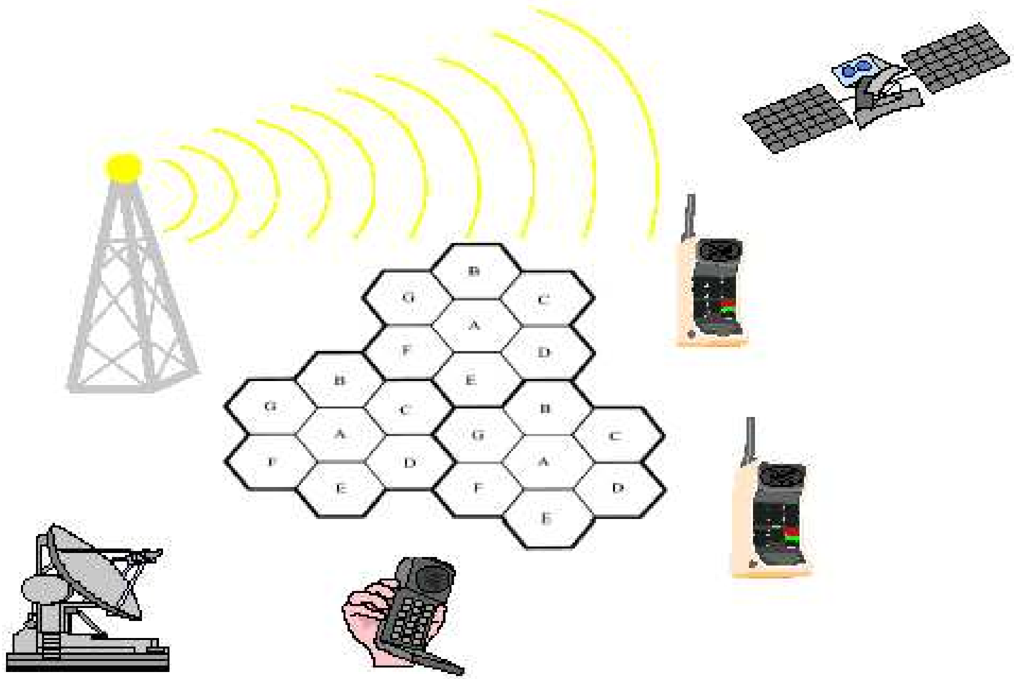
Chapter 1
INTRODUCTION TO WIRELESS COMMUNICATION SYSTEMS



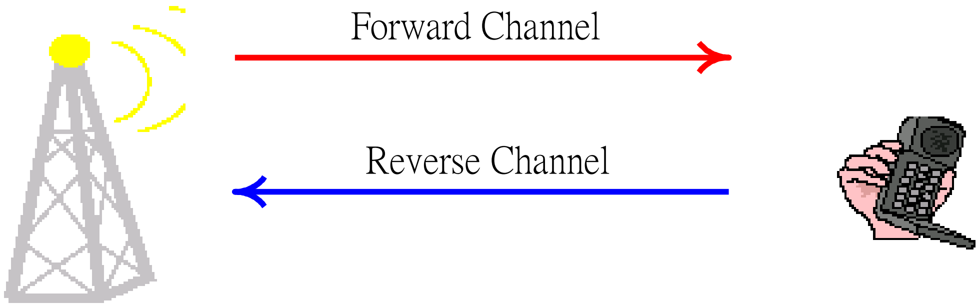
1.1 Evolution of Mobile Radio Communications

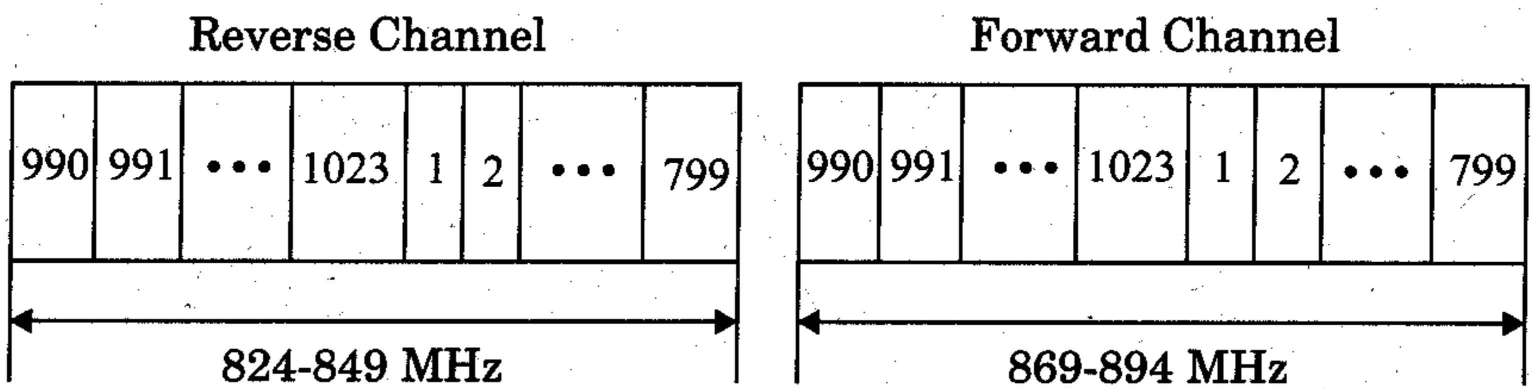
- Major Mobile Radio Systems
  - 1934 - Police Radio uses conventional AM mobile communication system.
  - 1935 - Edwin Armstrong demonstrate FM
  - 1946 - First public mobile telephone service - push-to-talk
  - 1960 - Improved Mobile Telephone Service, IMTS - full duplex
  - 1960 - Bell Lab introduce the concept of Cellular mobile system
  - 1968 - AT&T propose the concept of Cellular mobile system to FCC.
  - 1976 - Bell Mobile Phone service, poor service due to call blocking
  - 1983 - Advanced Mobile Phone System (AMPS), FDMA, FM
  - 1991 - Global System for Mobile (GSM), TDMA, GMSK
  - 1991 - U.S. Digital Cellular (USDC) IS-54, TDMA, DQPSK
  - 1993 - IS-95, CDMA, QPSK, BPSK

1.2 Example of Mobile Radio Systems

- Examples
  - Cordless phone
  - Remote controller
  - Hand-held walkie-talkies
  - Pagers
  - Cellular telephone
  - Wireless LAN
- Mobile - any radio terminal that could be moves during operation
- Portable - hand-held and used at walking speed
- Subscriber - mobile or portable user

- Classification of mobile radio transmission system
  - Simplex: communication in only one direction
  - Half-duplex: same radio channel for both transmission and reception (push-to-talk)
  - Full-duplex: simultaneous radio transmission and reception (FDD, TDD)
- Frequency division duplexing uses two radio channel
  - Forward channel: base station to mobile user
  - Reverse channel: mobile user to base station
- Time division duplexing shares a single radio channel in time.



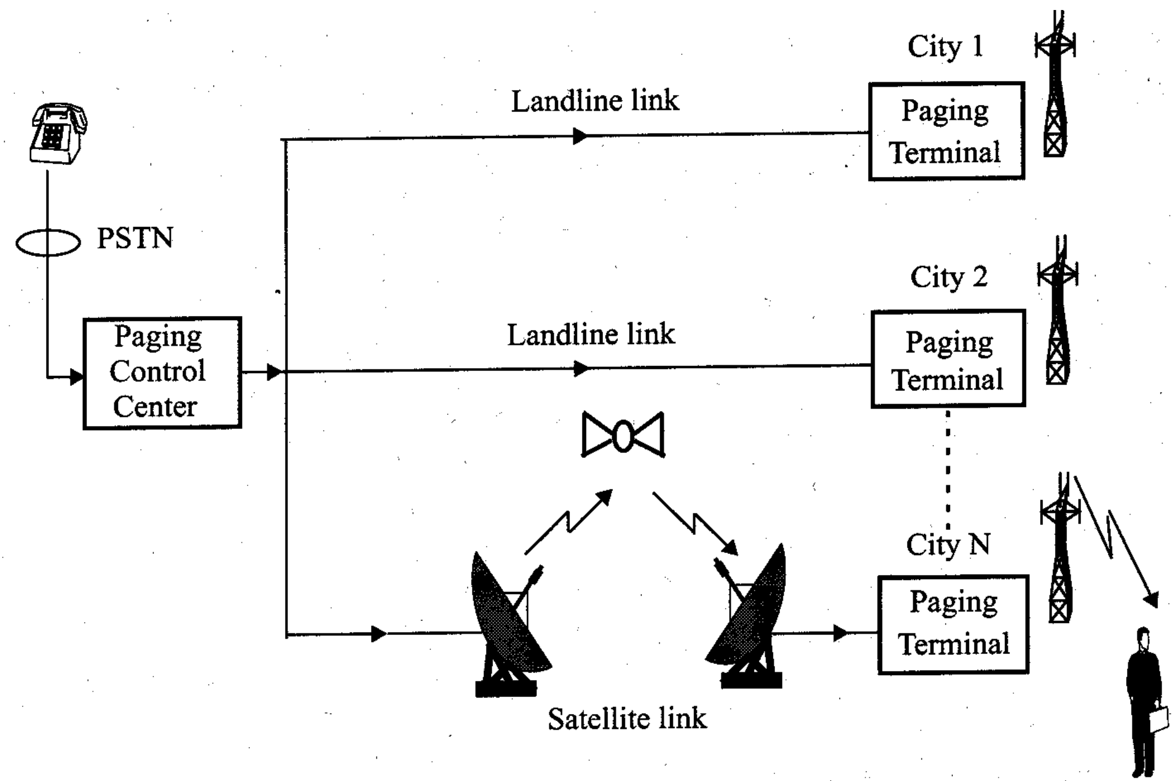


	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \le N \le 799$	$0.030N + 825.0$
	$990 \le N \le 1023$	$0.030\,(N - 1023) + 825.0$
Forward Channel	$1 \le N \le 799$	$0.030N + 870.0$
	$990 \le N \le 1023$	$0.030\,(N - 1023) + 870.0$

(Channels 800 - 989 are unused)

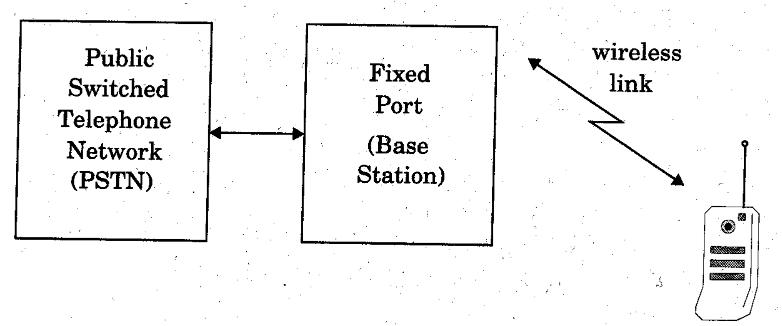
1.2.2 Paging Systems

- Conventional paging system send brief messages to a subscriber
- Modern paging system: news headline, stock quotations, faxes, etc.
- Simultaneously broadcast paging message from each base station (simulcasting)
- Large transmission power to cover wide area.



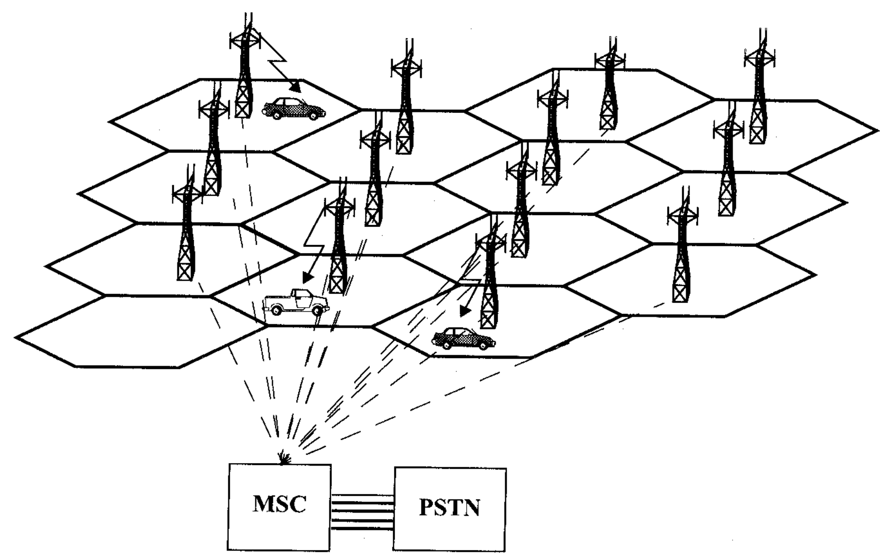
1.2.3 Cordless Telephone System

- Cordless telephone systems are full duplex communication systems.
- First generation cordless phone
  - in-home use
  - communication to dedicated base unit
  - few tens of meters
- Second generation cordless phone
  - outdoor
  - combine with paging system
  - few hundred meters per station



1.2.4 Cellular Telephone Systems

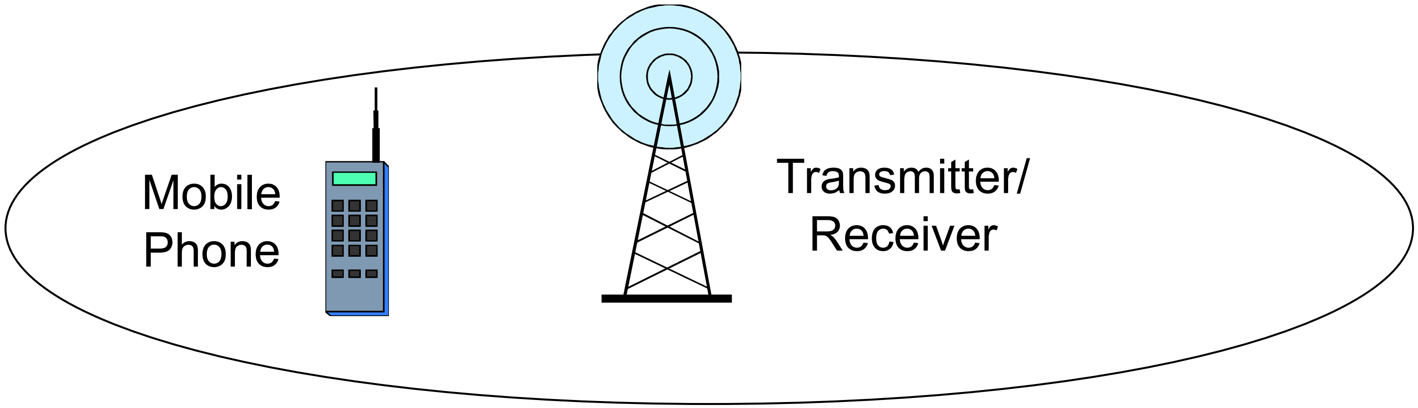
- Provide connection to the PSTN for any user location within the radio range of the system.
- Characteristic
  - Large number of users
  - Large Geographic area
  - Limited frequency spectrum
  - Reuse of the radio frequency by the concept of "cell".
- Basic cellular system: mobile stations, base stations, and mobile switching center.



- Communication between the base station and mobiles is defined by the standard common air interface (CAI)
  - forward voice channel (FVC): voice transmission from base station to mobile
  - reverse voice channel (RVC): voice transmission from mobile to base station
  - forward control channels (FCC): initiating mobile call from base station to mobile
  - reverse control channel (RCC): initiating mobile call from mobile to base station

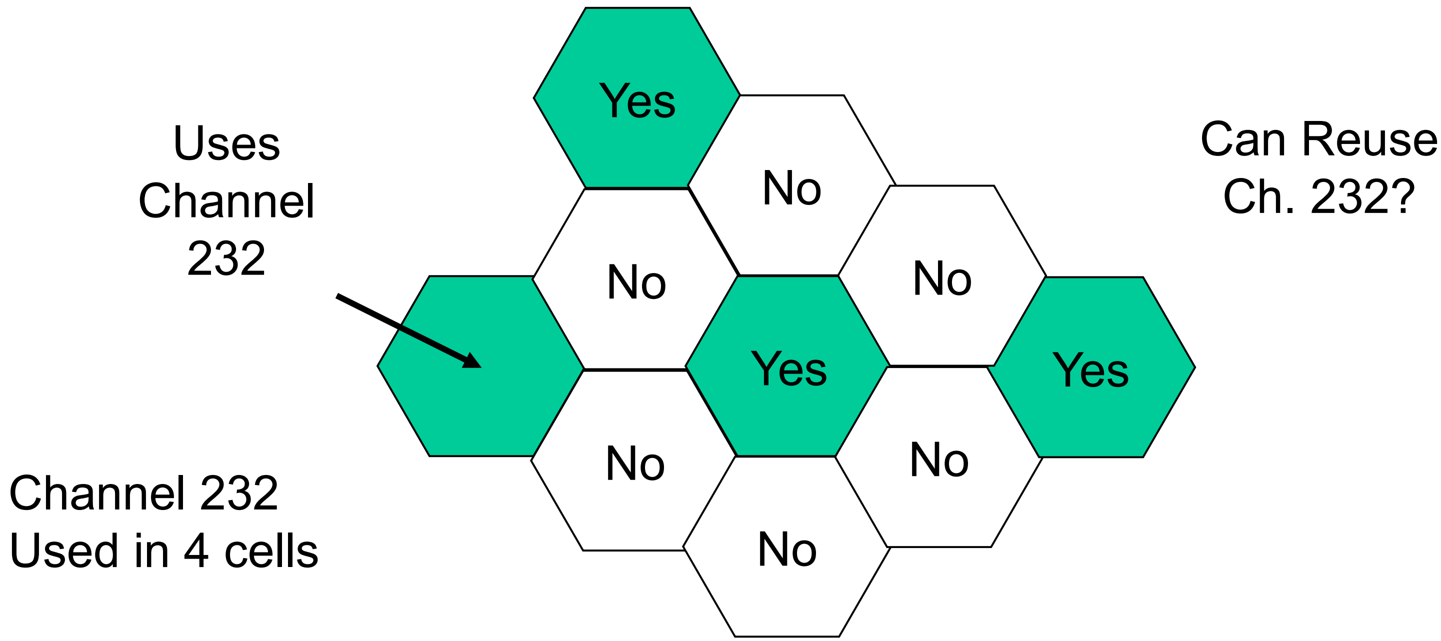
Cellular Telephones

- Original *Mobile Telephones*
  - One transmitter/receiver
  - Limited number of channels
  - For good service can support about 20 subscribers per channel (rough rule of thumb)



Cellular Telephones

- Divide Region into *Cells*
  - One *cellsite* (transmitter/receiver) per cell
  - Channels can be reused in non-adjacent cells



Cellular Telephones

- Channel Reuse
  - Without *channel reuse*, you can serve only about 20 subscribers per channel for good service
  - Rough rule of thumb
  - Otherwise, the system will not be available too often when people want to call or receive calls

Cellular Telephones

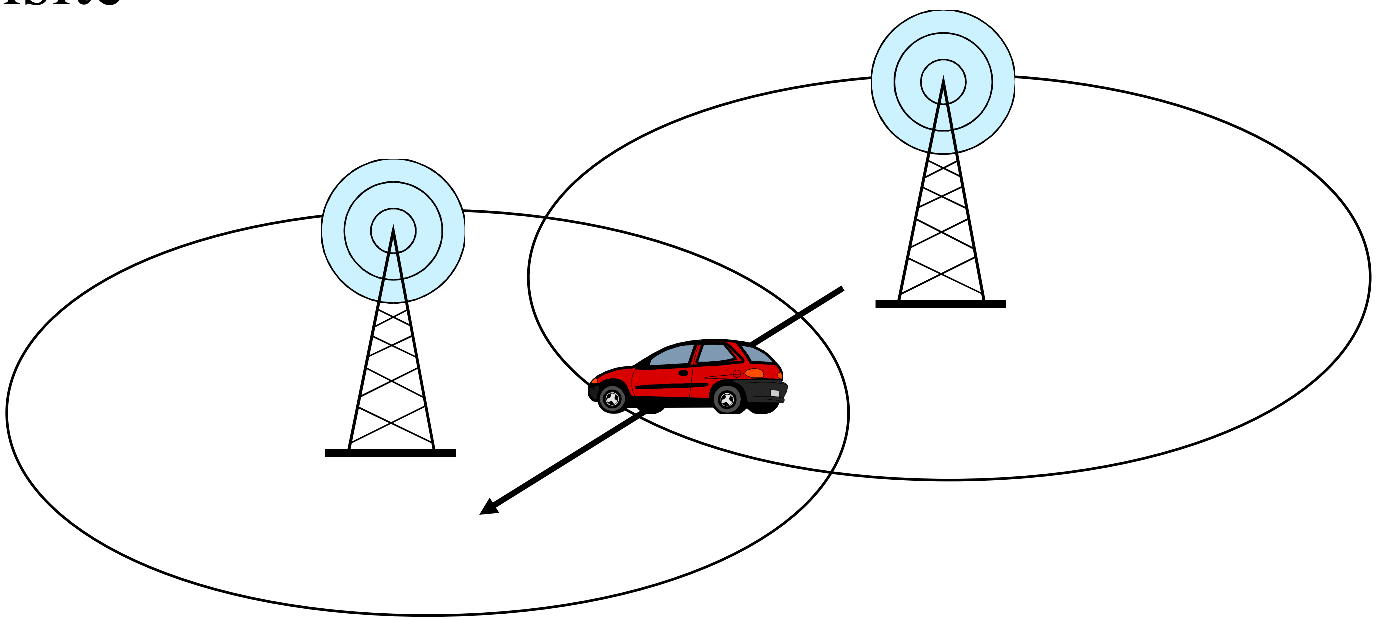
- Channel Reuse Rule
  - How many times can we reuse each channel in an area?
  - Channel reuse factor = Number of cells / 7
  - If 20 cells, reuse factor is about 3 (round off)
  - Can reuse each channel about 3 times
  - Rough rule of thumb

Cellular Telephones

- Capacity Calculation
  - If 100 channels and 15 cells
  - 100 channels
  - x 20 subscribers per channel
  - x 15/7 channel reuse factor
  - = about 4,000 subscribers (100 x 20 x 2)

Handoffs

- When you move to another cell within the same system, you get a *handoff*
  - You are transferred automatically to that cell's cellsite

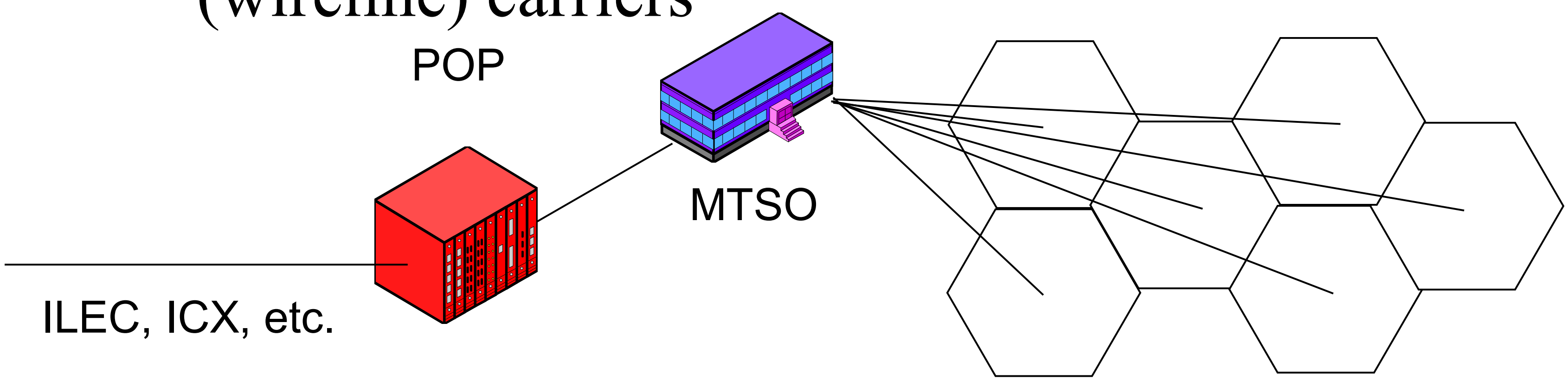


Roaming

- *Roaming* is when you take your cellphone to another city
  - Use it there to send and receive
  - Not always possible technically because of incompatible cellular technology
  - May be limited procedurally because of high rates of cellular fraud in some areas
  - Don't confuse this with *handoff*, which takes place *within a cellular system between cells*

Control

- *Mobile Telephone Switching Office*
  - Controls cellsites, handoffs, etc.
  - Calls go to/from *MTSO*
  - Connects to POP to link to traditional telephone (wireline) carriers



Placing a Call

New

- Enter number, hit send
- Cellphone broadcasts request
- Several cellsites receive, send to MTSO
- MTSO assigns cellphone to cellsite where signal is loudest
- MTSO sends message to cellphone via that cellsite, telling the phone what incoming, outgoing channels to use

Receiving a Call

New

- MTSO has each cellsite broadcast cellphone's ID number
- Cellphone transmits a response
- Responses from cellsites go to MTSO
- MTSO selects cellsite where signal is loudest
- MTSO sends message via the cellsite to cellphone, giving channels and telling the cellphone to ring

First Generation Cellular

- Analog or Digital Operation
  - Initially analog; U.S. States initially was analog using the *AMPS* standard
    - Limited use of digital *Cellular Digital Packet Data (CDPD)* standard
  - Europe and the rest of the world started with a large number of incompatible analog systems but settled on the digital *GSM* standard

First-Generation Cellular

- Large Cells
  - Usually only 20-40 per city
  - Limits channel reuse
- Limited Number of Channels
  - In U.S., 832 two-way channels
- No Compression
  - Each voice signal required a full two-way channel

First-Generation Cellular

- How Many Subscribers Can You Support?
  - 20 cells
  - Channel reuse is about 3 (20/7)
  - 832 channels
  - With channel reuse, 2,496 effective channels
  - 20 users per available channel
  - So only about 50,000 subscribers per city
  - Engineering tricks can extend, but only somewhat

Second-Generation Cellular

- *Personal Communication Service (PCS)*
  - Or Personal Communication Network (PCN)
- More channels
  - About 2,500
- Smaller cells permit more channel reuse
  - Don’t just say “smaller cells;” be explicit about channel reuse
- Compression of around 3:1
  - Supports more subscribers per channel

Second-Generation Cellular

- Digital
  - Cleaner signal
  - Paging and other digital services
  - Internet access

Potential System Capacity (Roughly)

Category	1st Gen	2nd Gen
Cells/City	30	100
Channel reuse (cells/7)	~4	~14
Channels	800	2,500
Effective channels	3,200	35,000
With compression	*3,200	105,000
Subscribers (x20/channel)	64,000	2,000,000

- *No compression in 1st generation

Second-Generation Cellular

- PCS Cellphones
  - Do not have to transmit as far because cells are smaller
    - Inverse cube law--if triple distance, 33 or 27 times the power required
    - Cellphones can be less expensive because use less power

Second-Generation Cellular

- PCS Cellphones
  - Large number of possible subscribers removes scarcity cost penalties
  - But vendors try to avoid simple price competition by offering more services made possible by digital technology

Second-Generation Cellular

- Most of World
  - Standardizing on DCS Technology
  - Based on GSM and usually called GSM
- U.S.
  - FCC did not specify a standard!
  - Different carriers use different technologies
  - Some have standardized on GSM
  - Your cellphone may not work with another carrier
  - Limits roaming

Generations: Recap

	1st	2nd
Analog/Digital	Both A&D	Digital
Cells	Large	Small
Channels (Approx.)	800	2500
Compression	No	Yes
U.S. Standardization	AMPS	Poor
International Standards	GSM	DCS

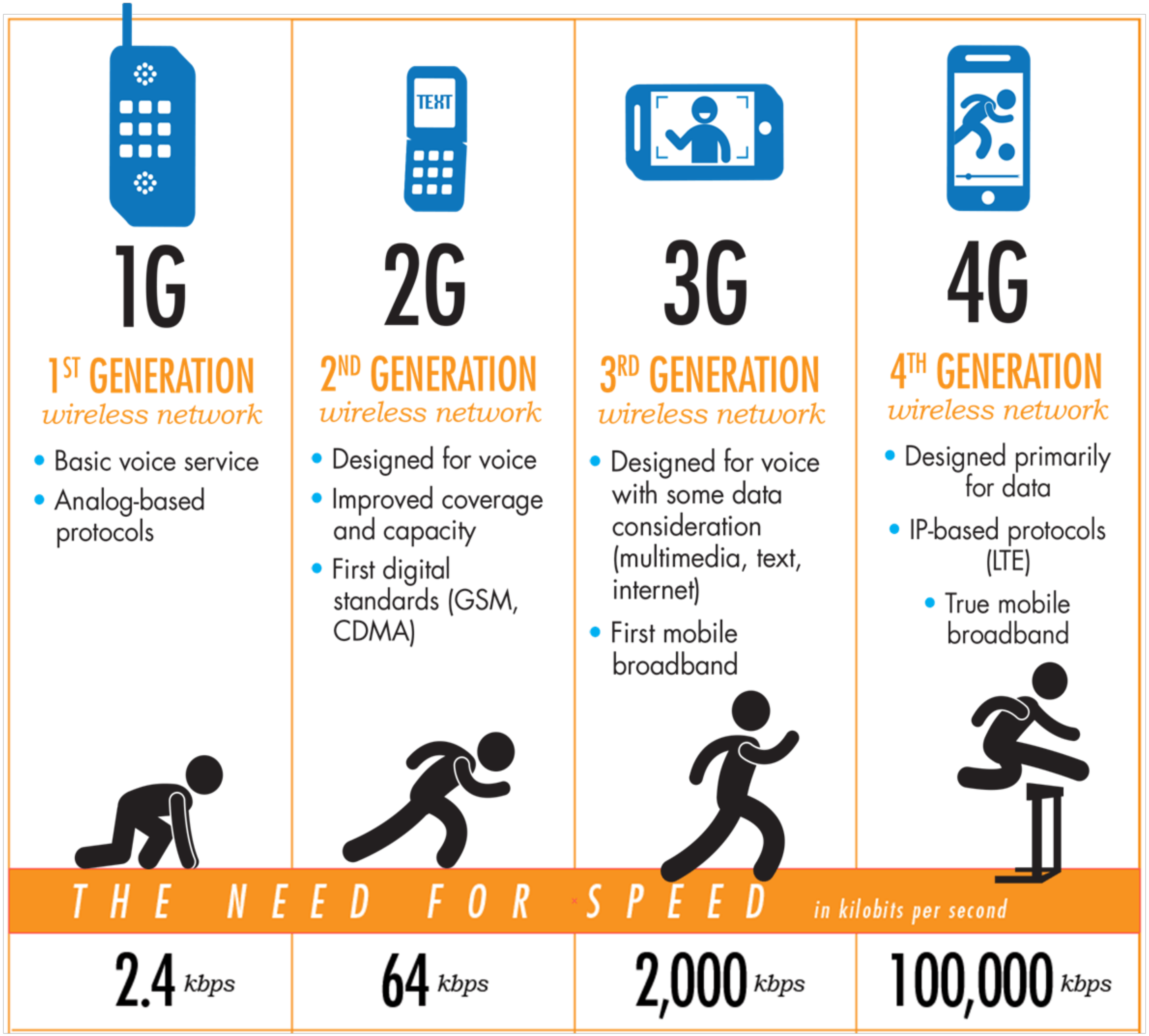
Second-Generation Cellular

New

- Data
  - Initially limited to about 10 kbps
  - 100 kbps coming over second-generation systems in some countries

Third-Generation (3G)

- Smarter Devices
  - Devices will have the power of a small PC
- Greater Number of Uses
  - Data, including internet access
  - Graphics and even video
- *International Mobile Telecommunications (IMT)*
  - European-led standard for 3G generation cellular


TEXT
1G
1ST GENERATION
wireless network
Basic voice service
Analog-based protocols
2G
2ND GENERATION
wireless network
Designed for voice
Improved coverage and capacity
First digital standards (GSM, CDMA)
3G
3RD GENERATION
wireless network
Designed for voice with some data consideration (multimedia, text, internet)
First mobile broadband
4G
4TH GENERATION
wireless network
Designed primarily for data
IP-based protocols (LTE)
True mobile broadband
THE NEED FOR SPEED
in kilobits per second
2.4 kbps
64 kbps
2,000 kbps
100,000 kbps

CELLULAR CONCEPT

"Provide additional radio capacity with no additional increase in radio spectrum"

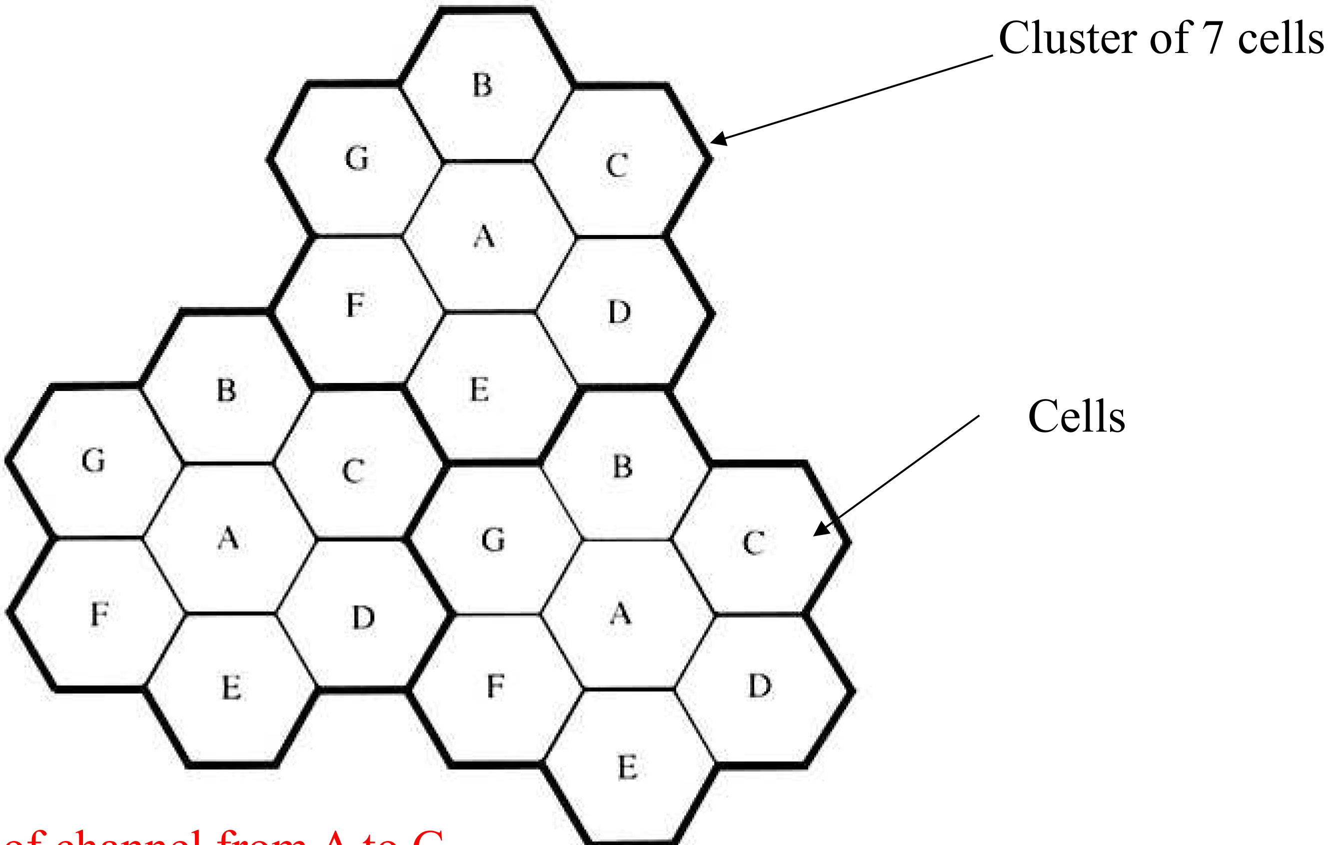
INTRODUCTION

- Early mobile radio system was to achieve a large coverage areas by using high powered transmitter with an antenna mounted on a tall tower
- In this case it is impossible to reuse those same frequencies throughout the system
- Since any attempts to achieve frequency reuse would result in interference

Cont..

- Cellular concept is a system level idea which calls for replacing a single , high power transmitter with low power small transmitters with each providing coverage to only a small portion of service area
- Each base station is allocated a portion of total no of channels available to entire system
- Nearby base station are assigned different groups of channels so that all the available channels are assigned to a relatively small no. of neighboring base stations
- Nearby BS are assigned different groups of channel so that interference bt. BS is minimized

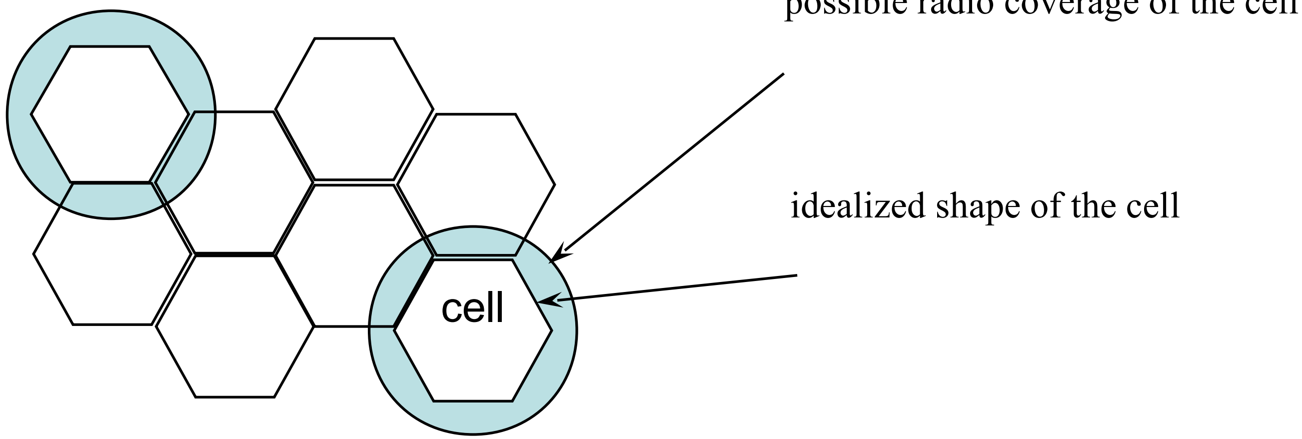
THE CELLULAR CONCEPT



- seven groups of channel from A to G
- footprint of a cell - actual radio coverage
- omni-directional antenna v.s. directional antenna

CELLULAR NETWORK

segmentation of the area into cells



- use of several carrier frequencies
- not the same frequency in adjoining cells
- cell sizes vary from some 100 m up to 35 km depending on user density, geography, transceiver power etc.
- hexagonal shape of cells is idealized (cells overlap, shapes depend on geography)
- if a mobile user changes cells
  handover of the connection to the neighbor cell

FREQUENCY REUSE

- Each cellular base station is allocated a group of radio channels within a small geographic area called a *cell*.
- Neighboring cells are assigned different channel groups.
- By limiting the coverage area to within the boundary of the cell, the channel groups may be reused to cover different cells.
- Keep interference levels within tolerable limits.
- Frequency reuse or frequency planning

"The design process of selecting and allocating channel groups for all of the cellular base station within a system is FREQUENCY REUSE/PLANNING"

- Consider a cellular system which has a total of ***S*** duplex channels.
- Each cell is allocated a group of ***k*** channels, $k \quad S$.
- The ***S*** channels are divided among ***N*** cells.
- The total number of available radio channels

$$S \quad kN$$

- The ***N*** cells which use the complete set of channels is called ***cluster***.
- The cluster can be repeated ***M*** times within the system. The total number of channels, ***C***, is used as a measure of capacity

$$C \quad MkN \quad MS$$

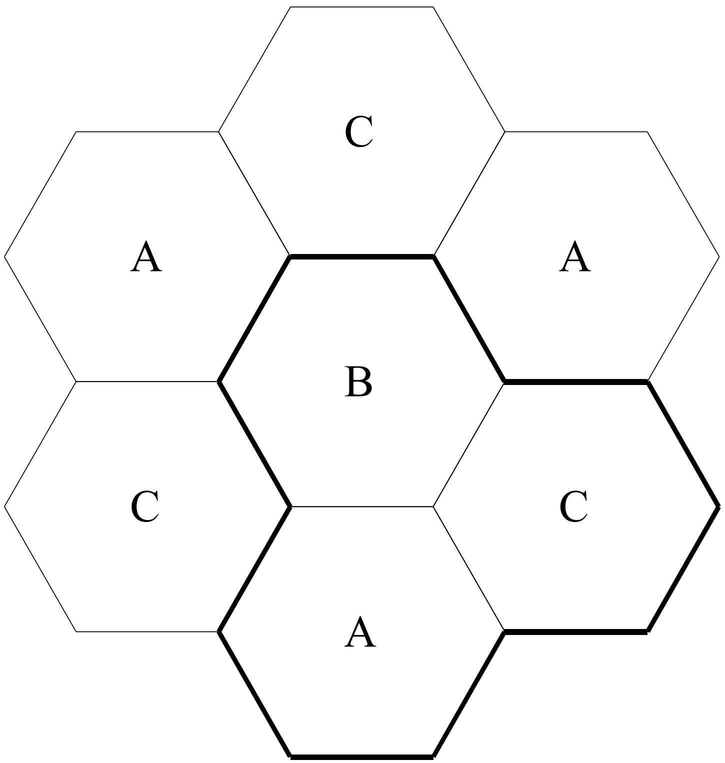
- The capacity is directly proportional to the number of replication ***M***.
- The cluster size, ***N***, is typically equal to 4, 7, or 12.
- Small *N* is desirable to maximize capacity.
- The frequency reuse factor is given by $1/N$

- Hexagonal geometry has
  - exactly six equidistance neighbors
  - the lines joining the centers of any cell and each of its neighbors are separated by multiples of 60 degrees.
- Only certain cluster sizes and cell layout are possible.
- The number of cells per cluster, *N*, can only have values which satisfy

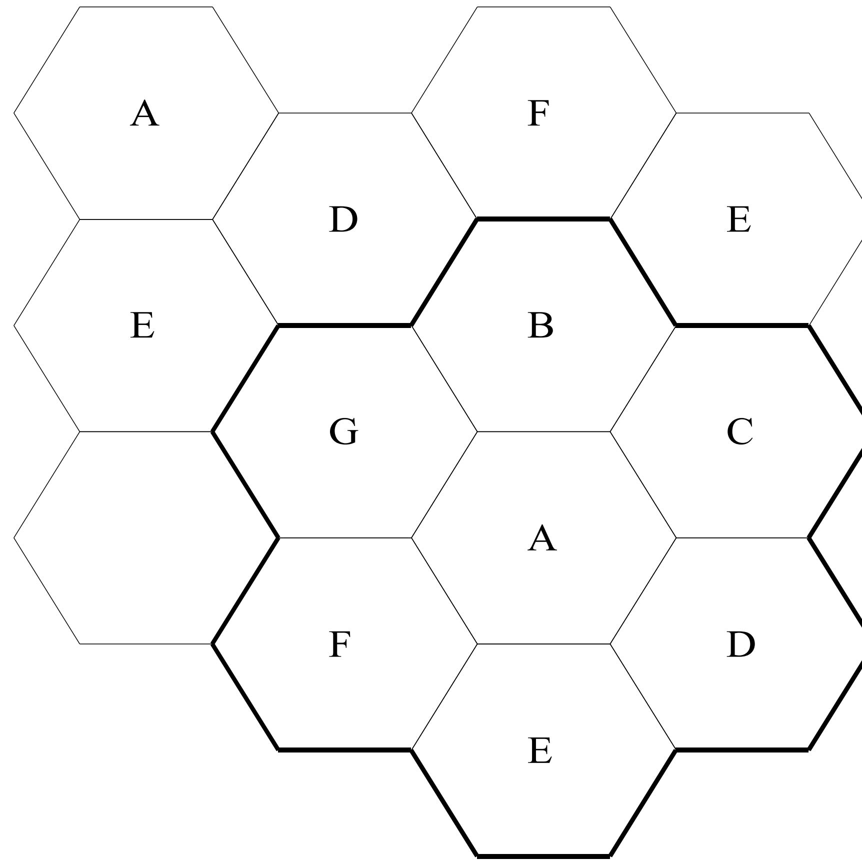
$$N = i^2 + ij + j^2$$

- Co-channel neighbors of a particular cell, ex, *i=3* and *j=2*.

CLUSTER SIZES AND CELL LAYOUT



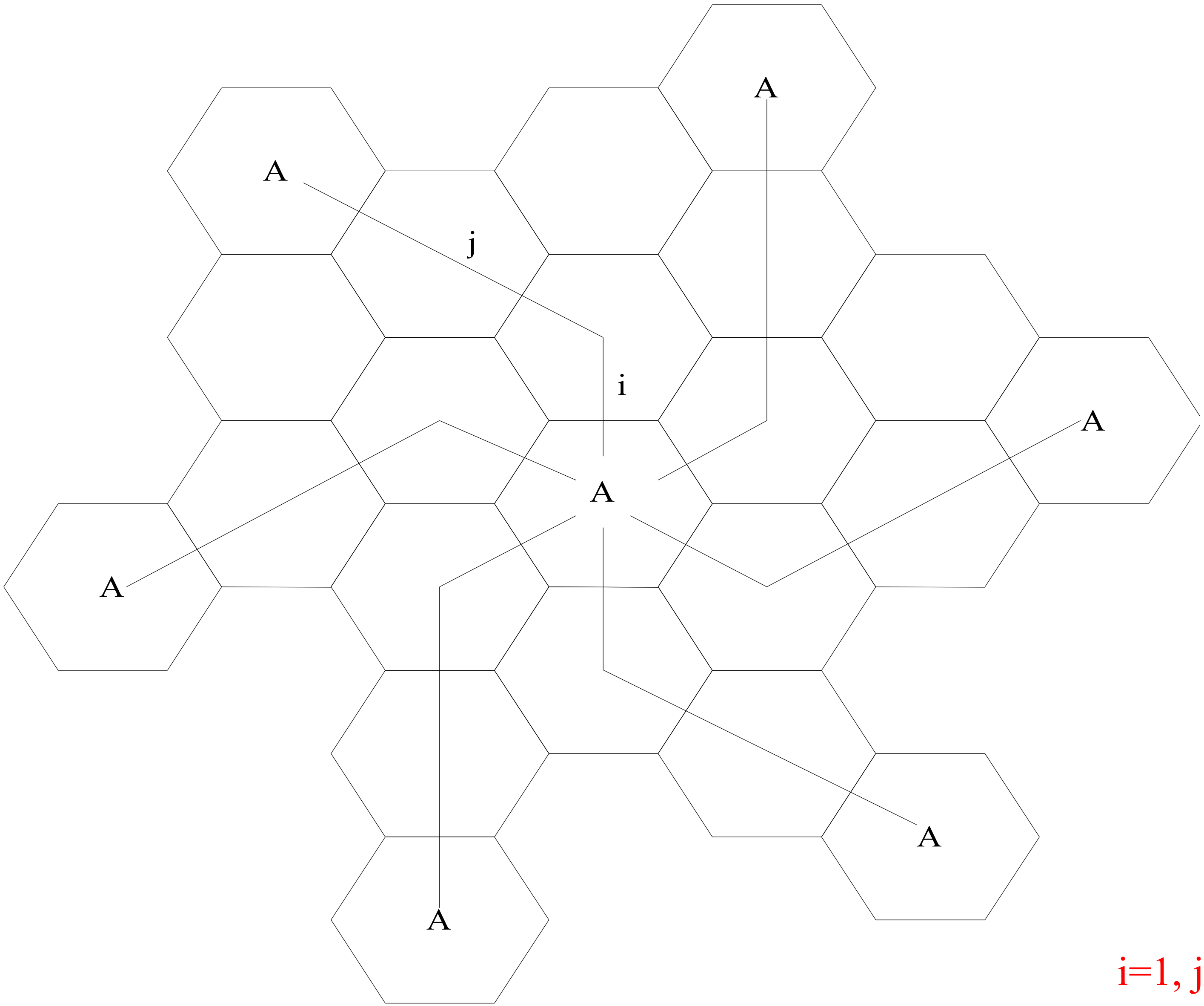
Eg for i=1,j=1



Eg for i=2,j=1

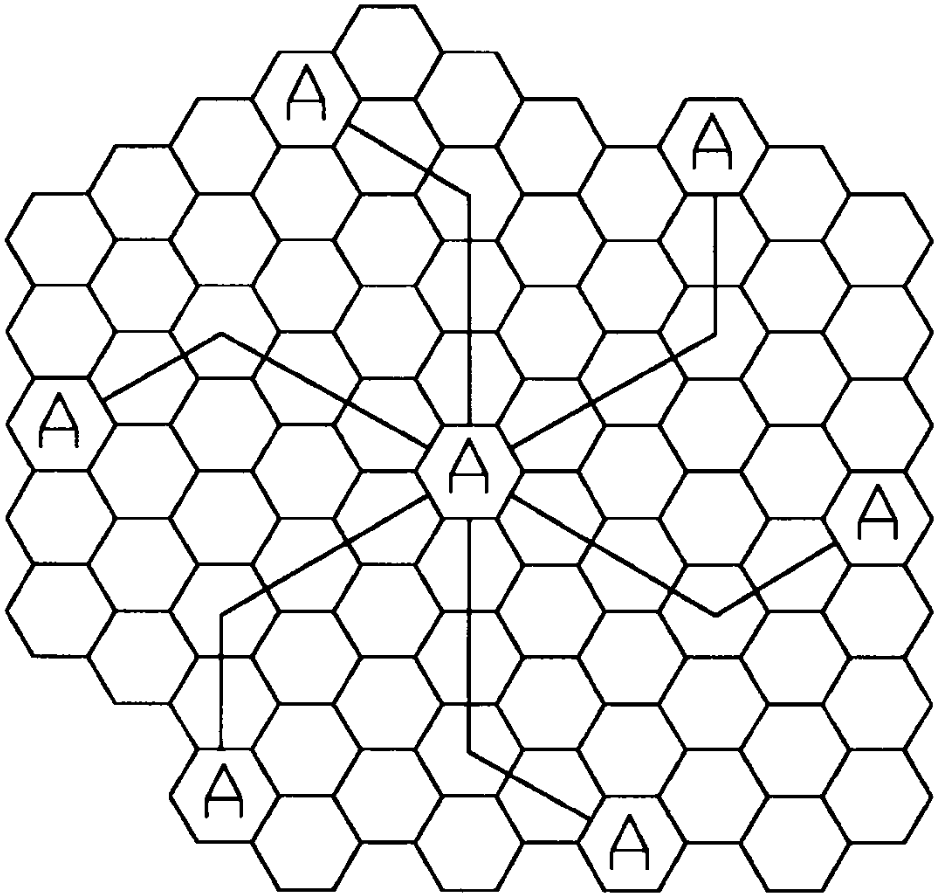
The factor N is called the cluster size and is given $N=i2+ij+j2$

CLUSTER SIZES AND CELL LAYOUT



i=1, j=2 , N=1+2+4=7

CELL REUSE EXAMPLE (N=19)



To find the nearest co-channel neighbor of a particular cell

1. Move 'i' cells along any chain of hexagons
2. Then turn 60 degrees counter-clockwise and
3. Move 'j' cells.

Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $I = 3$, $j = 2$). (Adapted from [Oet83] © IEEE.)

ADVANTAGES

- Solves the problem of spectral congestion and user capacity.
- Offer very high capacity in a limited spectrum without major technological changes.
- Reuse of radio channel in different cells.
- Enable a fix number of channels to serve an arbitrarily large number of users by reusing the channel throughout the coverage region.

CAPACITY EXPANSION IN CELLULAR SYSTEM

Techniques to provide more channels per coverage area is by

- Cell splitting
- Cell sectoring
- Coverage zone approches

CELL SPLITTING

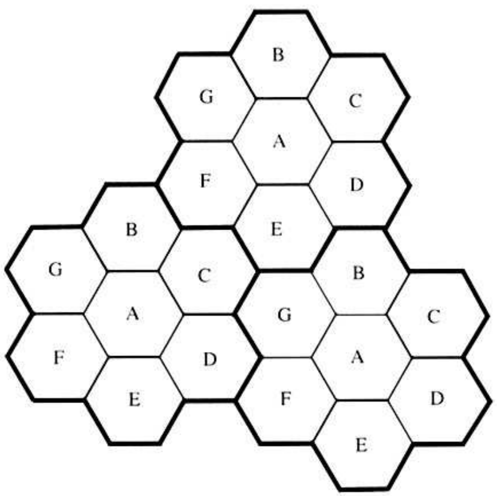
- Cell splitting increases the capacity of cellular system since it increases the number of times the channel are reused
- Cell splitting - defining new cells which have smaller radius than orginal cells by installing these smaller cells called MICROCELLS between existing cells
- Capacity increases due to additional number of channels per unit area

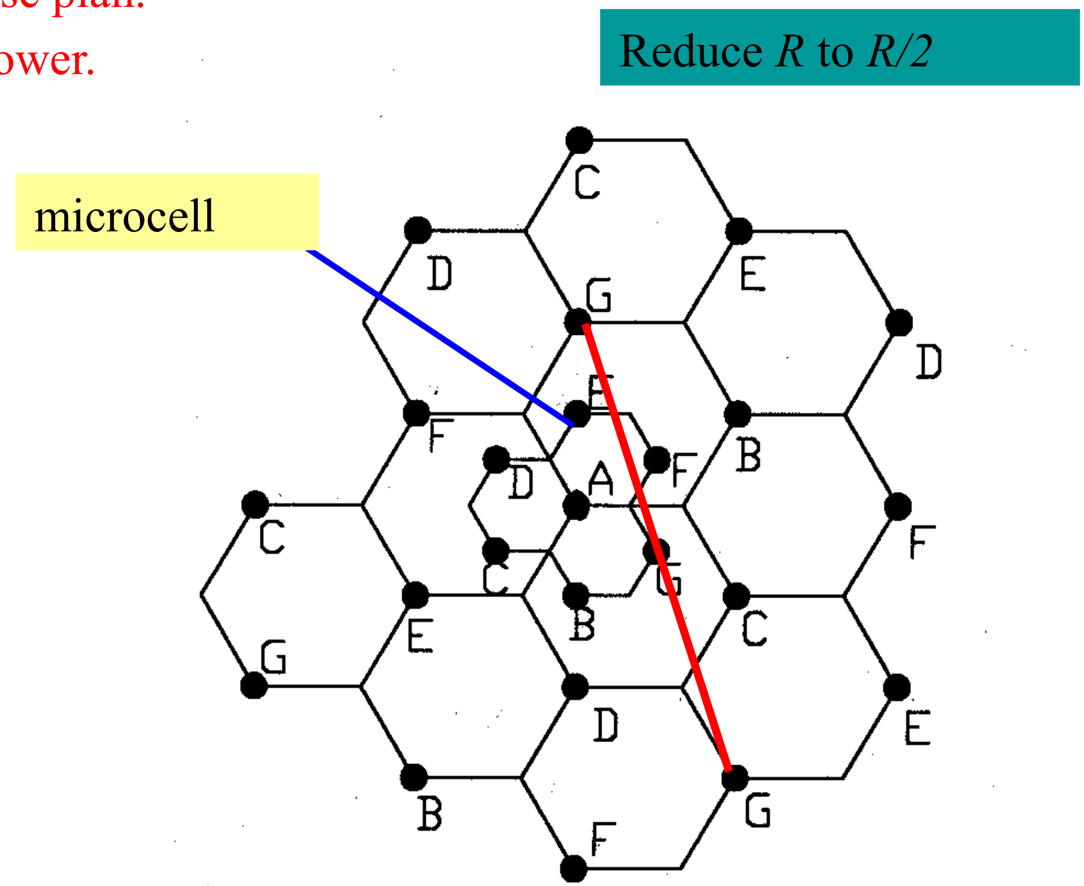
“Cell splitting is process of subdividing a congested cell into smaller cells each with its own base station(with corresponding reduction in antenna height and tx power)”

CELL SPLITTING

Split congested cell into smaller cells.

- Preserve frequency reuse plan.
- Reduce transmission power.





- Transmission power reduction from P_{t1} to P_{t2}
- Examining the receiving power at the new and old cell boundary

$$P_r[\text{at old cell boundary}] \quad P_{t1} R^{-n}$$

$$P_r[\text{at new cell boundary}] \quad P_{t2} (R/2)^{-n}$$

- If we take $n = 4$ (path loss) and set the received power equal to each other

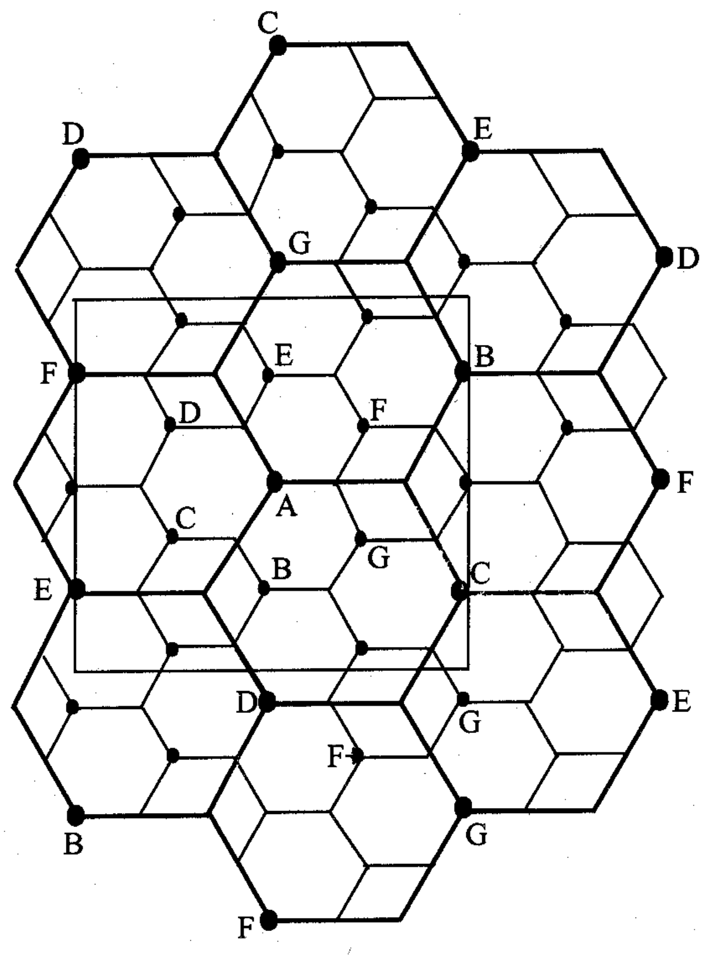
$$P_{t2} \quad \frac{P_{t1}}{16}$$

- The transmit power must be reduced by 12 dB in order to fill in the original coverage area.
- Problem:

  if only part of the cells are splited

  - Different cell sizes will exist simultaneously
- Handoff issues - high speed and low speed traffic can be simultaneously accommodated

CELL SPLITTING

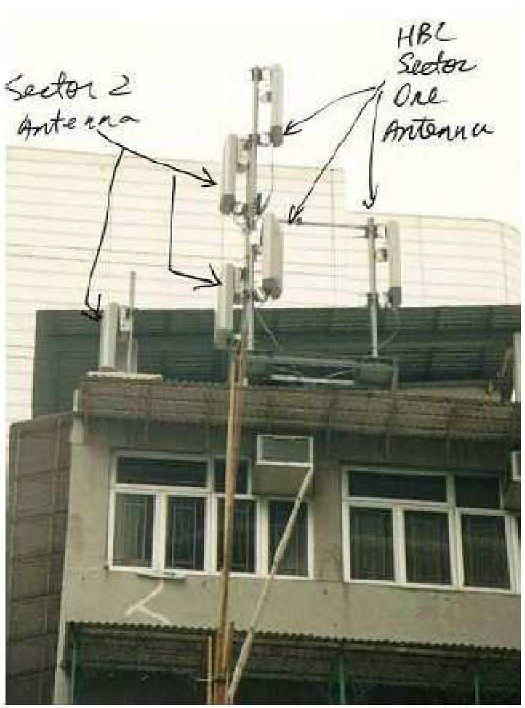


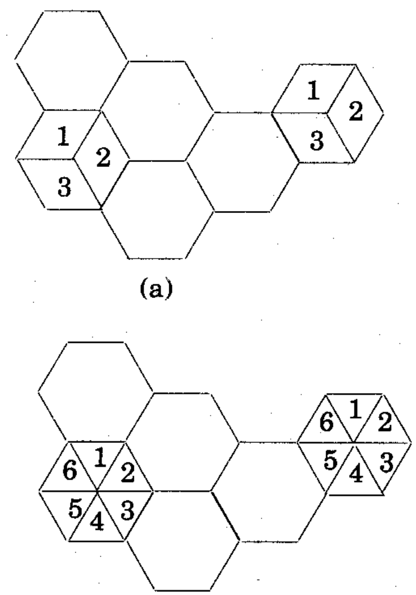
- Splitting cells in each CELL
- Antenna downtiliting

Illustration of cell splitting within a 3 km by 3 km square

2.7.2 Sectoring

- Decrease the *co-channel interference* and keep the cell radius *R* unchanged
  - Replacing single omni-directional antenna by several directional antennas
  - Radiating within a specified sector

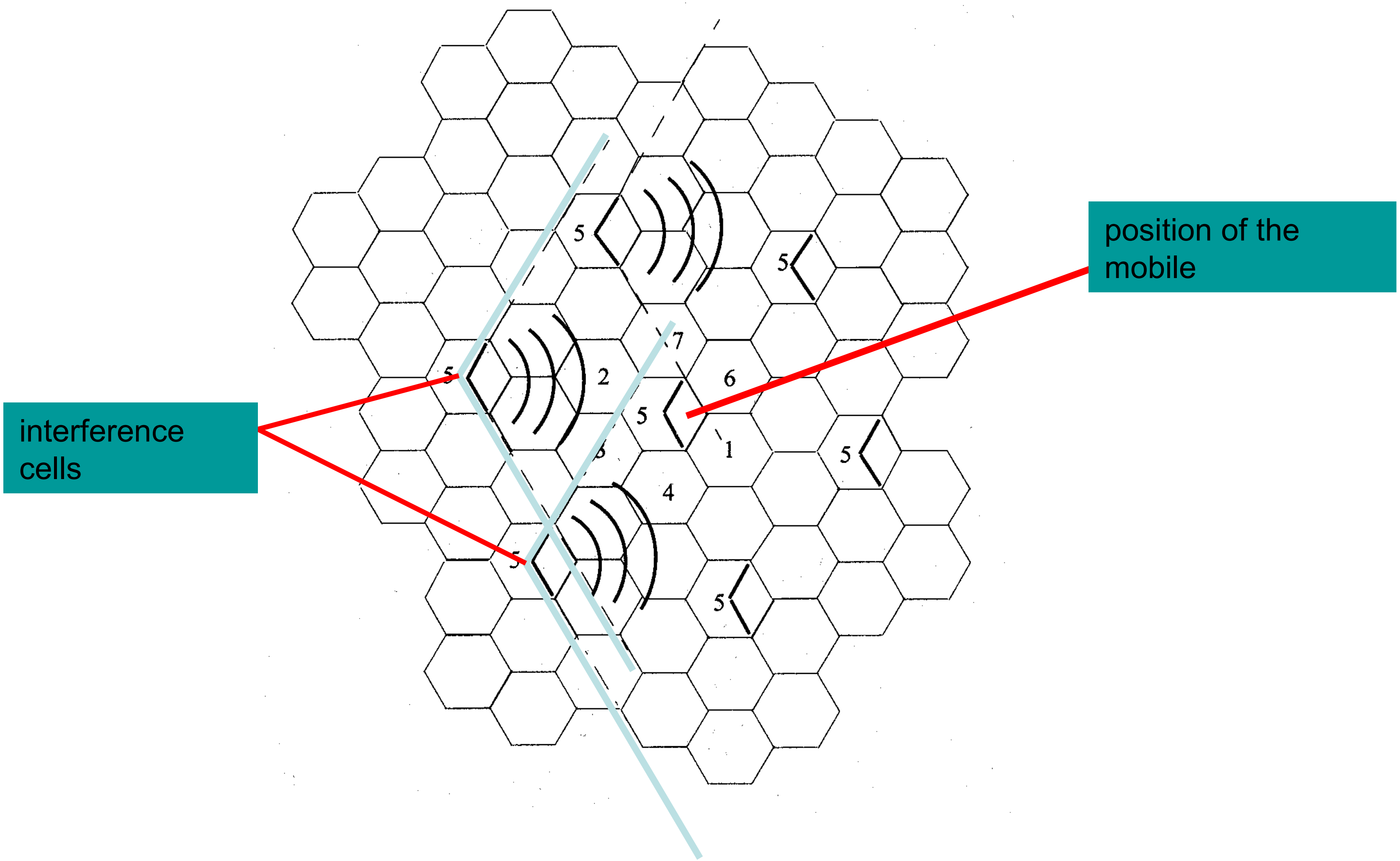




(a)

(b)

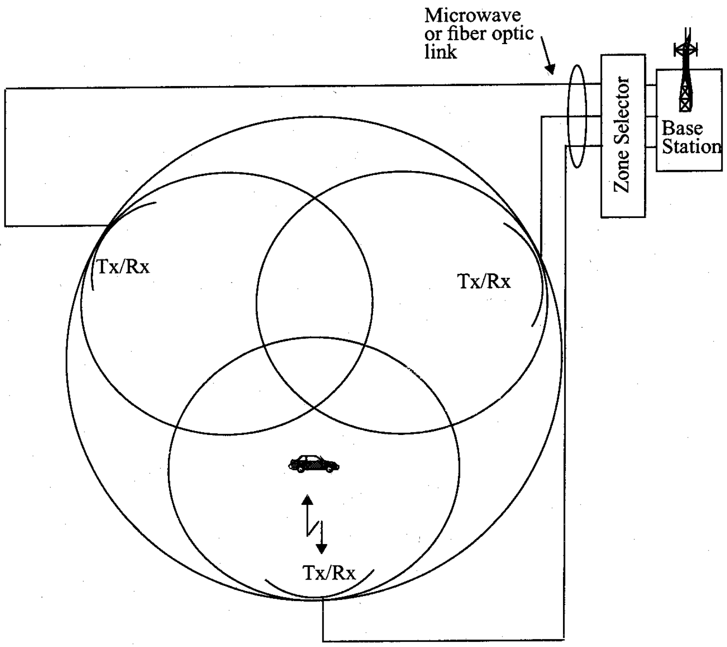
- Interference Reduction



2.7.3 Microcell Zone Concept

- Antennas are placed at the outer edges of the cell
- Any channel may be assigned to any zone by the base station
- Mobile is served by the zone with the strongest signal.

- Handoff within a cell
  - No channel re-assignment
  - Switch the channel to a different zone site
- Reduce interference
  - Low power transmitters are employed



Channel Assignment Strategies

- Frequency reuse scheme
  - increases capacity
  - minimize interference
- Channel assignment strategy
  - fixed channel assignment
  - dynamic channel assignment
- Fixed channel assignment
  - each cell is allocated a predetermined set of voice channel
  - any new call attempt can only be served by the unused channels
  - the call will be *blocked* if all channels in that cell are occupied
- Dynamic channel assignment
  - channels are not allocated to cells permanently.
  - allocate channels based on request.
  - reduce the likelihood of blocking, increase capacity.

Analog	Digital
Less bandwidth(**Advantage**)	Large bandwidth(**Disadvantage**)
More accurate (**Advantage**)	Less accurate due to the Quantization error that can not be avoided or corrected. (**Disadvantage**)
Low noise immunity (**Disadvantage**).	High noise immunity as the amplitude of the digital has two levels only and channel coding (error correcting codes) can be used. (**Advantage**)
Low level of security. (**Disadvantage**)	High level of security as you can use Encryption (Ciphering) and Authentication. (**Advantage**)
No signal conditioning and processing are used (**Disadvantage**)	Support complex signal conditioning and processing techniques such as source coding, encryption, and equalization((**Advantage**)
Low QOS. (**Disadvantage**)	High QOS. (**Advantage**)
You can use FDM only(**Disadvantage**)	You can use FDM, TDM, CDM, OFDM multiplexing techniques. (**Advantage**)
In mobile communications, analog supports voice service only. (**Disadvantage**)	In mobile communications, digital supports voice, SMS, data (you can access the internet), images and video call. (**Advantage**)
More difficult to design than Digital. (**Disadvantage**)	Easily designed using software (**Advantage**).

Multiple Access Techniques for Wireless Communication

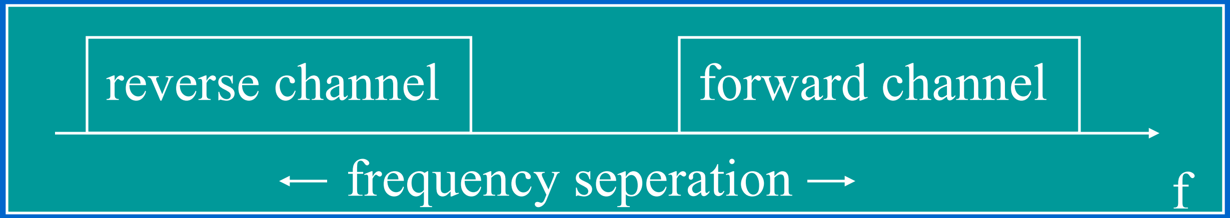
FDMA
TDMA
SDM

Introduction

- many users at same time
- share a finite amount of radio spectrum
- high performance
- duplexing generally required
- frequency domain
- time domain

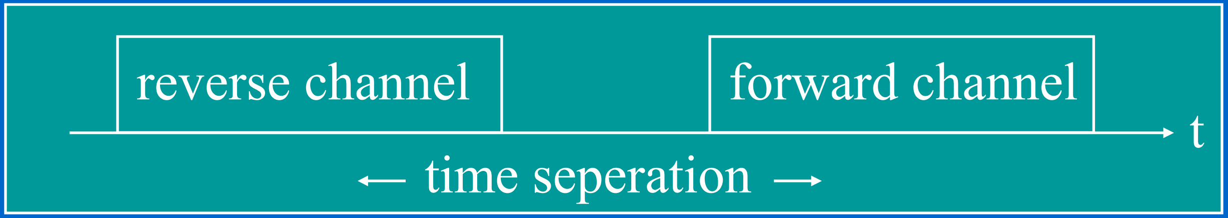
Frequency division duplexing (FDD)

- two bands of frequencies for every user
- forward band
- reverse band
- duplexer needed
- frequency seperation between forward band and reverse band is constant



Time division duplexing (TDD)

- uses time for forward and reverse link
- multiple users share a single radio channel
- forward time slot
- reverse time slot
- no duplexer is required



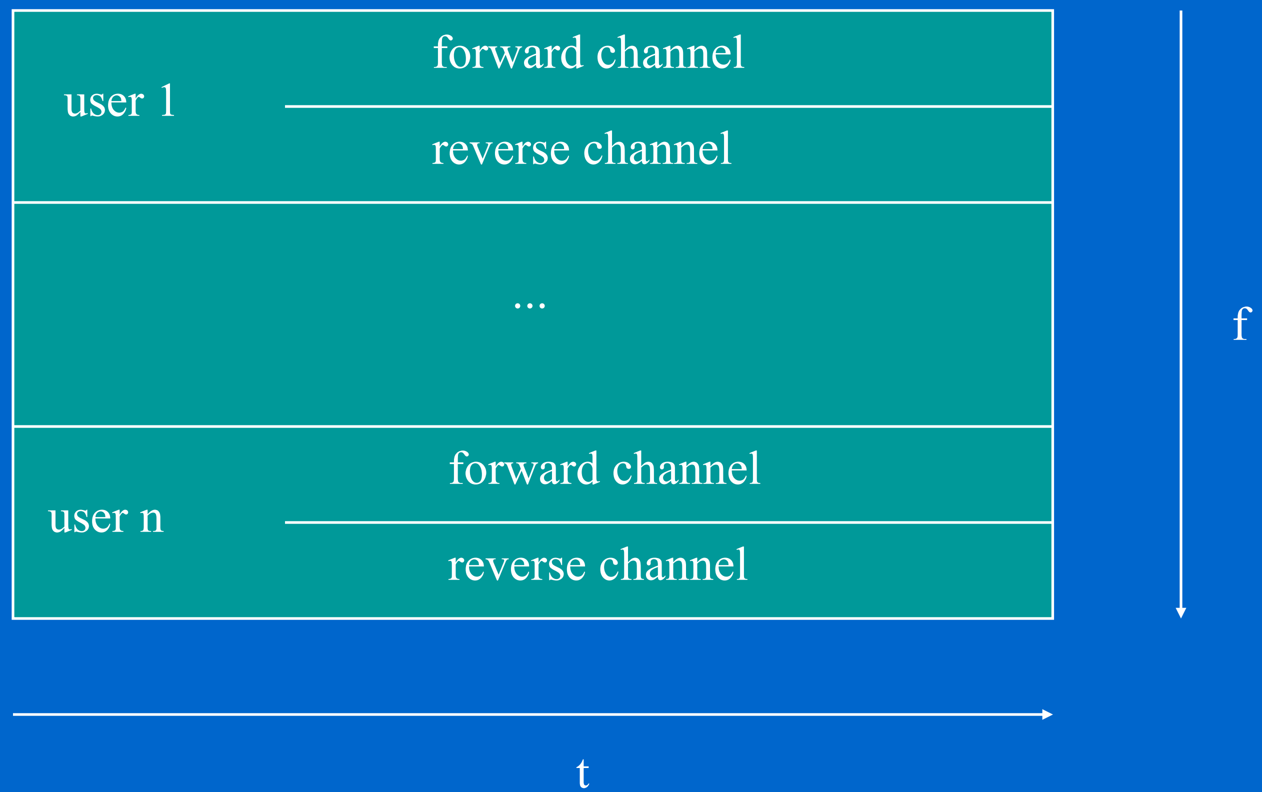
Multiple Access Techniques

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Space division multiple access (SDMA)
- grouped as:
- narrowband systems
- wideband systems

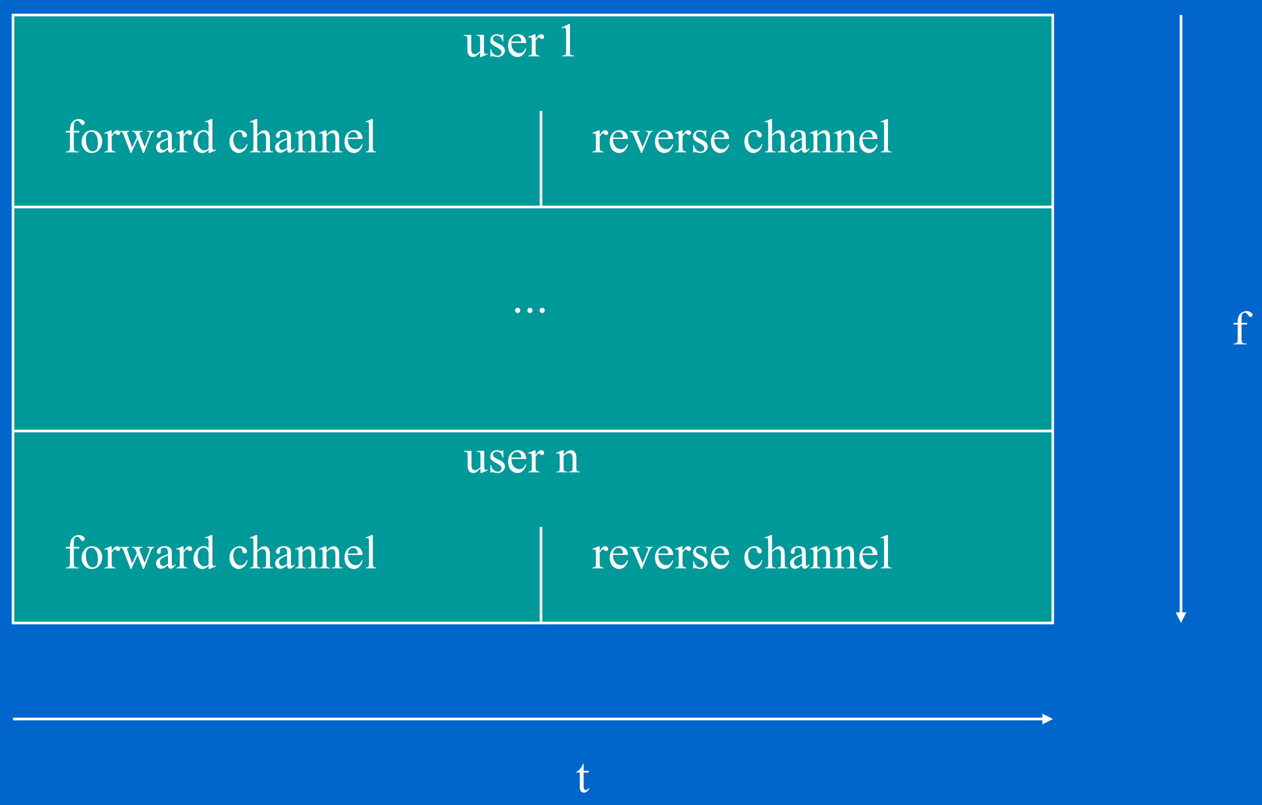
Narrowband systems

- large number of narrowband channels
- usually FDD
- Narrowband FDMA
- Narrowband TDMA
- FDMA/FDD
- FDMA/TDD
- TDMA/FDD
- TDMA/TDD

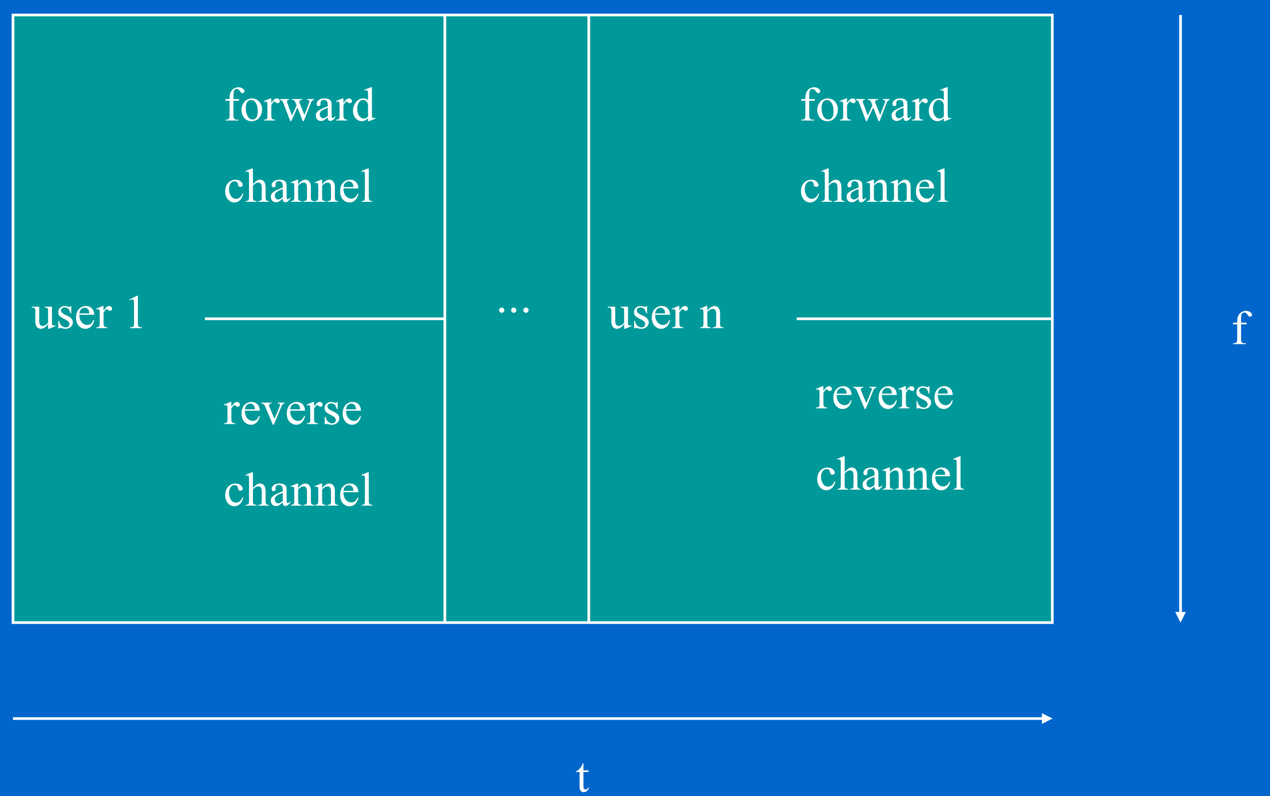
Logical separation FDMA/FDD



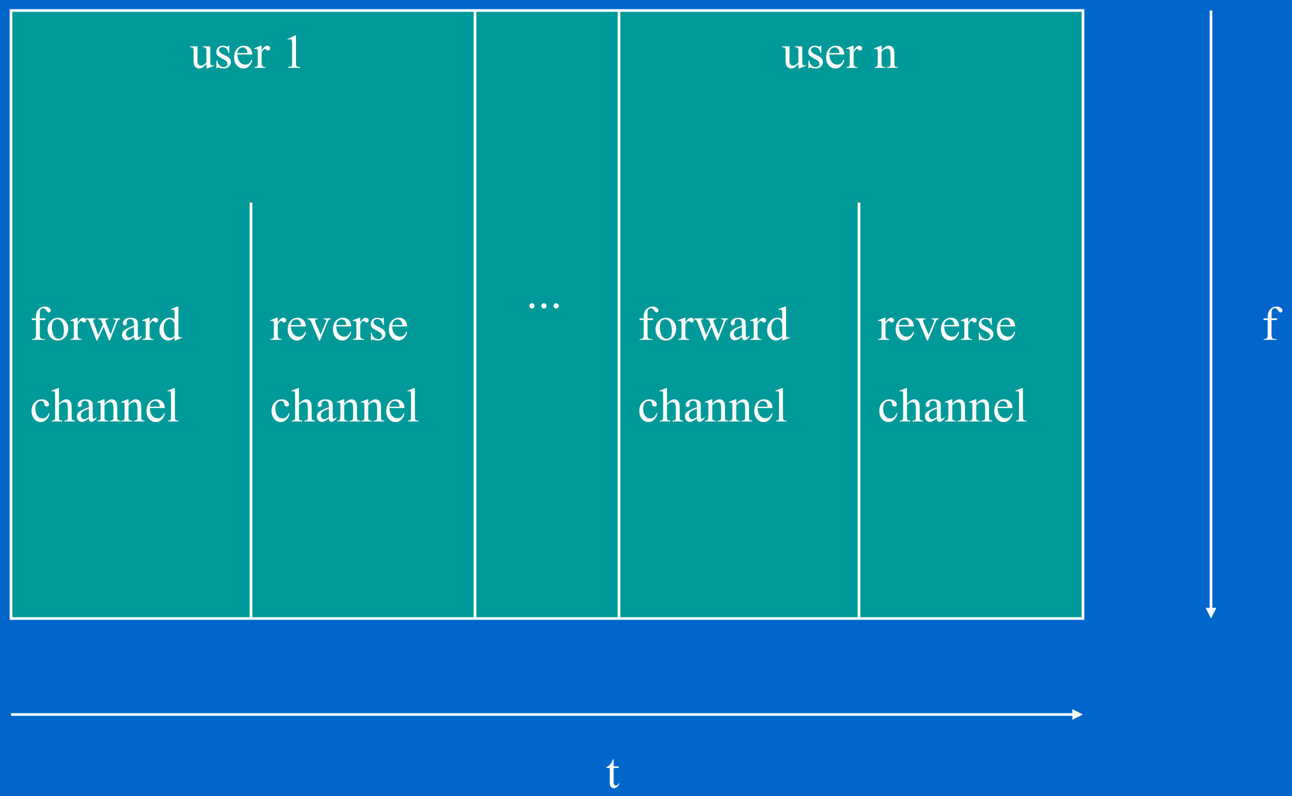
Logical separation FDMA/TDD



Logical separation TDMA/FDD



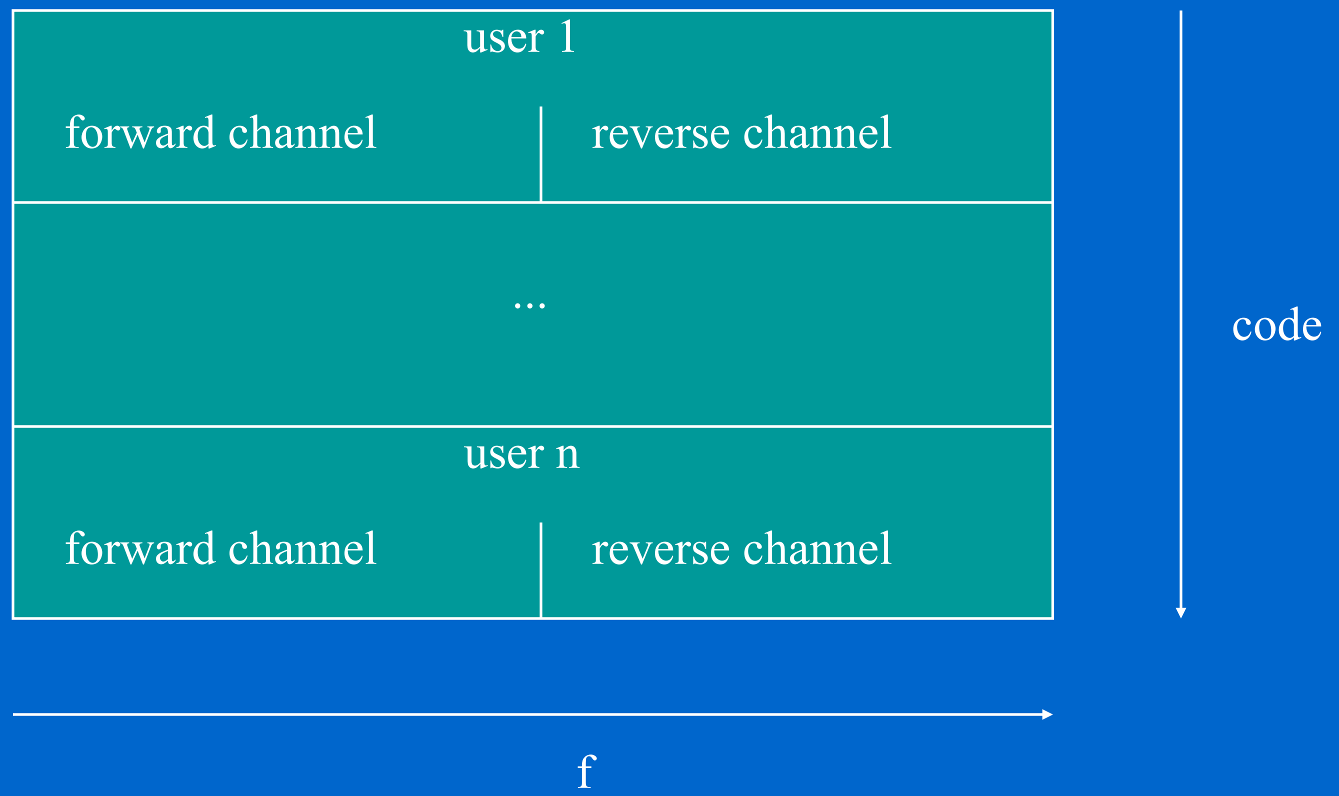
Logical separation TDMA/TDD



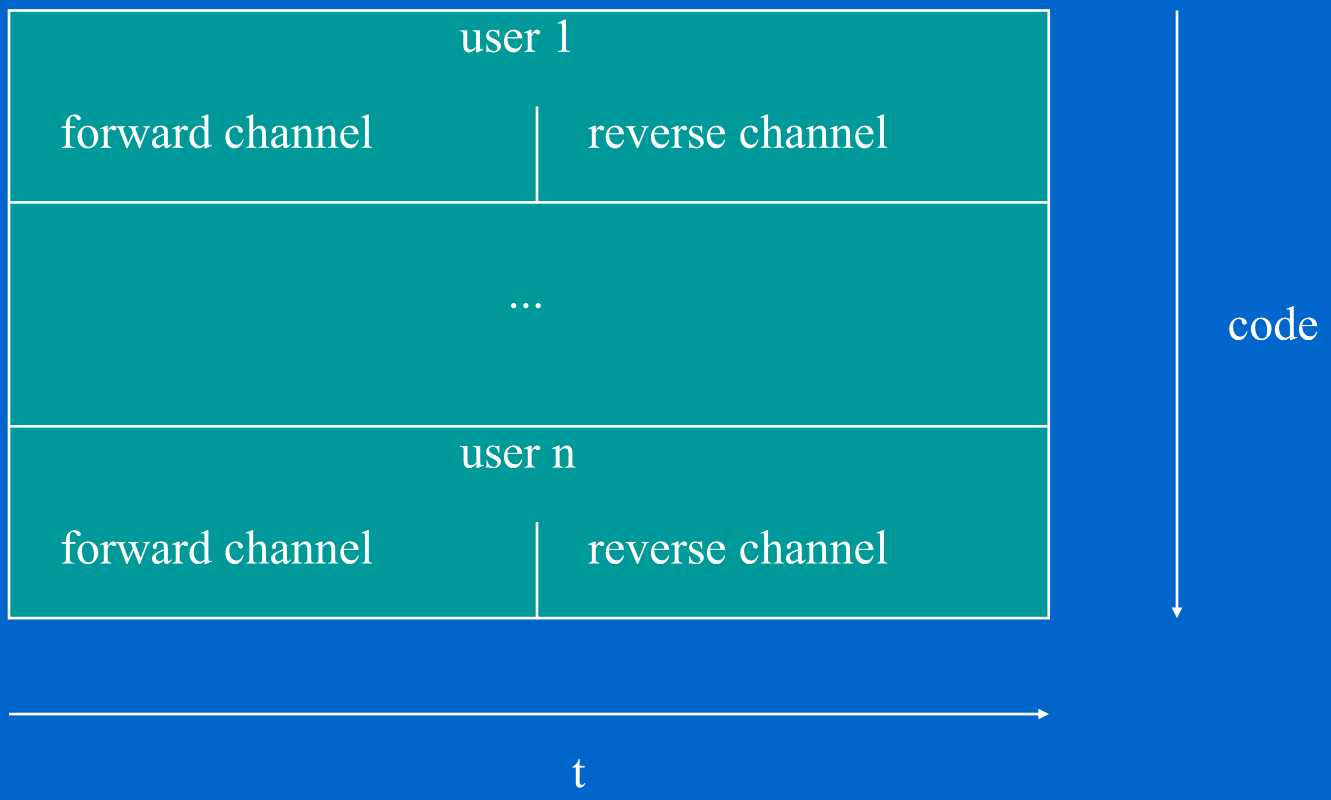
Wideband systems

- large number of transmitters on one channel
- TDMA techniques
- CDMA techniques
- FDD or TDD multiplexing techniques
- TDMA/FDD
- TDMA/TDD
- CDMA/FDD
- CDMA/TDD

Logical separation CDMA/FDD



Logical separation CDMA/TDD



Multiple Access Techniques in use

Cellular System	Multiple Access Technique
Advanced Mobile Phone System (AMPS)	FDMA/FDD
Global System for Mobile (GSM)	TDMA/FDD
US Digital Cellular (USDC)	TDMA/FDD
Digital European Cordless Telephone (DECT)	FDMA/TDD
US Narrowband Spread Spectrum (IS-95)	CDMA/FDD

Frequency division multiple access FDMA

- one phone circuit per channel
- idle time causes wasting of resources
- simultaneously and continuously transmitting
- usually implemented in narrowband systems
- for example: in AMPS is a FDMA bandwidth of 30 kHz implemented

FDMA compared to TDMA

- fewer bits for synchronization
- fewer bits for framing
- higher cell site system costs
- higher costs for duplexer used in base station and subscriber units
- FDMA requires RF filtering to minimize adjacent channel interference

Nonlinear Effects in FDMA

- many channels - same antenna
- for maximum power efficiency operate near saturation
- near saturation power amplifiers are nonlinear
- nonlinearities causes signal spreading
- intermodulation frequencies

Nonlinear Effects in FDMA

- IM are undesired harmonics
- interference with other channels in the FDMA system
- decreases user C/I - decreases performance
- interference outside the mobile radio band: adjacent-channel interference
- RF filters needed - higher costs

Number of channels in a FDMA system

$$N = \frac{B_t - B_{guard}}{B_c}$$

- N … number of channels
- B_t … total spectrum allocation
- B_{guard} … guard band
- B_c … channel bandwidth

Example: Advanced Mobile Phone System

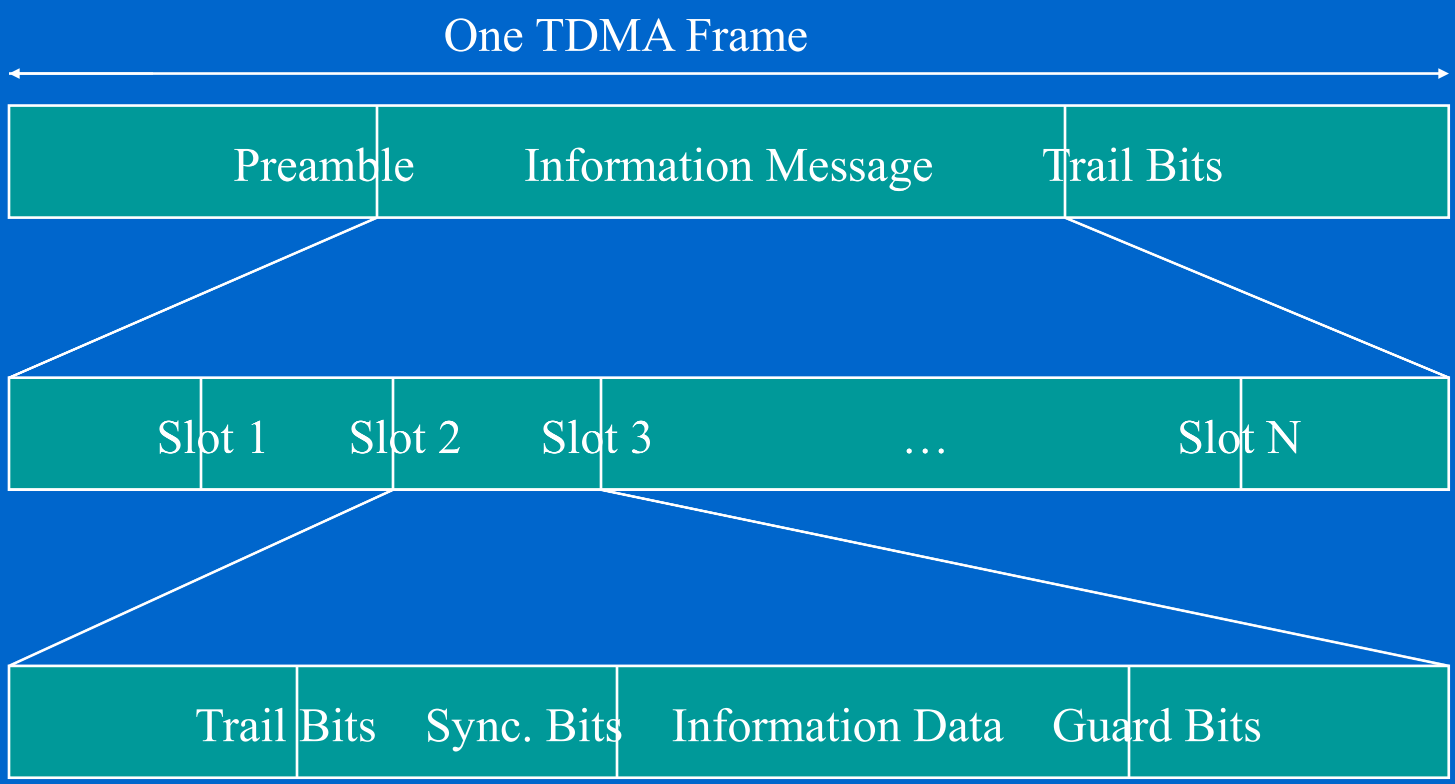
- AMPS
- FDMA/FDD
- analog cellular system
- 12.5 MHz per simplex band - B_t
- B_{guard} = 10 kHz ; B_c = 30 kHz

$$N = \frac{12.5E6 - 2*(10E3)}{30E3} = 416 \text{ channels}$$

Time Division Multiple Access

- time slots
- one user per slot
- buffer and burst method
- noncontinuous transmission
- digital data
- digital modulation

Repeating Frame Structure



The frame is cyclically repeated over time.

Features of TDMA

- a single carrier frequency for several users
- transmission in bursts
- low battery consumption
- handoff process much simpler
- FDD : switch instead of duplexer
- very high transmission rate
- high synchronization overhead
- guard slots necessary

Number of channels in a TDMA system

$$N = \frac{m*(B_{tot} - 2*B_{guard})}{B_c}$$

- N … number of channels
- m … number of TDMA users per radio channel
- B_{tot} … total spectrum allocation
- B_{guard} … Guard Band
- B_c … channel bandwidth

Example: Global System for Mobile (GSM)

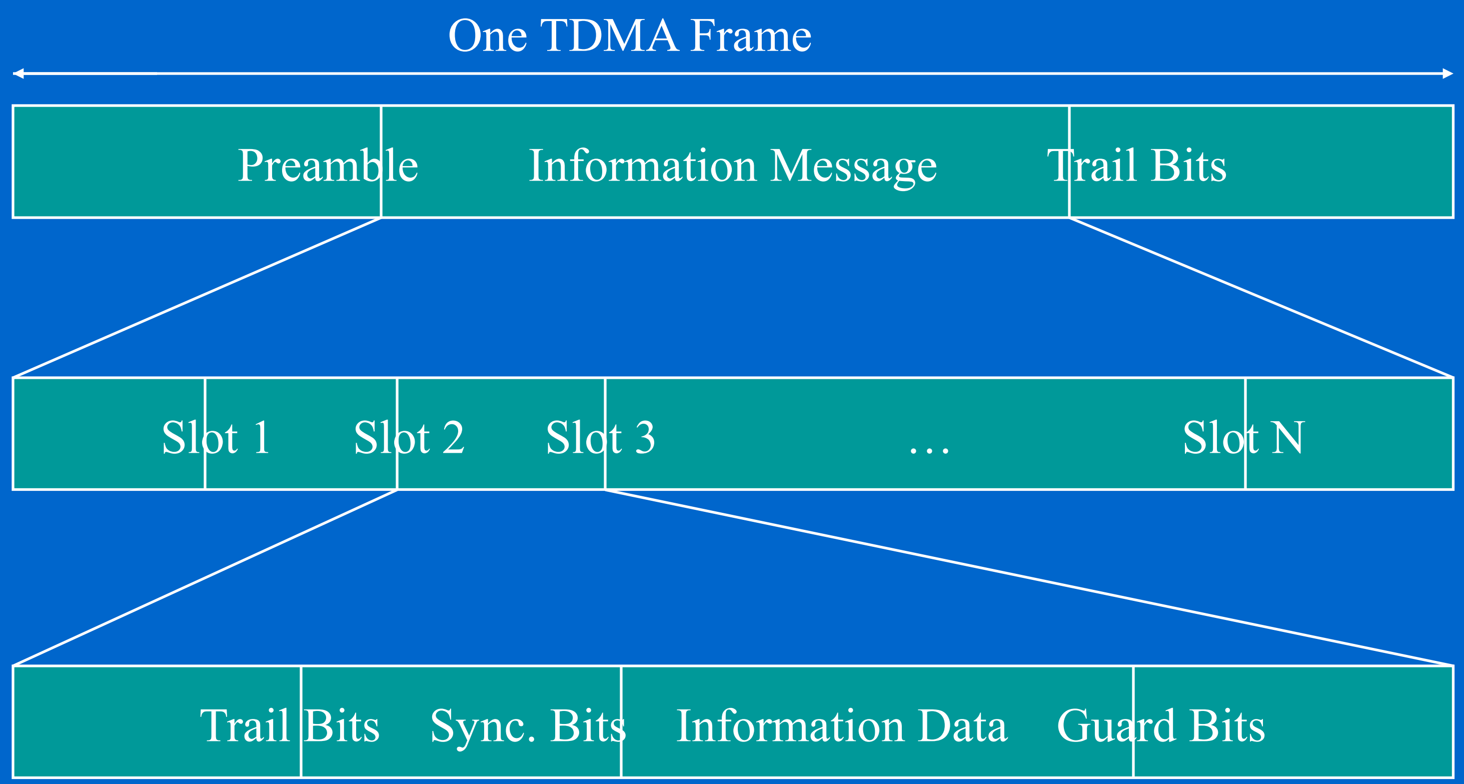
- TDMA/FDD
- forward link at B_{tot} = 25 MHz
- radio channels of B_c = 200 kHz
- if m = 8 speech channels supported, and
- if no guard band is assumed :

$$N = \frac{8*25E6}{200E3} = 1000 \text{ simultaneous users}$$

Efficiency of TDMA

- percentage of transmitted data that contain information
- frame efficiency η_f
- usually end user efficiency $< \eta_f$,
- because of source and channel coding
- How get η_f ?

Repeating Frame Structure



The frame is cyclically repeated over time.

Efficiency of TDMA

$$b_{OH} = N_r * b_r + N_t * b_p + N_t * b_g + N_r * b_g$$

- b_{OH} … number of overhead bits
- N_r … number of reference bursts per frame
- b_r … reference bits per reference burst
- N_t … number of traffic bursts per frame
- b_p … overhead bits per preamble in each slot
- b_g … equivalent bits in each guard time intervall

Efficiency of TDMA

$$b_T = T_f * R$$

- b_T … total number of bits per frame
- T_f … frame duration
- R … channel bit rate

Efficiency of TDMA

$$\square_f = (1 - b_{OH}/b_T) * 100\%$$

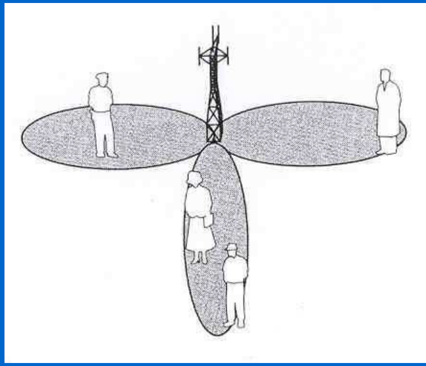
- $\square_f$ … frame efficiency
- b_{OH} … number of overhead bits per frame
- b_T … total number of bits per frame

Space Division Multiple Access

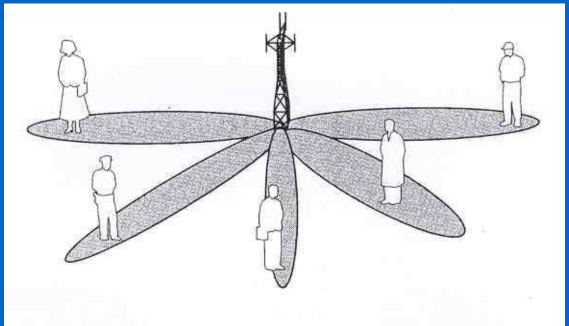
- Controls radiated energy for each user in space
- using spot beam antennas
- base station tracks user when moving
- cover areas with same frequency:
- TDMA or CDMA systems
- cover areas with same frequency:
- FDMA systems

Space Division Multiple Access

- primitive applications are "Sectorized antennas"



- in future adaptive antennas simultaneously steer energy in the direction of many users at once



Reverse link problems

- general problem
- different propagation path from user to base
- dynamic control of transmitting power from each user to the base station required
- limits by battery consumption of subscriber units
- possible solution is a filter for each user

Solution by SDMA systems

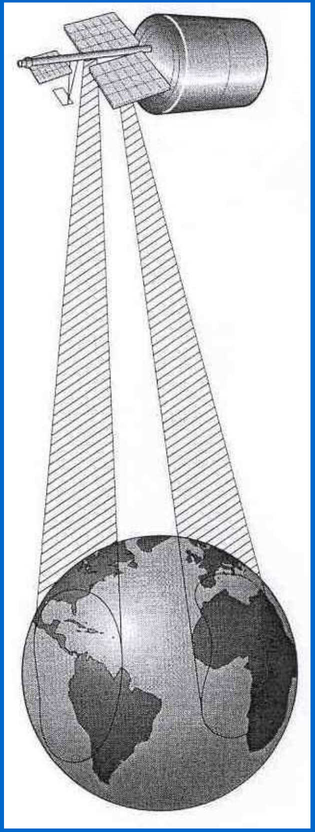
- adaptive antennas promise to mitigate reverse link problems
- limiting case of infinitesimal beamwidth
- limiting case of infinitely fast track ability
- thereby unique channel that is free from interference
- all user communicate at same time using the same channel

Disadvantage of SDMA

- perfect adaptive antenna system: infinitely large antenna needed
- compromise needed

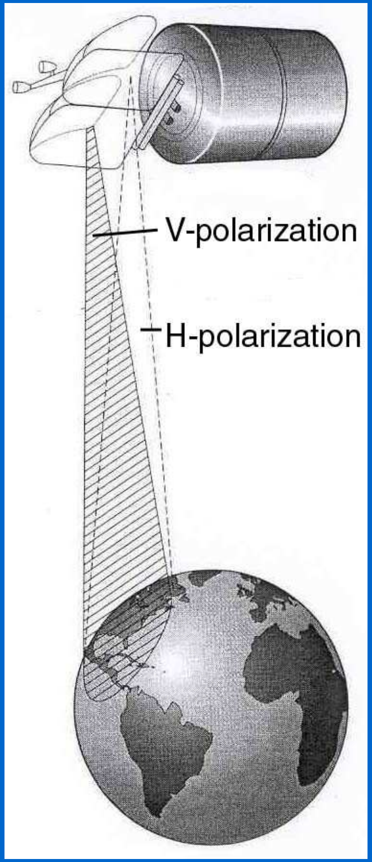
SDMA and PDMA in satellites

- INTELSAT IVA
- SDMA dual-beam receive antenna
- simultaneously access from two different regions of the earth



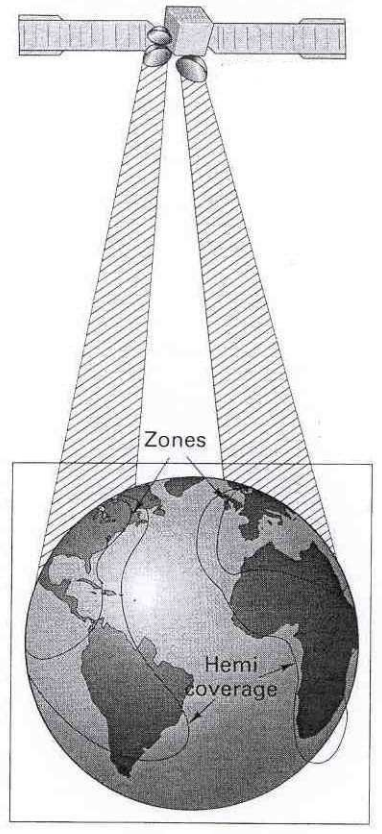
SDMA and PDMA in satellites

- COMSTAR 1
- PDMA
- separate antennas
- simultaneously access from same region



SDMA and PDMA in satellites

- INTELSAT V
- PDMA and SDMA
- two hemispheric coverages by SDMA
- two smaller beam zones by PDMA
- orthogonal polarization



Capacity of Cellular Systems

- channel capacity: maximum number of users in a fixed frequency band
- radio capacity : value for spectrum efficiency
- reverse channel interference
- forward channel interference
- How determine the radio capacity?

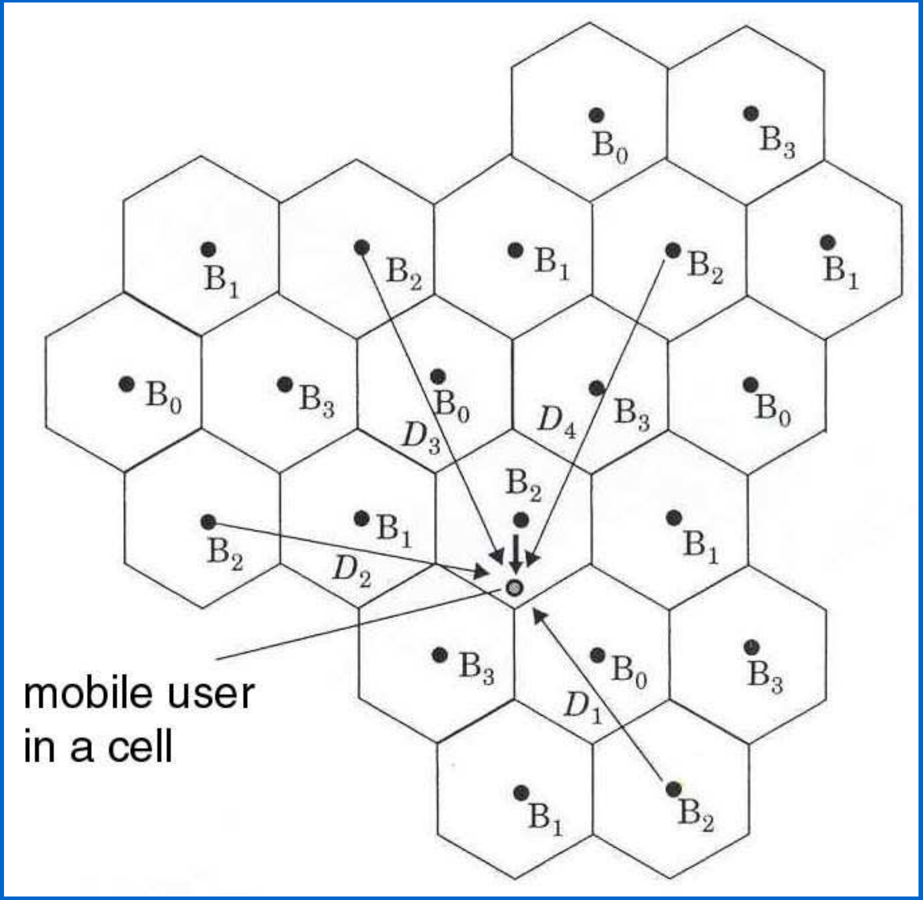
Co-Channel Reuse Ratio Q

$$Q = D/R$$

- Q … co-channel reuse ratio
- D … distance between two co-channel cells
- R … cell radius

Forward channel interference

- cluster size of 4
- D0 … distance serving station to user
- DK … distance co-channel base station to user



Carrier-to-interference ratio C/I

- M closest co-channels cells cause first order interference

$$\frac{C}{I} = \frac{D_0^{-n_0}}{\sum_{k=1}^{M} D_K^{-n_k}}$$

- n_0 … path loss exponent in the desired cell
- n_k … path loss exponent to the interfering base station

Carrier-to-interference ratio C/I

- Assumption:
- just the 6 closest stations interfere
- all these stations have the same distance D
- all have similar path loss exponents to n_0

$$\frac{C}{I} = \frac{D_0^{-n}}{6 * D^{-n}}$$

Worst Case Performance

- maximum interference at $D_0 = R$
- $(C/I)_{min}$ for acceptable signal quality
- following equation must hold:

$$1/6 * (R/D)^{-n} \geq (C/I)_{min}$$

Co-Channel reuse ratio Q

$$Q = D/R = (6*(C/I)_{min})^{1/n}$$

- D … distance of the 6 closest interfering base stations
- R … cell radius
- $(C/I)_{min}$ … minimum carrier-to-interference ratio
- n … path loss exponent

Radio Capacity m

$$m = \frac{B_t}{B_c * N} \text{ radio channels/cell}$$

- Bt … total allocated spectrum for the system
- Bc … channel bandwidth
- N … number of cells in a complete frequency reuse cluster

Radio Capacity m

- N is related to the co-channel factor Q by:

$$Q = (3*N)^{1/2}$$

$$m = \frac{B_t}{B_c * (Q^2/3)} = \frac{B_t}{Bc * \left(\frac{6}{3^{n/2}} * \left(\frac{C}{I} \right)_{min} \right)^{2/n}}$$

Radio Capacity m for n = 4

$$m = \frac{B_t}{B_c * \sqrt{2/3 * (C/I)_{min}}}$$

- m … number of radio channels per cell
- $(C/I)_{min}$ lower in digital systems compared to analog systems
- lower $(C/I)_{min}$ imply more capacity
- exact values in real world conditions measured

Compare different Systems

- each digital wireless standard has different $(C/I)_{min}$
- to compare them an equivalent (C/I) needed
- keep total spectrum allocation B_t and number of rario channels per cell m constant to get $(C/I)_{eq}$:

Compare different Systems

$$\left(\frac{C}{I}\right)_{eq} = \left(\frac{C}{I}\right)_{min} * \left(\frac{B_c}{B_{c'}}\right)^2$$

- B_c … bandwidth of a particular system
- $(C/I)_{min}$ … tolerable value for the same system
- B_c' … channel bandwidth for a different system
- $(C/I)_{eq}$ … minimum C/I value for the different system

C/I in digital cellular systems

$$\frac{C}{I} = \frac{E_b * R_b}{I} = \frac{E_c * R_c}{I}$$

- R_b … channel bit rate
- E_b … energy per bit
- R_c … rate of the channel code
- E_c … energy per code symbol

C/I in digital cellular systems

- combine last two equations:

$$\frac{(C/I)}{(C/I)_{eq}} = \frac{(E_c * R_c)/I}{(E_c' * R_c')/I'} = \left(\frac{B_c'}{B_c}\right)^2$$

- The sign ‘ marks compared system parameters

C/I in digital cellular systems

- Relationship between R_c and B_c is always linear ($R_c/R_c' = B_c/B_c'$)
- assume that level I is the same for two different systems ($I' = I$) :

$$\frac{E_c}{E_c'} = \left(\frac{B_c'}{B_c}\right)^3$$

Compare C/I between FDMA and TDMA

- Assume that multichannel FDMA system occupies same spectrum as a TDMA system
- FDMA : $C = E_b * R_b$; $I = I_0 * B_c$
- TDMA : $C' = E_b * R_b'$; $I' = I_0 * B_c'$
- E_b … Energy per bit
- I_0 … interference power per Hertz
- R_b … channel bit rate
- B_c … channel bandwidth

Example

- A FDMA system has 3 channels , each with a bandwidth of 10kHz and a transmission rate of 10 kbps.
- A TDMA system has 3 time slots, a channel bandwidth of 30kHz and a transmission rate of 30 kbps.
- What's the received carrier-to-interference ratio for a user ?

Example

- In TDMA system C'/I' be measured in 333.3 ms per second - one time slot

$$\frac{C'}{I'} = \frac{E_b * R_b'}{I0 * Bc'} = \frac{1/3*(E_b*10E4 \text{ bits})}{I0*30kHz} = \frac{3*R_b*E_b}{3*I} = \frac{3*C}{3*I}$$

- In this example FDMA and TDMA have the same radio capacity (C/I leads to m)

Example

- Peak power of TDMA is 10logk higher then in FDMA (k … time slots)
- in practice TDMA have a 3-6 times better capacity

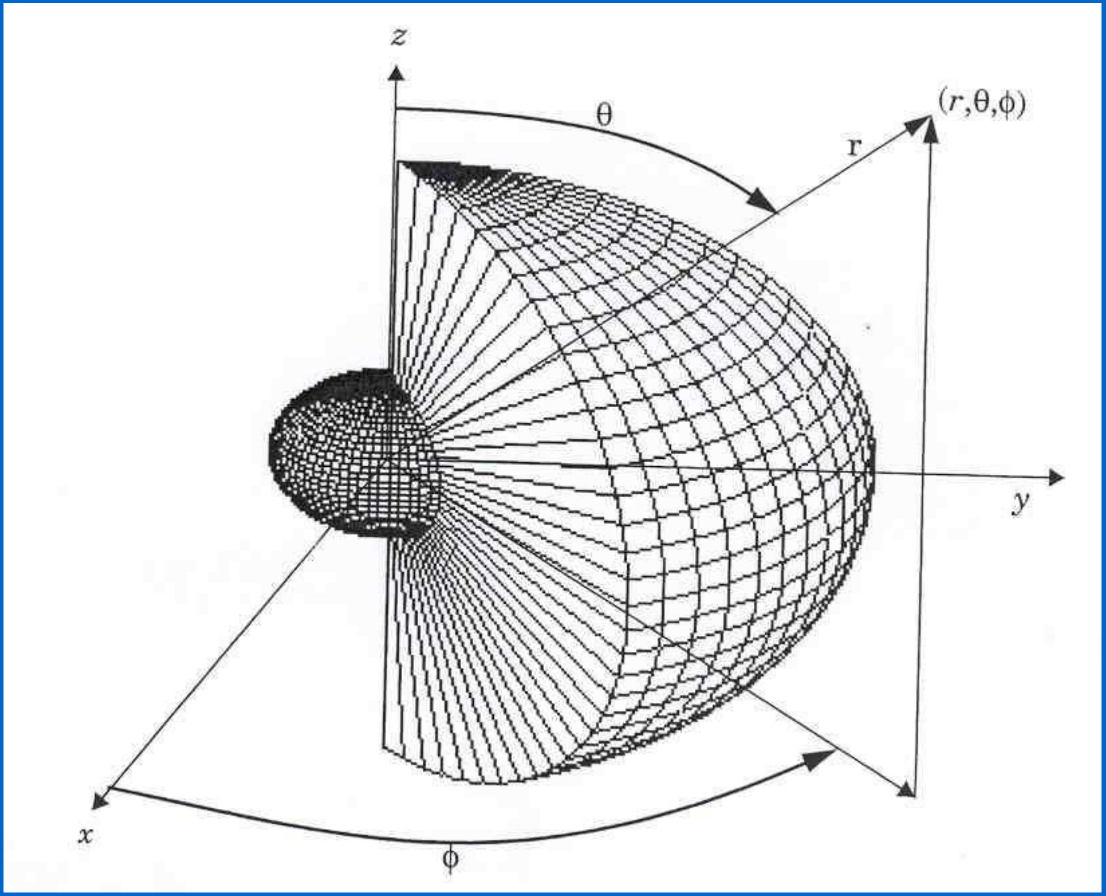
Capacity of SDMA systems

- one beam each user
- base station tracks each user as it moves
- adaptive antennas most powerful form
- beam pattern G(□) has maximum gain in the direction of desired user
- beam is formed by N-element adaptive array antenna

Capacity of SDMA systems

- G(□) steered in the horizontal □ -plane through 360°
- G(□) has no variation in the elevation plane to account which are near to and far from the base station
- following picture shows a 60 degree beamwidth with a 6 dB sideslope level

Capacity of SDMA systems



Capacity of SDMA systems

- reverse link received signal power, from desired mobiles, is $P_{r;0}$
- interfering users i = 1,…,k-1 have received power $P_{r;I}$
- average total interference power I seen by a single desired user:

Capacity of SDMA

$$I = E\left\{ \sum_{i=1}^{K-1} G(\theta_i)\, P_{r;I} \right\}$$

- θ_i … direction of the i-th user in the horizontal plane
- E … expectation operator

Capacity of SDMA systems

- in case of perfect power control (received power from each user is the same) :

$$P_{r;I} = P_c$$

- Average interference power seen by user 0:

$$I = P_c \, E \left\{ \sum_{i=1}^{K-1} G(\theta_i) \right\}$$

Capacity of SDMA systems

- users independently and identically distributed throughout the cell:

$$I = P_c * (k - 1) * 1/D$$

- D … directivity of the antenna - given by max(G())
- D typ. 3dB …10dB

Capacity of SDMA systems

- Average bit error rate P_b for user 0:

$$P_b = Q\left(\sqrt{\frac{3\,D\,N}{K-1}}\right)$$

- D … directivity of the antenna
- Q(x) … standard Q-function
- N … spreading factor
- K … number of users in a cell

Capacity of SDMA systems