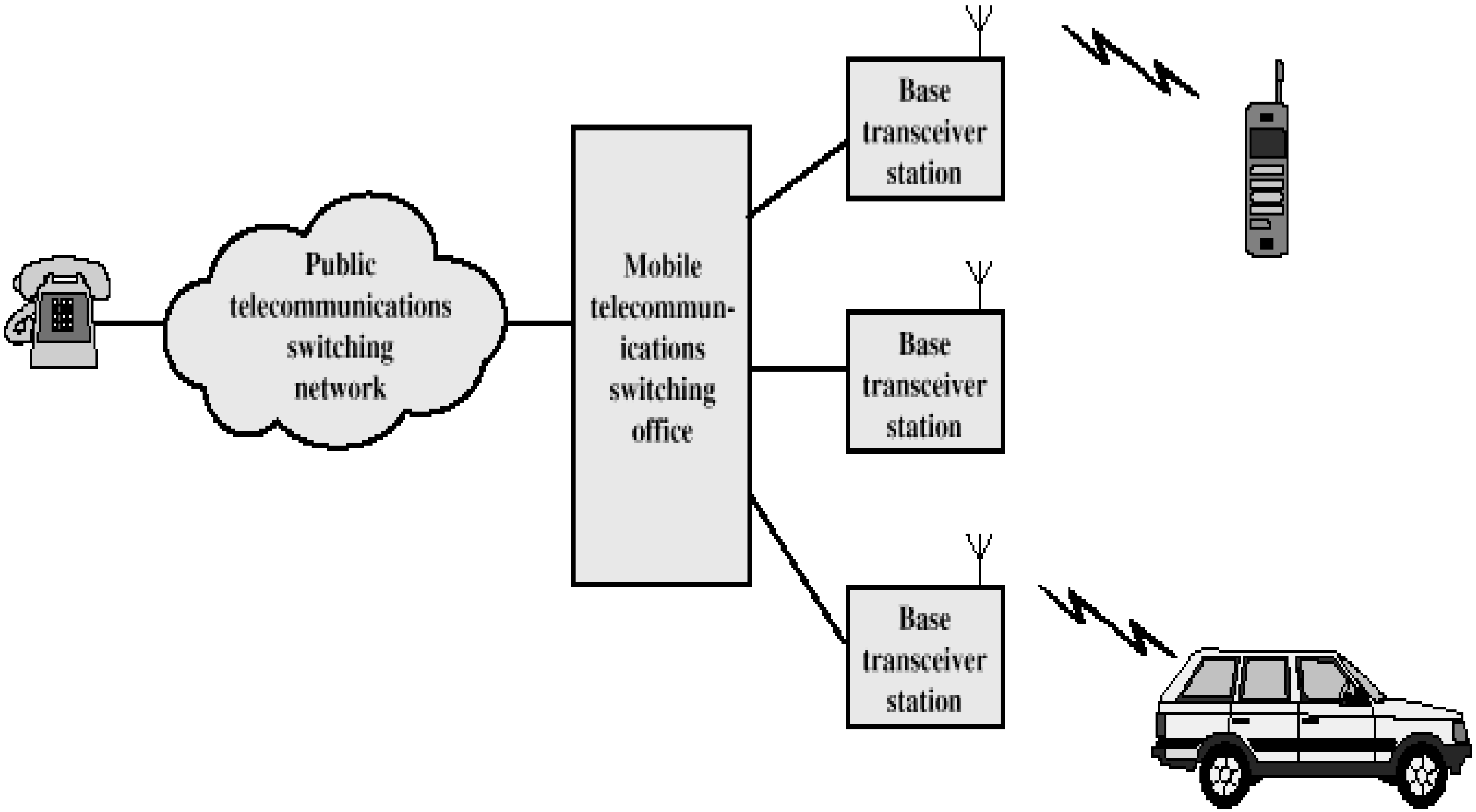
Cellular Network Organization

- 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)

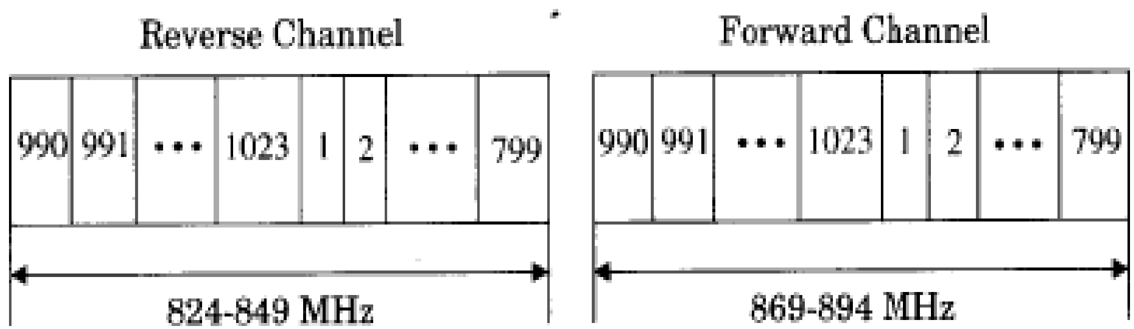
Frequency Reuse

- 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
  - The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called **FREQUENCY REUSE**

Cellular System



Frequency Spectrum Allocation



	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \leq N \leq 799$	$0.030N + 825.0$
	$990 \leq N \leq 1023$	$0.030(N - 1023) + 825.0$
Forward Channel	$1 \leq N \leq 799$	$0.030N + 870.0$
	$990 \leq N \leq 1023$	$0.030(N - 1023) + 870.0$

(Channels 800 - 989 are unused)

FCC Spectrum Allocation

- In 1983 FCC allocated 40MHz of spectrum in the 800 MHz band for US AMPS (666 Duplex Channels)
- Each Channel having one-way bandwidth of 30 kHz or 60 kHz for each duplex channel
- According to FCC, each city (market) was allowed to have TWO cellular radio system providers
- In 1989, FCC granted an additional 10MHz (166 Duplex Channels)

Wireless System Definitions

- Base Station: A fixed station in a mobile radio system.
- Control Channel: Radio channels used for transmission of call setup, call request, call initiation and other beacon purposes
- Forward Channel: Radio Channel used for transmission of information from the Base Station to the Mobile

Wireless System Definitions

- Mobile Station: Can be hand-held or installed in vehicle
- Mobile Switching Center (MSC): connects the cellular base stations and the mobiles to PSTN. Also called MTSO
- Reverse Channel: Radio Channel used for transmission from Mobile to Base Station
- Roamer: A mobile station which operates in a service area other than that from which service has been subscribed

Wireless System Definitions

- Page: A brief message broadcast over the entire service area
- Full Duplex: Allows simultaneous two-way communication, FDD or TDD
- Half Duplex: At any given time user can only either transmit or receive information
- Handoff: The process of transferring a mobile station from one channel or base station to another

Examples of Mobile Radio Systems

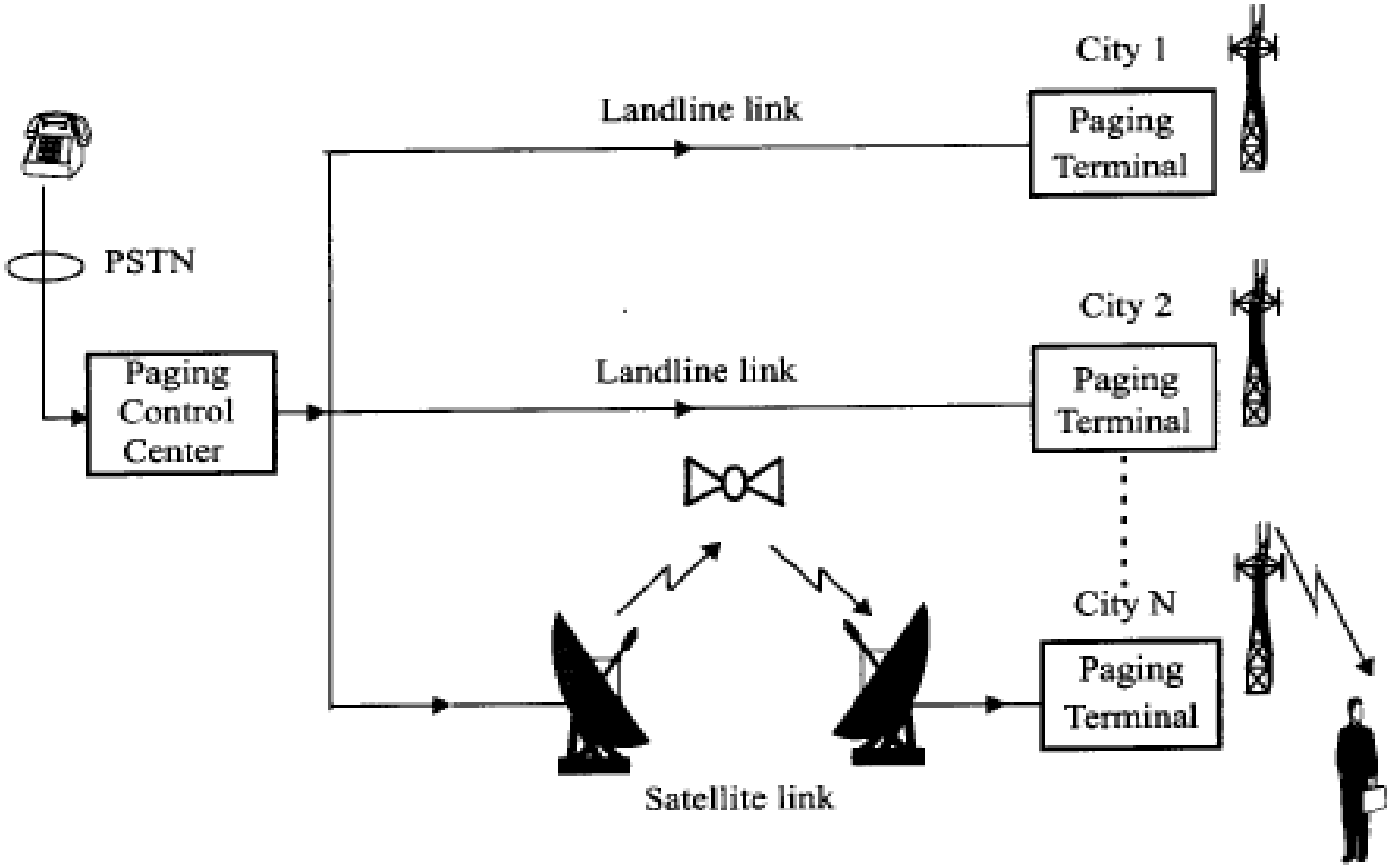
- Garage door openers
- Remote controllers for home entertainment systems
- Cordless phones
- Walkie-Talkies
- Pagers
- Cellular telephone

Cost, complexity, & performance of these systems vary widely

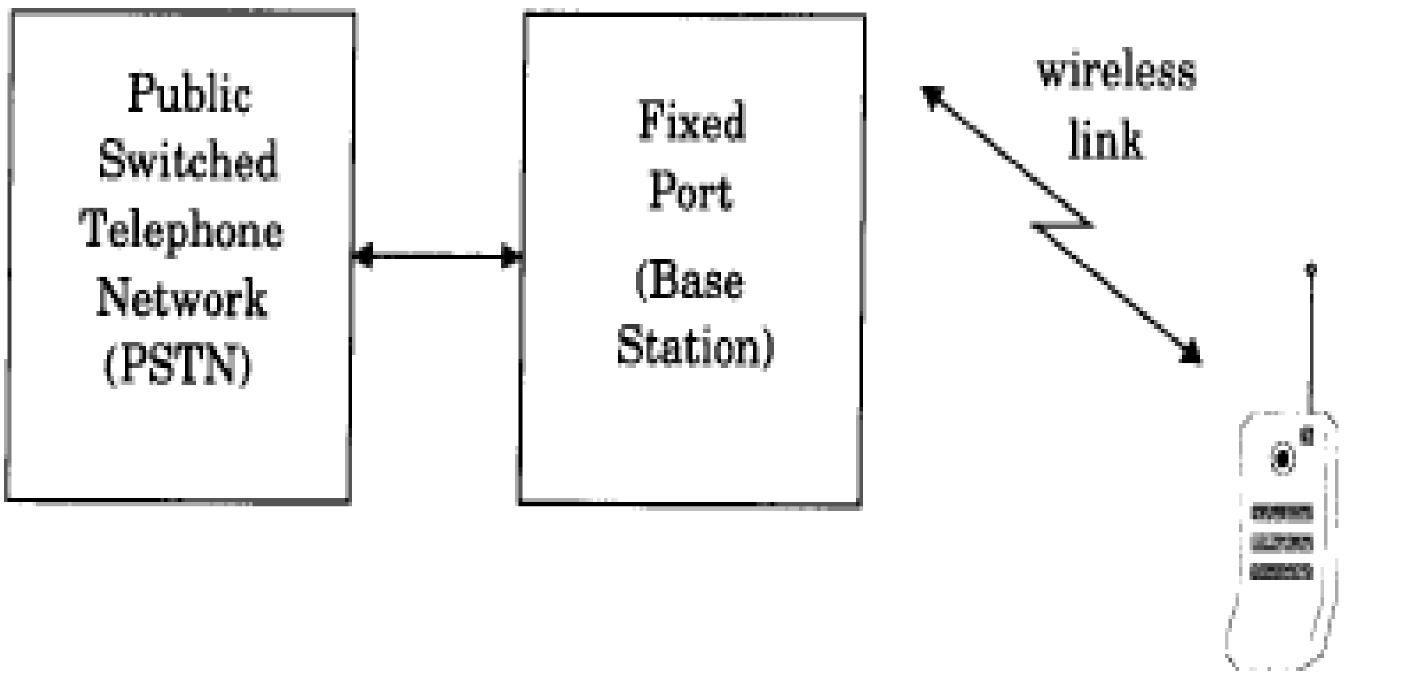
Types of Mobile Transmission Systems

- Simplex-Pagers
- Half-Duplex-Push-to-Talk and Release-to-Listen
- Full-Duplex-Cell Phones-FDD or TDD
- FDD-provides simultaneous radio transmission channels for subscriber and the base station
- TDD-a portion of the time is used to transmit from base station to subscriber and remaining time to transmit from subscriber to base station

Wide Area Paging System

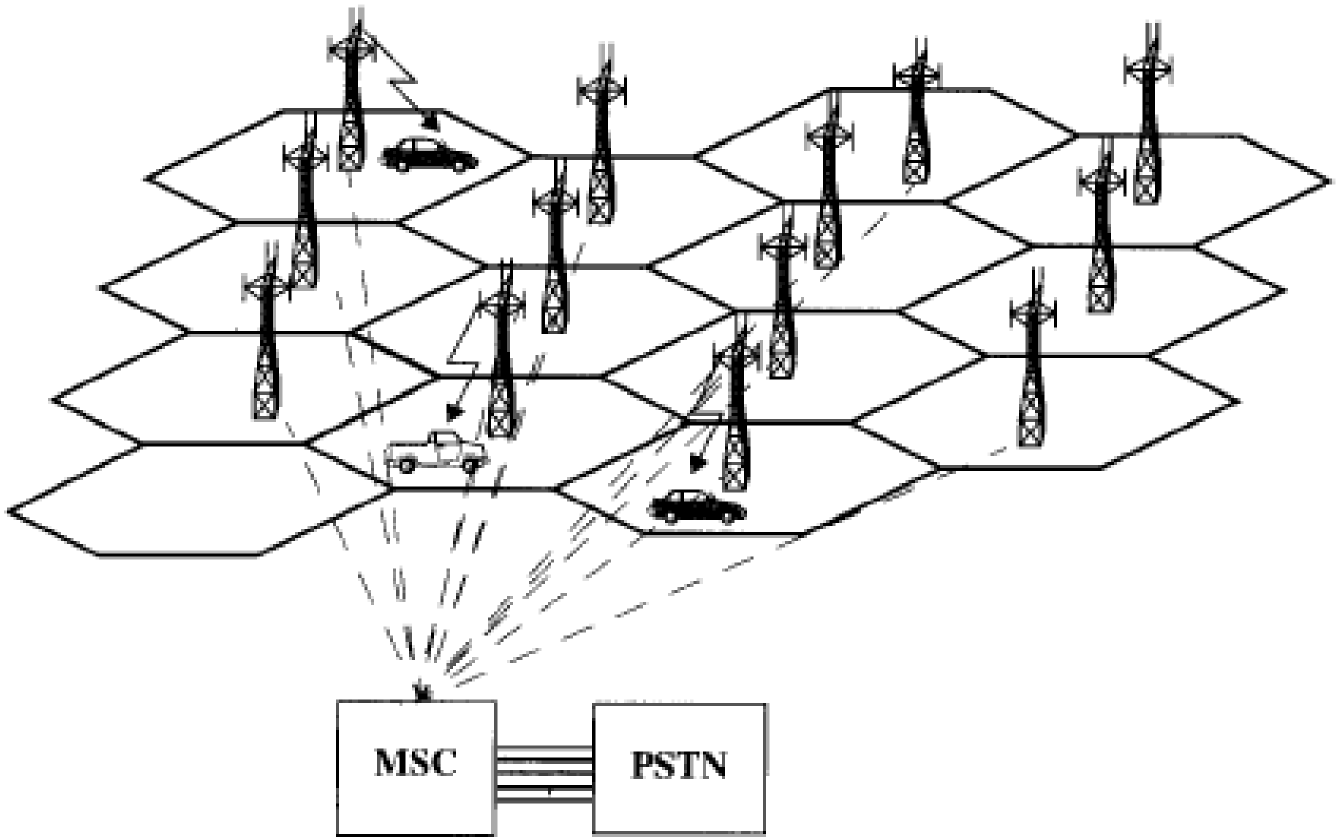


A Cordless Telephone System



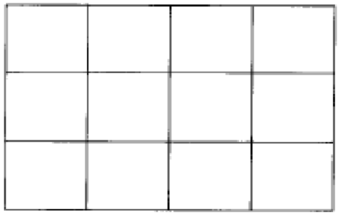
'a cordless telephone system.

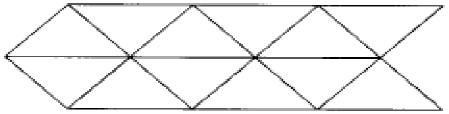
Cellular System



Different Geometrical Shapes

- A cell is the smallest geographical area covered by a base station
- Shapes such as triangles, squares are not well suited since the distance from the centre of the cell to different points of the perimeter are different
- Ideal shape is circle; however, this will leave a number of “zones” outside the coverage
- Optimal shape is hexagonal and is reasonably close the ideal shape


(a)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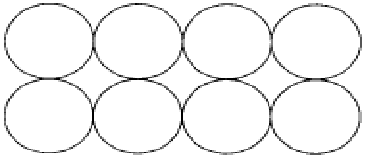
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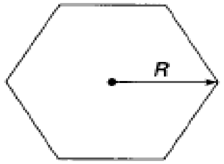


(d)

Steps in an MTSO Controlled Call between Mobile Users

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

Cellular System Capacity

S=Number of Duplex Channels available for the entire system

k ($<S$)=number of channels allocated for each cell

N=Number of cells among which S channels are divided uniquely. Thus,

$$S = k\,N$$

Cellular System Capacity

- N cells which collectively use the complete set of available S channels is called a CLUSTER
- If a cluster is replicated M times in the coverage area, the capacity of the system becomes

$$C= M x k x N = MS$$

The Frequency Reuse Factor of a cellular system is therefore=1/N

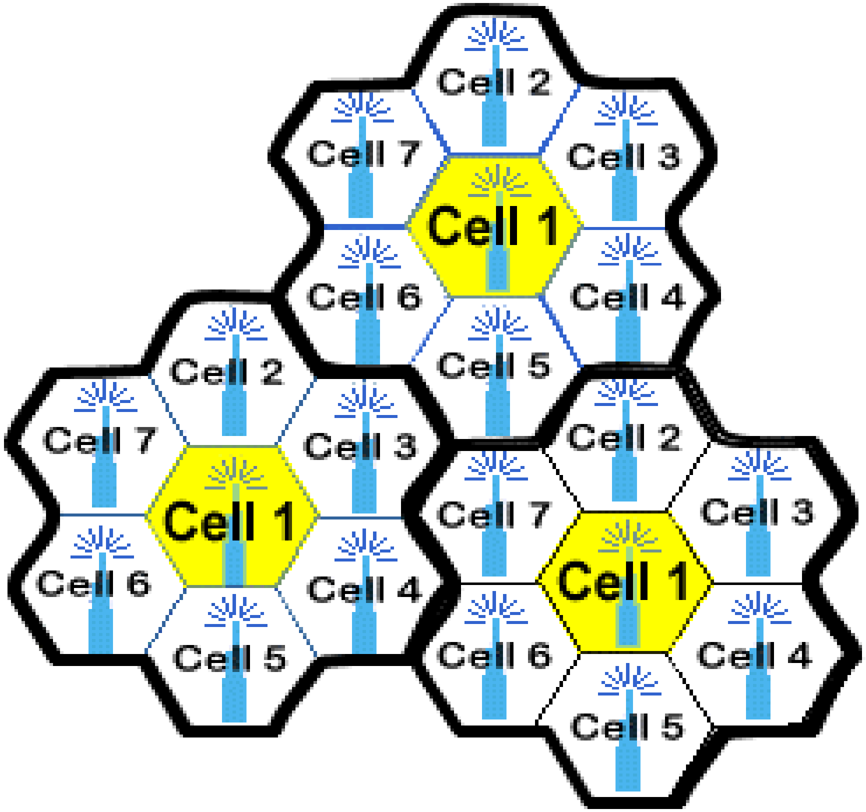
Cellular System Capacity

- The capacity of a cellular system is directly proportional to the number of times a cluster is repeated in a fixed service area
- If the cluster size N is reduced while the cell size is kept constant, more clusters are required to cover a given area; hence more capacity (C)
- The large cluster size indicates that the ratio between the cell radius and distance between co-channels is large

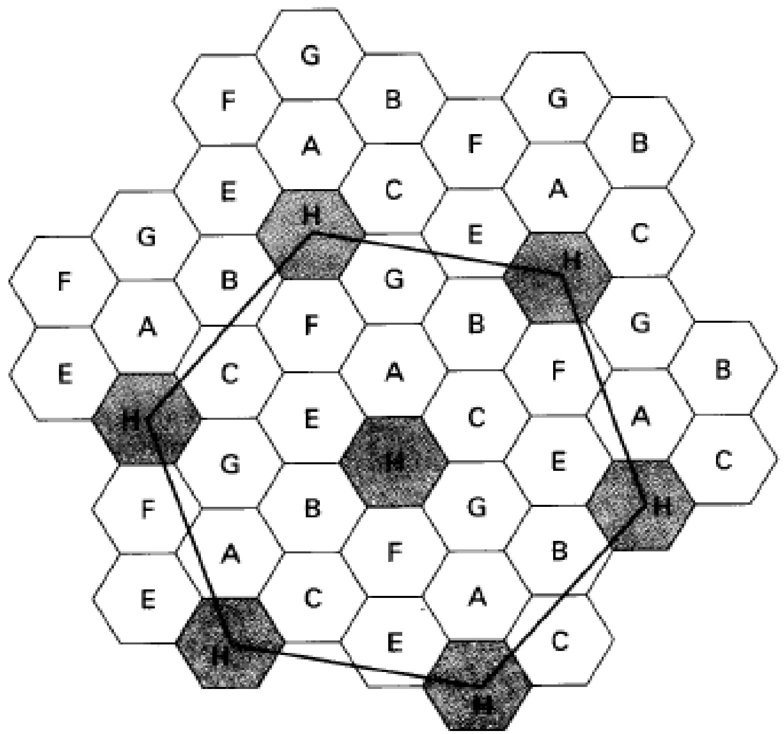
Cellular System Capacity

- A small cluster size, on the other hand, indicates that co-channel cells are located much closer
- The value of N is a function of how much interference a mobile or base station can tolerate
- From a design viewpoint, the smallest possible value of N is desirable to maximize the capacity over a given coverage area

N=7 Cellular System



Expanded N=7 System



Co-channels & Adjacent Channels

- Co-channels cells are cells that use the same set of frequencies
- Interference between signals from these cells is called co-channel interference
- Adjacent Channels cells are cells that use adjacent set of frequencies
- Interference resulting from signals which are adjacent in frequency to the desired signal is called adjacent channel interference

Location of Co-channel cells

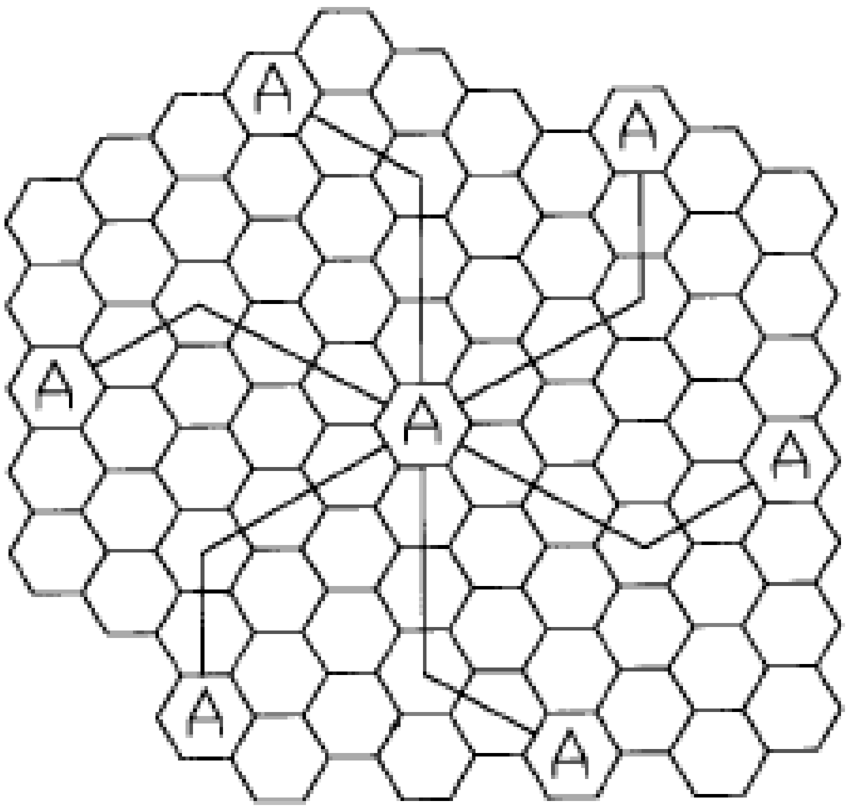
- Due to hexagonal geometry, the number of cells per cluster, N, can only have values which satisfy the equation:

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

where i and j are non-negative integers

- To locate the nearest co-channel, (i) move i cells along any chain of hexagons and then (ii) turn 60 degrees CCW and move j cells

N=19, i=3, j=2 System



Example of Frequency Allocation

- If a total of 33MHz bandwidth is allocated to a particular FDD cellular system which uses two 25 kHz simplex channels to provide full-duplex voice and control channels, compute the number of channels available per cell if a system uses (a) 4-cell reuse, (b) 12-cell reuse, and (3) 7-cell reuse. 1 MHz is allocated to control channels. Determine equitable distribution of control and voice channels.

Channel Assignment strategies

- For efficient utilization of the radio spectrum, a frequency reuse scheme that is consistent with the objectives of increasing capacity and minimizing the interference is required
- Fixed or dynamic channel assignment strategies are used
- In fixed channel assignment strategy, each cell is allocated a predetermined set of voice channels in a particular cell

Channel Assignment strategies

- Any call attempt within the cell can only be served by the unused channels in that particular cell
- If all the channels in that cell are occupied, the call will be blocked
- Several variations of the fixed strategy exists
- In one such variation, known as borrowing strategy, a cell is allowed to borrow channels from a neighbouring cell if all of its own channels are already occupied

Channel Assignment strategies

- Mobile Switching Center (MSC) supervises such borrowing procedure
- In a dynamic channel assignment strategy, voice channels are not allocated to difference cells permanently
- Each time a call request is made, the serving base station requests a channel from MSC
- The switch allocates a channel based on an algorithm; likelihood of future call blocking

Co-channel Interference & System Capacity

- When the size of each cell is same and the base stations transmit the same power, the co-channel interference ratio is independent of the power transmitted and becomes a function of:
- R=cell radius
- D=Distance between centers of the nearest co-channel cells
- That is, Q=D/R=Co-channel reuse ratio

System Capacity

- The co-channel reuse ratio, Q, for hexagonal geometry is given by

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

- Small Q provides larger capacity since the cluster size N is small
- Large Q improves quality of transmission, due to a smaller level of co-channel interference

System Capacity

- A trade-off must be made between the capacity and the quality of transmission
- Co-channel Reuse Ratio for some N

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

Signal-to-Interference Ratio

- Let i_0 be the number of co-channel interfering cells. Then the Signal-to-Interference ratio (SIR) is given by:

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

Signal-to-Interference Ratio

- S is the desired power from the desired base station
- I_i is the interference power caused by the ith interfering cell base station
- If the signal levels of co-channel cells are known, then SIR can be easily found for the forward link using the equation for S/I

Propagation Measurements

- The average received power at a distance *d* from the transmitting antenna is given by:

$$P_r = P_0 \left(\frac{d}{d_0} \right)^{-n}$$

$$P_r(dBm) = P_0(dBm) - 10log\left(\frac{d}{d_0}\right)$$

- P_0 is the power received at a close-in reference point at a distance d_0
- n is the path exponent factor

Propagation Measurements

- If D_i is the distance of the *i* th interferer from the mobile, the received power at a given mobile due the *i* th interfering cell will be proportional to $(D_i)^{-n}$

Where *n* is the path loss exponent can take values 2<*n*<4

Signal-to-Interference Ratio (SIR)

- The expression for SIR becomes:

$$\frac{S}{I} = \frac{(R)^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}$$

$$= \frac{(\sqrt{3N})^{n}}{i_0}$$

Signal-to-Interference Ratio (SIR)

- Assumptions made are:
- 1) Transmit power of each base station is equal
- 2) Path loss exponent is the same throughout the coverage area
- Only first layer of interfering cells are considered
- All interfering base stations are equidistant from the desired base station

Signal-to-Interference Ratio (SIR)

- SIR relates to cluster size, N, which in turn determines the overall capacity of the system
- Example: 6 closest cells create significant interference and approximately all are at equidistant from the base station; US AMPS uses FM and 30 kHz channels and recommends 18dB for SIR. n= 4 (worst case path loss factor). This implies N=6.49
- Thus a minimum cluster size of 7 is required to meet the requirement of 18dB of S/I

Signal-to-Interference Ratio (SIR)

- If a signal to interference ratio of 15dB 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 exponent is (a) $n = 4$; and (b) $n = 3$. Assume there are 6 co-channel cells in the first-tier and all of them are at the same distance from the mobile

Signal-to-Interference Ratio (SIR)

- Case (a) Consider a 7-cell reuse pattern
- Using the equation $Q = \frac{D}{R} = \sqrt{3N}$, the co-channel reuse ratio is 4.583
- Using equation $\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0}$, $\frac{S}{I}$ =18.66dB
- Since this is greater than the minimum required 15 dB of S/I, $N = 7$ can be used

Signal-to-Interference Ratio (SIR)

- Case (b) Consider a 7-cell reuse pattern
- Using the equation $Q = \frac{D}{R} = \sqrt{3N}$, the co-channel reuse ratio is 4.583
- Using equation $\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0}$, $\frac{S}{I}$ =12.05dB
- Since this is less than the minimum required 15 dB of S/I, we need larter N

Signal-to-Interference Ratio (SIR)

- Using equation $N = i^2 + ij + j^2$ and $i = j = 2$ we get $N = 12$
- With this value of N, $Q = D/R$=6.0
- Using this new value of Q and $n = 3$, we get
- $\frac{S}{I} = 36 = 15.56dB$
- This satisfies our requirement

Adjacent Channel Interference

- Results from imperfect receiver filters which allow nearby frequencies to leak into pass band
- Particularly serious when an adjacent channel user is transmitting in very close range to subscriber's receiver

$$\frac{S}{I} = (20)^{-n}$$

Trunking & Grade of Service

- Cellular systems relay on trunking
- Trunking allows a large number of users to share a relatively small number of channels in a cell
- That is, trunking provides access to each user, on demand, from a pool of available channels
- Trunking exploits statistical behavior of users

Grade of Service

- There is a trade-off between the number of available circuits and the likelihood that a particular user finding no circuits are available
- To design a trunked radio systems that can handle specific capacity at a specific Grade of Service, we need to go into Traffic Engineering concepts

Erlang

- 1 Erlang=the amount of traffic intensity carried by a channel that is completely occupied = 1 call-hour per hour = 1 call-minute per minute
- A radio channel that is occupied for 30 minutes during an hour carries 0.5 Erlang traffic

Grade of Service (GoS)

- GoS is a measure of the ability of a user to access a trunked system during the busiest hour
- GoS is a benchmark used to define the desired performance of a trunked system
- GoS defines the likelihood that a call is blocked or the likelihood of a call experiencing a delay greater than a certain queuing time

Two types of Trunking System

- Blocked Calls Cleared System (Earlang B System
- Blocked Calls Delayed System (Earlang C System)

Blocked Call Cleared System

- Traffic Generated by each user = Call Request Rate x Holding time
- That is $A_u = \lambda H$

where λ is the average number of call requests, H is holding time, and A_u is the traffic intensity generated by each user

Blocked Call Cleared System

- If there are U users in the system, the offered traffic is

$$A=U\,A_u$$

- If in the system there are C circuits/channels available and traffic is equally distributed, the traffic intensity per channel is:

$$A_c = U\,A_u/C$$

Blocked Call Cleared System

- Assumptions:
- 1) There are memoryless arrivals of request
- 2) Probability of users occupying the channel is exponentially distributed
- 3) There are finite number of channels available

Blocked Call Cleared System

- The GoS or Probability of blocking is given by:

$$\Pr[blocking] = GoS = \frac{\dfrac{A^C}{C!}}{\displaystyle\sum_{k=0}^{C} \frac{A^k}{k!}}$$

Example

- How many users can be supported for 0.5% blocking probability for the following number of trunked channels: i) 5 and ii) 10. Assume each user generates 0.1 Erlang of traffic

  i) C=5, GoS=0.005, A_u =0.1 Erlang

  From Formula A=1.13 which implies

  11 users

Example

- ii) Given C=10; $A_u = 0.1$; GOS=0.005
- From Table A=3.96
- Therefore, $U = \frac{A}{A_u} = \frac{3.96}{0.1} \approx 39$ users

Example of System Design

- An urban area has a population of 2 million residents. Three competing trunked mobile networks provide cellular service in the area. System A has 394 cells, 19 channels each; System B has 98 cells with 57 channels each; System C has 49 cells with 100 channels each. Find the number of users that can be supported at 2% blocking probability. Each user averages 2 calls/hour at an average of 3 minutes per call.

Example continued

- GoS=0.02, C=19 implies A=12 Erlangs
- GoS=0.02, C=57 implies A=45 Erlangs
- GoS=0.02, C=100 implies A=88 Erlangs
- System A: 120 users/cell
- System B: 450 users/cell
- System C: 880 users/cell

Example continued

- Total number of users: 134500
- System A: 120x394=47280
- System B: 450x98 =44100
- System C: 880x49=43120
- Total Market penetration=6.725%

Example-2

- A city has an area of 1,300 square miles and is covered by a cellular system using 7-cell reuse pattern. Each cell has a radius of 4 miles and the city is allocated 40 MHz of spectrum with full-duplex channel of 60kHz bandwidth. GoS is 2% and Erlang B is specified. Each user offers a load of 0.03 Erlangs.

- Find: Number of cells required; Number of channels/cell; Traffic intensity of each cell; The maximum carried traffic; Total number of users that can be served; Number of Mobiles per channel

Example-2

- Number of cells Required

  Total coverage area=1300 Sq. miles

  Cell radius=4 miles

  Area of each cell=2.5981xR^2=41.57 Sq. mi

  Number of cells=1300/41.57= **31 cells**

Example-2

- Number of channels/cell

  =allocated spectrum/(channel width x frequency reuse factor)

  =40,000,000/(60,000 x 7)

  =95 channels/cell
- C=95; GoS=0.02; From chart Traffic intensity per cell, A, is 84 Earlangs
- Maximum carried Traffic=Number of cells x Traffic intensity per cell

  =31x84=2604 Erlangs

Example-2

- Total Number of users that can be served
  =Total Traffic/traffic per user
  =2604/0.03=86,800 users
- Number of Mobiles per Channel
  =Number of users/number of channels
  =86,600/666=130 mobiles/channel

Channel Assignment Strategies

- Dynamic Assignment Strategy

  Voice channels are not allocated to different cells permanently

  Each time a call request is made, the serving Base Station requests a channel from MSC; Switch then allocates channel based on likelihood of future blocking, the frequency of use of the channel, the reuse distance of the channel etc.

Channel Assignment Strategies

- In Dynamic strategies, MSC collects real-time data on:

  Channel occupancy

  Traffic Distribution

  Radio Signal Strength Indications

- Makes the MSC complex but provides increased channel utilization & reduced call blocking probability

Handoff Strategies

- When a mobile moves into a different cell, while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station
- Processing handoff is an important operation in any cellular system
- Handoffs must be performed successfully and as frequently as is required

Handoff Strategies

- Handoff involves

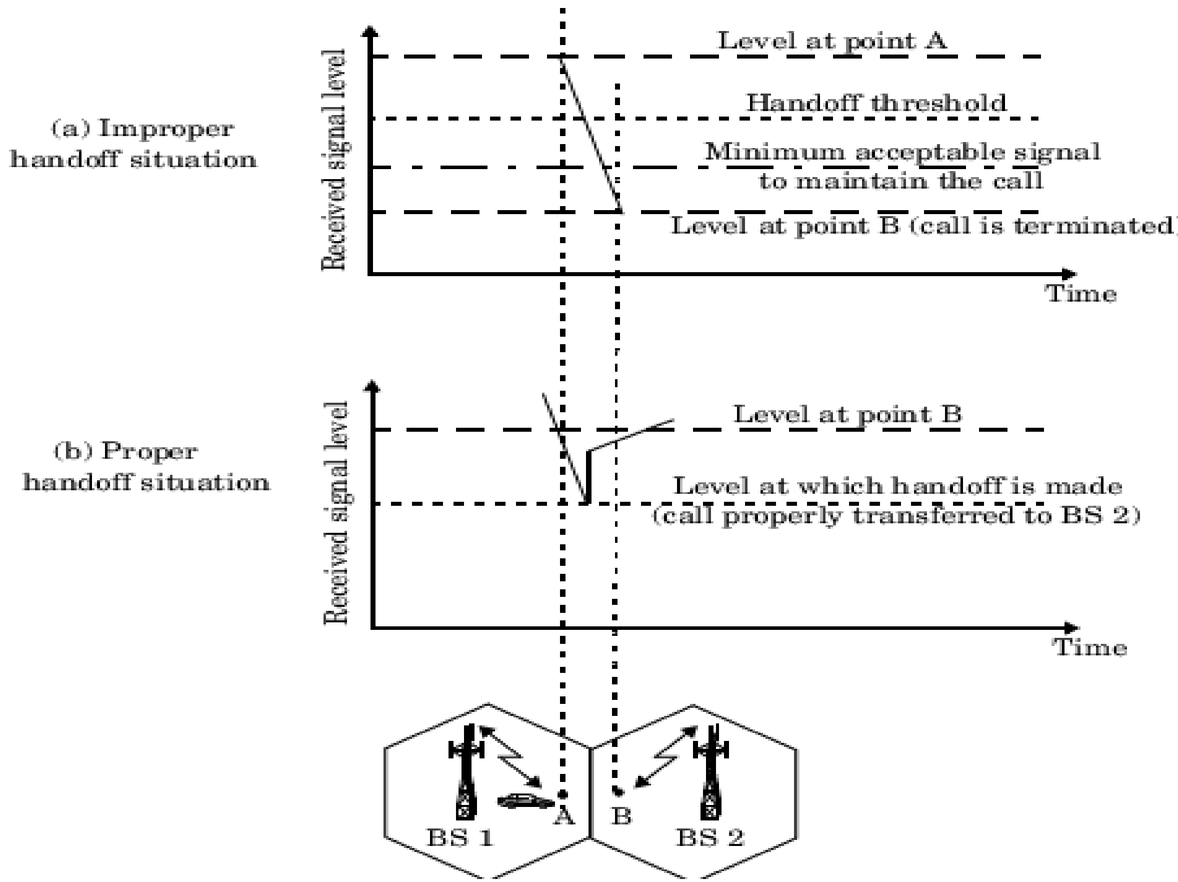
  Identifying a new base station

  Allocation of new channel associated with the new base station

Handoff Strategies

- System designers specify optimum signal level to initiate a handoff (-90dBm to -100dBm)
- Threshold=Power (handoff) – Power (minimum usable)
- Too small a threshold may result in insufficient time to complete handoff
- Too large a threshold may result in unnecessary handoff

Handoff scenario at cell boundary



US AMPS Channel Allocation

- Total Channels = 832
- Operator A: 416 Channels
- Operator B: 416 Channels
- Out of 416 Channels, 395 are voice channels and 21 are control channels
- 395 Channels are divided into 21 subsets each containing 19 channels
- In each subset the closest adjacent channel is 21 channels away

US AMPS Channel Allocation

- In a 7-cell reuse system, each cell uses 3 subsets of channels.
- Every channel in the cell is assured of being separated by at least 7 channels
- Each cell uses channels in the subset iA+iB+iC, i an integer from 1 to 7
- The shaded set of numbers correspond to the control channel

1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	
43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	
64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	
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523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	B SIDE
544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	
565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	
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649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	-	-	-	
-	-	-	-	-	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	
733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	
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775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	
796	797	798	799																		