Wireless and Mobile Communications:

Reference Book: Theodore S. Rappaport

Lecture 1: Introduction

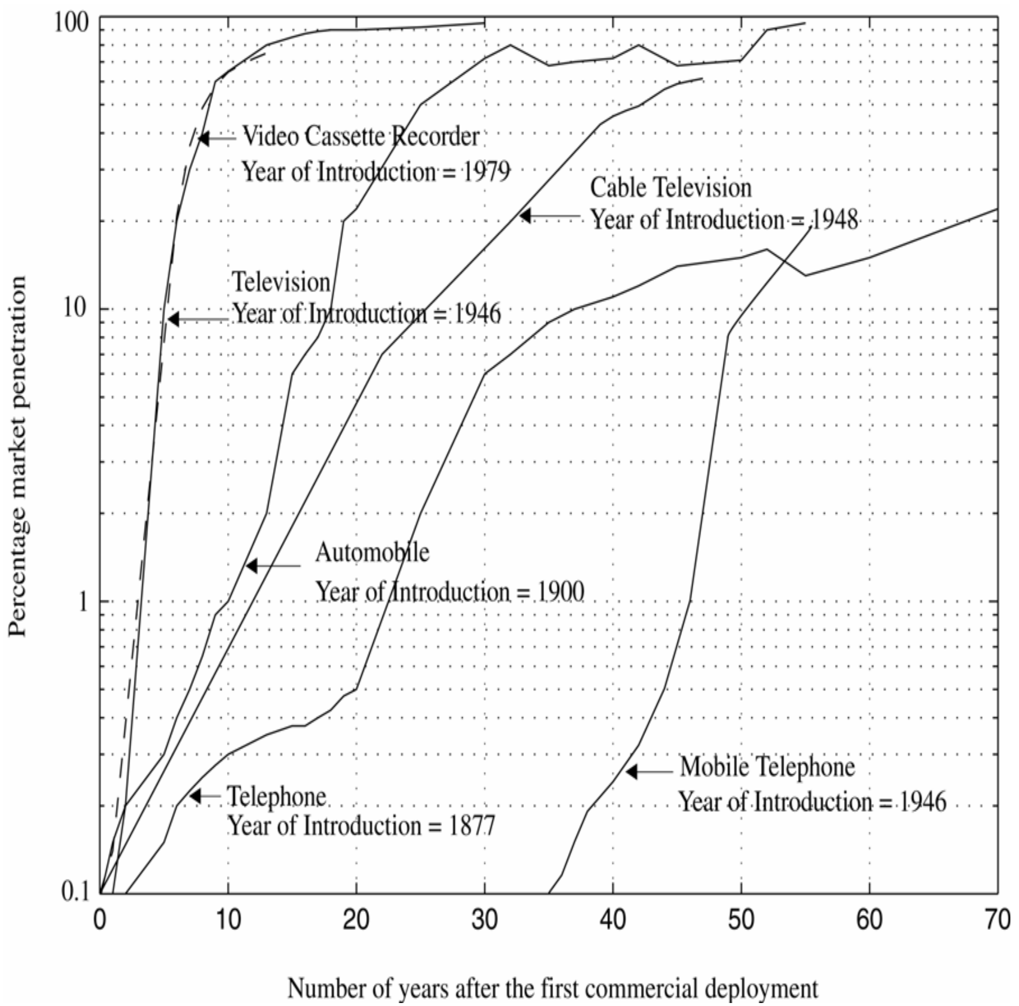
Chapter 1 - Introduction to Wireless Communication Systems

"The ability to communicate with people on move"
-1st invented by Guglielmo Marconi in 1897
-Demonstrated radio's ability to provide continuous contacts with ships sailing the English Channels.
-Then rapid growth.
-Digital and R.F fabrication improvements.
-New large scale circuit integration & other miniaturization technologies
-Smaller , cheaper and more reliable
-Digital switching technology - Facilitated large scale deployment of affordable, easy to use radio communication
- Driven by consumer demand.

I. History

♦ Wired Communications
- 1834 – Gauss and Weber build telegraph system in Germany
- 1844 – Morse connects Baltimore and Washington by telegraph
- 1858 – First transatlantic telegraph cable laid
- 1876 – Alexander Bell demonstrates telephone
- 1911 – New York can telephone Denver

♦ Wireless Communications → Not so "new"
- had slow growth at first compared to other inventions. But now is growing very rapidly.



- 1899 − Marconi sends first radio message across Atlantic
- 1905 − Hulsmeyer detects ships with radar
- 1927 − US & Europe telephones linked by HF radio
- 1934 − AM mobile police radios for public safety widely used
- 1935 − Edwin Armstrong demonstrates FM radio system, which became the primary modulation technique.
- 1940 − First microwave radar
- 1965 − First commercial communication satellite
- 1968 − AT&T proposes cellular phone system to Federal Communications Commission (FCC)
- 1983 − FCC allocates spectrum for analog cellular service (AMPS)
- 1990 − GSM digital cellular service introduced in Europe
- 1995 − FCC auctions new Personal Communication Service (PCS) licenses in U.S. for digital services
- 1998 − 40 million cellular phone users in U.S.
- 2000 − In some countries, mobile users outnumber conventional wireline customers.
- 2001 − 630 million subscribers worldwide (as compared to 1 billion wired phone lines.
- 2001 − Over 1% of worldwide wireless subscribers have abandoned wired telephone service for home use.
- 2005 − Over 130 million cellular phone users in U.S. (out of population of 300 million including children).

II. Frequencies

♦ RF − Radio Frequency
 1 MHz to 1 GHz
• general classification, not absolute
 100 MHz to 1 GHz
• more widely used definition
♦ Microwave
 1 GHz to 300 GHz − general
 1 GHz to 100 GHz − more widely used
♦ Trends towards use of higher frequencies
 greater signal bandwidth (BW) per channel
 more users and/or higher data rates
 but more difficult to design! → more money, more engineering required for
sharper filters, better tuned oscillators, etc.

Flow Graph of gradual growth:

Telegraph
I
Telephone
I
Radio message in ships (English Channel)
I
Ship detection with radar
I
US & Europe telephone link by HF radio
I
AM mobile police radio for public safely
I
FM radio
I
First microwave radar, first commercial communication Satellite.
I
1G: Cellular phone (AMPS)
I
2G: GSM
I
2.5G: GPRS
I
3G:WCDMA

Examples of wireless communication systems:

Home Appliances: * TV remote control.
* Garage door opener.

1. Paging system:

-Sends a brief message to another subscriber.
-Types of message: Numeric, alpha numeric and voice.

Objective:

-To notify a subscriber of the need to call a particular telephone number. Or
-Travels to a known location to receive further instruction.
-Modern paging system has facilities like- news headlines, stock quotations and faxes may be send.

Method:

-Dial via paging system access number with a telephone key pad or modem.

-Issued message called page.
-The paging system then transmit the page through out the service area using Base Station which broadcast the page on a radio carrier.

Range:

- Simple – 2 to 5 km.
- Wide area paging system :
  Provides world wide coverage.
  Wide area paging system consist of:
  - Network of telephones lines.
  - Many BS.
  - Large powerful transmitter &
  - A receiver.

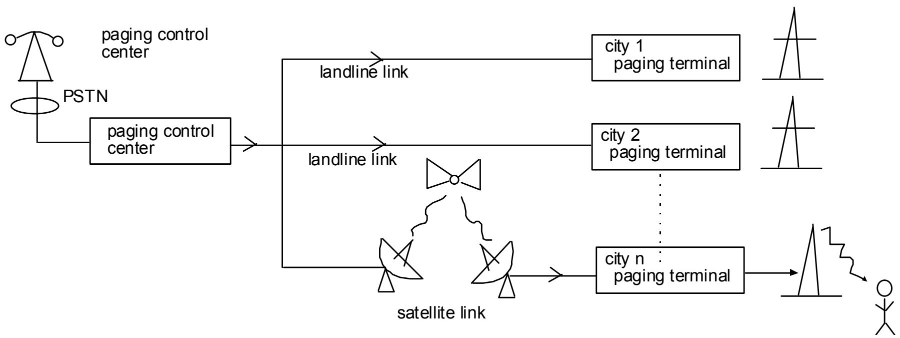
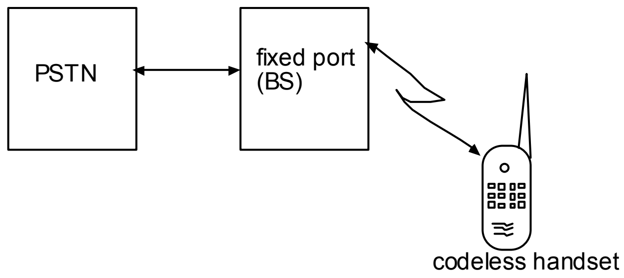


Fig. wide area paging system.

2. Cordless Telephone system:



- Full duplex communication system.
- Uses radio to connect a portable handset to dedicated BS.
- Which then connected to dedicated telephone line with specific telephone number on PSTN.

1st generation

- Manufactured in 1980.
- Portable unit communicates with dedicated base units.
- Only over short distance (few meters).
- Just an extension of wired telephone lines.
- Transciever connected a subscriber line on the PSTN.
- Primarily for home use.

2nd generation:

- Allows subscriber to use their handset at many outdoor locations within urban centers.
- Modern
  - cordless combine with paging system.
  - Subscriber may first be paged, then response to the page using codeless telephone.
  - Has limitation on mobility over a larger distance.
- Coverage upto few hundred meters.

Cellular Telephone Systems:

- Provides wireless connection to the PSTN for any user location within the range of the system.
- Accommodates large number of user over the large geographical areas.
- With limited frequency spectrum.
- Quality Of Service
  - o High as compared to landline.
  - o Achieved by BS transmitter is limited to small geographical area.
  - o Uses frequency reuse concept.

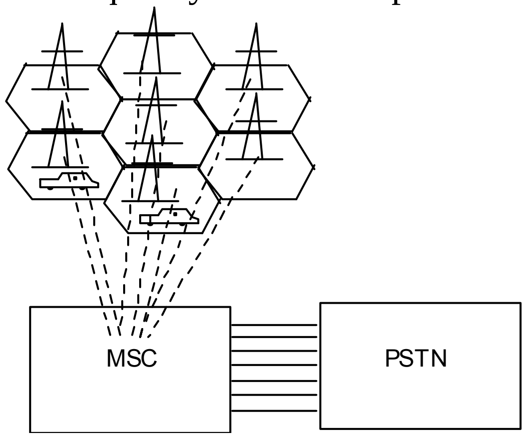


Fig. A cellular system.

- Basic cellular system consist of:
  - o Mobile station.
  - o Base station.
  - o MSC(mobile switching center) OR mobile switching telephone office(MTSO).

Mobile station:

- Each mobile communicates via radio with BS.
- Contains transceiver, an antenna and control circuitry.
- May be mounted in a vehicle or used a handheld portable unit.

BS:

- Consists of several Transmitter and receiver.
- Simultaneously handle full duplex communications.
- Generally have tower which support transmitting and receiving antennas.
- BS serves as a bridge between all mobile users in the cell and connects the simultaneous mobile calls via telephone lines or microwave links to MSC.

MSC:

- It coordinates the activates of all the BS and
- Connects the entire cellular system to the PSTN.
- MSC handles multiple subscribers, various simultaneous conversations at a time.
- Accommodates all billing and system maintenance function.
- In large cities several MSCs are used by the single carrier.

Common Air interface (CAI):

- Communication between base station and mobile.
- Specifies four different channels. 2 for voice and 2 for control.
- Channels used for voice channels are forward voice channel (FVC) and reverse voice channel (RVC).

- Channels used for initiating calls forward control channel (FCC) and reverse control channel. Often called setup channel.
- Control channel transmit and receives data message for call initialization and service request.
- FCC – broad cast all traffic requests for all mobiles in a system.
- RCC- sends acknowledgement.
- Cellular phones- Scans for strongest FCC, once found stayed “captured” to particular FCC, then sends voice over it.

How the cellular call is made?

- Call initiated by landline subscriber.
  Fig. 1.6, pg. 16
- Call initiated by mobile.
  Fig. 1.7, pg. 17

- Cellular phone turned on but not yet engaged in a call.
- Scans the group of forward control channel for strongest signal.
- Monitors the control channels until the signal drops below a usable levels.
- Again scan the control channel in search of strongest BS signal.
- Control channels occupies 5% of the total number of channels available and 95% dedicated to voice and data for end users.
- When the telephone call is placed to a mobile user MSC dispatches the requests to all the BS.
- MIN (mobile identification number) is then broadcast as a paging message over all FCC.
- Mobile receives the paging message sent by the BS which monitors and responds by identifying itself over RCC.
- BS relay acknowledgement sent by mobile and informs MSC of handshake.
- MSC instructs BS to move the call to an unused voice channel within the cell.
- Here , BS signals the mobile to change frequency to an unused VC and RVC.
- Using another data message instruct the mobile to ring then instructing the user to answer the phone.
- One the call is in progress.
- MSC adjusts the transmitter power of the mobile unit and BS to maintain call quality.
- Out of range - handoff.
- Done by MSC.

When the mobile originates a call:

- call initiates request on the reverse control channel.
- Mobile unit transmit:
  - MIN and ESN (electronic serial no).
  - Also transmits station class indicates mark transmit power level for particular user.
- BS receives this and sends to MSC.
- MSC validates requests.
- Makes connections to the called party PSTN.

- Instructs unused FVC and RVC for communication.

Roaming: Allows subscriber to operates in service areas other then one from which service is subscribed.

- (Service area different from home registered as a roamer)
- Receives inform from HLR.

4.Emerging

- WLAN: Wireless Local Area Networks
- Mobile computers/email
- Wireless Local Loop (WLL)
- • local phone service via wireless connection
- • prominent in non-industrialized nations
- • cheaper to install than wired lines
- • new IEEE 802.16 standard has been developed for WLL.
- Wireless-enabled Personal Digital Assistants (PDAs)
- Wireless Device Connectivity between computer peripherals (printers,
- monitors, keyboards, etc.) – Bluetooth
- Satellite to **mobile** ground units → Land Mobile Satellite (LMS)
- • Motorola/Iridium
- Digital Cellular/PCS
- • PCS = Personal Communication Services
- • Several types of services and capabilities are offered
- Radio Frequency Identification Tags (RFID's) on merchandize in
- warehouses and stores.
- Sensor networks – small devices wirelessly communicating among
- themselves to monitor environments using a variety of sensors.

Table 1.4 Wireless Communications System Definitions

Base Station	A fixed station in a mobile radio system used for radio communication with mobile stations. Base stations are located at the center or on the edge of a coverage region and consist of radio channels and transmitter and receiver antennas mounted on a tower.
Control Channel	Radio channel used for transmission of call setup, call request, call initiation, and other beacon or control purposes.
Forward Channel	Radio channel used for transmission of information from the base station to the mobile.
Full Duplex Systems	Communication systems which allow simultaneous two-way communication. Transmission and reception is typically on two different channels (FDD) although new cordless/PCS systems are using TDD.
Half Duplex Systems	Communication systems which allow two-way communication by using the same radio channel for both transmission and reception. At any given time, the user can only either transmit or receive information.
Handoff	The process of transferring a mobile station from one channel or base station to another.
Mobile Station	A station in the cellular radio service intended for use while in motion at unspecified locations. Mobile stations may be hand-held personal units (portables) or installed in vehicles (mobiles).
Mobile Switching Center	Switching center which coordinates the routing of calls in a large service area. In a cellular radio system, the MSC connects the cellular base stations and the mobiles to the PSTN. An MSC is also called a mobile telephone switching office (MTSO).
Page	A brief message which is broadcast over the entire service area, usually in a simulcast fashion by many base stations at the same time.
Reverse Channel	Radio channel used for transmission of information from the mobile to base station.
Roamer	A mobile station which operates in a service area (market) other than that from which service has been subscribed.
Simplex Systems	Communication systems which provide only one-way communication.
Subscriber	A user who pays subscription charges for using a mobile communications system.
Transceiver	A device capable of simultaneously transmitting and receiving radio signals.

Lecture 2.Generations (wireless communication systems):

1st Generation:

- These systems used analog ckt-switched technology.
- With frequency Division Multiple Access (FDMA).
  - Multiple users are provided access to systems by dividing spectrum up into frequency bands.
  - Different users use diff. freq bands.
  - Work mainly in the 800-900 Mhz bands.
- The network had a low traffic capacity.
  - Unreliable handover.
  - Poor voice quality.
  - Poor security.
- Use voice calls only.
- These systems typically allocated one 25 Mhz frequency band for the signals to be sent for the cell BS to the hand set and the second different 25 mhz band for signals being returned from handset to BS.
- These bands were then split into a no of communication channels each of which would be used by particular callers.
- Examples
  - AMPS (Advanced mobile phone systems users.
  - Uses 30khz voice channels.

2nd Generation:

- A mobile phone systems that used purely digital technology.
  - Avoid the risk of interference &
  - Dropped calls at handoffs.
- Has advanced feature like caller identify and text messaging and faximile
- Access technology –
  - TDMA/FDD or CDMA/FDD.
  - TDMA:
    - Signal is digitized .
    - User occupies different time slots.
  - CDMA/FDD
    - Spread spectrum.
    - Direct sequence.
    - Frequency hopped.
- Has the concept of Base station controller.
- Mobile assisted handoff.
- Data rate upto 9.6kbps , not suitable for web browsing and multimedia applications.

Four Popular Standard for 2G:

1. **(GSM – Global system for mobile):**
   - Two frequency bands of 25Mhz bandwidth are used.
   - The band of 890 – 915 Mhz dedicated to uplink from MS to BS. &.
   - Band 935-960 Mhz used for downlink form BS to MS.
   - Each band is divided into 124 carrier frequency.
     - 8 time slotted user for each 200 kHz radio channel.
     - Therefore total no of possible channels = 124×8 producing 992(max) simultaneous conversations.
2. **Interim Standard 136 (IS -136):**
   - Also called North American Digital cellular (NADC).
   - Three time-Slotted users per 30k Hz channel.
   - Popular in North American, South America & Australia.
3. **Pacific Digital Cellular.**

- Japanes standard.
- Similar to IS-136.

4. Interim Standard 95 (IS-95)

- CDMA
- Also known as CDMA one .
- 64 user in 1025 MHz channel orthogonally coded.
- Can be used in 800 Mhz & 1900 Mhz bands.

Advantages of 2G:

Many phones are compatible with more then one technology.

(a) Dual mode: (CDMA in PCS band Analog)
(b) Trial mode: (CDMA in PCS band, CDMA in cellular band analog.)

Drawbacks of 2G:

- 2G technology used ckt switched data modems channel that limit data users to a single ckt switched voice channel.
- Throughput less.

Application possible:

- Limited internet browsing.
- Short message.
    - SMS in GSM.
    - Can send short message to another subscribers phones.
    - Popular in Europe and Japan.
- 2.5 G allows existing 2G equipment to be modified for higher data rate transmissions.
- More advanced applications are possible.
    - Web browsing.
- Wireless application protocol(WAP) that allocates standard webpages to be viewed in acompressed format.
- Email
- Mobile commerce.
- Location based services. (map, directions etc).
- Japan: First county to have a successful widespread mobile data service.
    - From NTT DOCOMO (company).
    - Emode.
        - Proprietary data service
        - Games
        - Color graphics.
        - Interactive web page browsing at 9.6 kbps.
        - Surprisingly popular: 25 million subscriber.

Migration path:

- A 2.5 G technology must match an upgrade path for the 2G technology that is in place.
- Same air interface.
    - Do not want to require wholesale RF equipment changes at the base stations.
- Upgrade to software.
- Addition of more equipment to work with base station equipment.

TDMA upgrades:

- 3 upgrade paths for GSM.

- 2 are also upgrades for IS-136.

1. **High speed ckt switched data (HSCD) for GSM:**
   - Allows subscriber to use groups of times slots in TDMA.
   - Upto 57.6kbps.
     - Four 1404 kbps channels.
   - Ideal for "Voice like" services.
     - Since it still uses voice channel capability.
     - Streaming voice or low quality video.
     - Interactive web sessions.
   - Only requires a software change at GSM base station.
2. **Generalized packet radio service (GPRS) for GSM and IS-136:**
   - Good for data applications.
     - Email , faxes, web browsing.
   - Assumes users download much more than the upload.
     - Slower data rate upload than download.
   - Shares individual radio channels and time slots.
     - All data is sent as packets.
     - Can support many more users, since user traffic is usually bursty
     - Users transmits in short bursts and then are idle.
   - Completely refined air interface to handle packet data .
   - GPRS units tune into GPRS radio channels and are "Always on" to send data at any time.
   - If all 8 times slots are taken by one users, can achieve 171.2 kbps.
     - 8 times 21.4 kbps (rate with error coding)
     - Applications must provide their own error correction bits.
       - Add additional bits (like CRC codes) to be able to detect errors.
       - Takes away form the 171.2kbps.
     - Cannot achieve 171.2 kbps when others users are also sending data.
   - Upgrade requirements:
     - Connections of BS into data network through routers and internet gateway.
     - New software at BS.
     - No change to RF hardware.
   - Started for GSM but upgraded to also support IS-136.

3. **Enhanced data rates for GAM Evolution (EDGE) for GSM and IS-136:**
   - More advance upgrade to GSM than GPRS.
     - Additional new hardware and software at BS.
     - Support technology path to 3G.
     - Different modulation technology possible than GSM.
   - Adaptive modulation that uses the best modulation for instantaneous conditions of the network.
     - Packets are sent with different amount of error coding.
       - The more error coding is used , the more capable the system is at receiving from bad channel quality.

- Start sending with maximum error protection and maximum data rate.
  - Subsequent packets sent with less protection and lower data rate.
  - Until match is found with network conditions.
- Much higher data rates.
  - Practical raw data rates upto 384 kbps .
    - For single user taking a full 200 khz GSM channel
  - Can achieve server megabits per seconds by using multiple GSM channels.
  - Upgrade path for IS-95 A to IS-95 B. for 2.5G CDMA .
    - Only one upgrade path for IS-95.
    - Users can use upto 8 CDMA codes simultaneously.
      - 14.4kbps*8 = 115.2 kbps.
      - Practical throughput is 64kbps that can actually be achieved.

Third Generation(3G) wireless Networks:

- Unparallel new capabilities.
- Multi megabit internet access .
- Voice communication over internet protocol.
- Voice activated calls.
- "Always on" access.
- Receiving line music.
- Virtual home entertainment.
- Broadcasting
- Interactive video.
- Simultaneous voice and data.

- New spectrum allocation are being considered for 3G.
  - Although specrum auctions have been delayed due to downturns in the telecommunication industry.
- Two major competing camps.
  - Based on what 2G technology is used already by each camp.
  - GSM/IS-136/PDC (by the 3G partnership project for Wideband CDMA-3GPP) versus IS-95/IS-95B (by the 3G partnership project for cdma2000 - 3GPP2).

1. Wideband-CDMA (W-CDMA) or the Universal Mobile Telecommunication systems (UMTS)
   - From GSM/IS -136/PDC
   - Evolved since 1996.
   - From European Telecommunication Standards Institutue(ETSI).
   - Backwards compatible with GSM, IS-136, PDC, HSCSD, GPRS, and EDGE.
     - Equipment for the previous technology will work in UMTS.
     - Network structure same as GSM.
     - Bit level packing same as GSM.
   - Additional bandwidth and capacity.

   - WCDMA focuses on 3GPP standard body WCDMQ.
   - Developing both for wide area mobile cellular coverage using PDD and indoor cordless type using TDD.
- Up to 2.048 Mbps per user.
   - If user is stationary.
   - Many types of high data rates services are possible.
     - Videoconferencing.
     - Virtual home entrertainment.
     - Broadcasting.
     - Games.
     - Interactive video.
     - All from a small portable wireless video.
   - Up to 8 Mbps in the future.
- Needs a minimum spectrum allocation of 5 Mhz.
   - Instead of 200 khz for GSM.
   - Requires complete change of RF equipment at each base station.
   - 6 times more efficient use of spectrum that GSM.
   - Uses CDMA.
- Installation will likely be slow and gradual because ev-CDMA requires expensive BS equipment.
   - Need dual-mode and tri-mode phones in the meantime.
   - To switch between 2G,2.5G and 3G depending on location.

2. CDMA 2000

- From IS-95/IS-95B.
- Works within original 2G CDMA channel bandwidth of 1.25 MHz.
- Allows wireless carriers to introduce 3G in a gradual manner.
   - Can introduce 3G capabilities at each cell.
   - Do not have to change out entire base stations.
   - Do not have to use different spectrum.
   - Examples: Sprint PC's 3G.
     - They can Gradually implement 3G while offering a simple form of 3G at first.
- First air interface: cdma2000 1xRTT.
   - 1X = one times the original IS-95(cdmaOne) channel bandwidth.
   - RTT = Radio Transmission Technology.
   - Commonly just referred to as cdma2000 1X.
   - Instantaneous data rate of 307 kbps.
     - Typical rates upto 144 kbps.
     - Depends on number of users.
     - Depends on velocity of the user.
     - Depends on the propagation conditions.
- Uses twice as many voice users as 2G CDMA standard.
- Provides subscriber unit with upto 2 times standby time for longer lasting battery life.
   - Uses rapidly adjusting baseband singling and chipping rates.
   - No additional RF equipment is needed.
     - All changes make in software or with additional hardware.

- CDMA2000 1xEV.
  - EV = Evolutionary enhancement.
  - High data rate packet standard overlaid on existing IS-95, IS-95B, and cdma2000 networks.
- 1xEV-DO
  - Data only channel
  - Restricts a 1.25 Mhz channel strictly on data users.
  - Supports greater than 2.4 Mbps throughput per user.
  - Actual data rates usually much lower.
  - Typical: Several hundred kbps.
  - Highly dependent on number of users, propagations, and velocity of mobile.
- 1xEV-DV
  - Data and voice channel
  - 144 kbps with twice as many voice channels as IS-95B.

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- Ultimate 3G CDMA
  - Multicarrier 3x and beyond.
  - 3xRTT uses three adjacent 1.25MHz channels.
  - Three channels can be operated simultaneously in parallel.
    - No new RF hardware is needed.
  - Three channels can be operated as a group.
    - New RF hardware is needed.
  - Throughput of 2 Mbps.
    - Similar to W-CDMA.
  - Advocates of cdma2000 3xRTT claim a much more seamless and less expensive upgrade path compared to W-CDMA.
    - Can use the same spectrum.
    - Same RF equipment.
    - Same air interface framework.
- What summarizes the difference in 2G and 3G?
- Rapid growth of demand for internet connectivity.
  - Can use wireless connections where there is inadequate telecommunication infrastructure.
    - Particularly in developing nations.
    - Inexpensive.
    - Rapidly deployable.
  - One broadband Internet connection could handle all needs for a home or office.
    - Voice , data, cable, internet, tec.
  - Local loop.
    - Old telephone term for a loop of copper to connect a telephone to a telephone central office.
    - Now used to mean a “last-mile” connection to a home or office.
- Fixed wireless.
  - Much more predicable wireless channel.
    - No mobility.
    - Time-invariant
  - Uses high frequencies.
    - 28 Ghz and higher.

    - Allows very high gain directional antennas to be used.
    - Antennas can be of small physical size.
    - Tens or hundreds of megabits per second are possible without distortion.
  - Line-of-sight.
    - Much like light.
    - Cannot have any obstructions in between Tx and Rx.
    - Can be affected by weather.

- Little market in the U.S.
  - New types of service.
  - Unproven.
  - Dependent on millimeter wave equipment that is still expensive.
  - But large potential market in developing countries.

VII. Wireless Local Area Networks (WLAN's)

- Local Area Networks on the order of 100 meters or less in diameter.
- Use unlicensed spectrum.
  - So owner does not need a license to set up a WLAN.
  - Unlicensed use has been encouraged through lots of spectrum allocation at several frequency levels (900 Mhz, 2.4Ghz, 5.7Ghz.).
- IEEE 802.11
  - Predominant standard in the U.S.
  - Uses CDMA.
  - 802.11 – 2Mbps in 2.4 GHz band.
  - 802.11b – 11Mbps, 5.5 Mbps, in addition to 2 Mbps in 2.4 Ghz band .
    - Named Wi-Fi by the Wireless Ethernet Compatability Alliance. (www.wi-fi.com)
    - Goal is to promote interoperability between vendors (interoperability between one vendor's wireless card and a different vendor's wireless access point).
  - 802.11a -54 Mbps in 5 Ghz band with much shorter range (only about 1/3 the range of 802.11b).
  - Also 802.11g is being developed for a different type of radio transmission approach.
  - And 802.11i is addressing an important non-radio issue – security.
  - Also 802.11f (roaming) and 802.11x (security keys)!
  - There are lots of technical details we will not discuss yet.

- HIPERLAN:
  - High performance radio Local Area Networks
  - European standard.
  - Current standard: UP to 20 Mbps.
  - HIPERLAN/2: Up to 54 Mbps.

- WLAN performance depends heavily on how well the WLAN is installed.
    - Needs good placement of equipment.
    - Author discusses tools for easy and effective installation based on a building floor plan.

VIII. Bluetooth and Personal Area Networks: (PAN's)

- Roaming the wire.
    - Ability to replace cumbersome cords.
        - Printer cables.
        - Headphone cables.
        - Mouse cables.
    - Ability to move equipment throughout an office.
- Bluetooth.
    - Open standard.
    - Embraced by over 1,000 manufactures.
    - Uses an *Ad-hoc network approaches.*
        - Important in WLANs, military applications, etc.
            - Seen in WLANs, military applications, etc.
    - In "ad hoc networks" devices talk to whatever other devices they can talk to.
        - Ad hoc – Formed for or concerned with one specific purpose (usually also considered temporary).
        - Networks of devices that are all peers and talk to whoever is near enough.
        - As devices move, they change their connections with other devices.
        - May have to send data through a sequence of neighbors to reach and end destination.
    - No "base station" concept.

    - Why would Bluethooth want to use an ad-hoc approach?

    - Bluethooth is named after King Harold Bluetooth , 10th century Viking who united Denmark and Norway.
        - Goal is to unify the connectivity chores of applications.
    - Within 10 meters ranges.
    - Uses 2.4 Ghz ISM unlicensed band.
    - Uses frequency hopping spread spectrum.
- Wearable computers.
    - New opportunities for computes that are worn.
    - PDAs, cell phones, smart cards, position location devices all could be wireless.
        - In a personal area Network (PAN).

The Cellular Concept - System Design Fundamentals

I. Introduction

Early mobile:

- Design objective:

To use a single, high powered transmitter with antenna wanted on a tall tower.
(Applied in Bell system in New York City had early mobile radio)

- Low cost
- Achieved good coverage but
  Impossible to reuse those same frequencies throughout the system (Result- interference)
  (Bell system in New York City had 12 simultaneous channels for 1000 square miles)
- Small # users
- Poor spectrum utilization

What are possible ways we could increase the number of channels available in a cellular system?

Solution:

Cellular concept:

Goals of a Cellular System
- High capacity
- Large coverage area
- Efficient use of limited spectrum

- Frequency reuse pattern – Figure

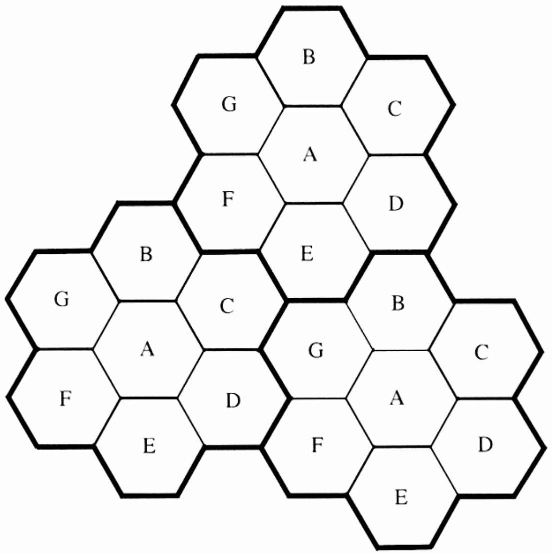


Figure 3.1 Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

- Cells labeled with the same letter use the same group of channels.
- Cell Cluster: group of *N* cells using complete set of available channels
- Many base stations, lower power, and shorter towers
- Small coverage areas called "cells"
- Each cell allocated a % of the total number of available channels
- Nearby (adjacent) cells assigned different channel groups

• to prevent interference between neighboring base stations and mobile users

 Same frequency channels may be reused by cells a “reasonable”
distance away
• reused **many** times as long as interference between same channel
(co-channel) cells is < acceptable level
 As frequency reuse ↑ # possible simultaneous users ↑ # subscribers ↑ but system cost ↑ (more towers)
 To increase number of users without increasing radio frequency
allocation, reduce cell sizes (more base stations) # possible simultaneous users ↑
 The cellular concept allows all mobiles to be manufactured to use the
same set of frequencies

***** A fixed # of channels serves a large # of users by reusing channels in a coverage area *****

Frequency Reuse/Planning

♦ The design process involves selecting & allocating groups of channels to cellular base stations

♦ Two competing/conflicting objectives:

1) maximize frequency reuse in specified area
2) minimize interference between cells

♦ Cells

 base station antennas are designed to cover a specific cell area

 hexagonal cell shape assumed for planning

• simple model for easy analysis → circles leave gaps

• actual cell “footprint” is amorphous (no specific shape)

- where Tx successfully serves mobile unit

 base station location

• cell center → omni-directional antenna (360° coverage)

- not necessarily in the exact center (can be up to *R/4* from the ideal location)

• cell corners → sectored or directional antennas on 3 corners with 120° coverage.

- very common

- Note that what is defined as a “corner” is somewhat flexible → a sectored antenna covers 120° of a hexagonal cell.
- So one can define a cell as having three antennas in the center or antennas at 3 corners.

System Capacity

For finding out the capacity of the system let us consider a system having

(Note: Most of this discussion relates to FDMA/TDMA based systems like GSM, AMPS, etc. Frequency reuse is different for CDMA systems.)

♦ *S* : total # of duplex channels available for use in a given area; determined by:

 amount of allocated spectrum

 channel BW → modulation format and/or standard specs. (e.g. AMPS)

♦ *k* : number of channels for each cell ($k < S$)

♦ *N* : cluster size → # of cells forming *cluster*

♦ $k = S / N$

♦ $S = k N$

♦ *M* : # of times a cluster is replicated over a geographic coverage area

♦ System Capacity = Total # Duplex Channels = *C*

$C = M S = M k N$

(assuming exactly *MN* cells will cover the area)

Here, we can see that,

♦ If cluster size (*N*) is reduced and the geographic area for each cell is kept constant:

 The geographic area covered by each *cluster* is smaller, so *M* must ↑ to cover the entire coverage area (more clusters needed).

 S remains constant (same number of channels per cluster).

 So *C* ↑.

 The smallest possible value of *N* is desirable to maximize system capacity.

♦ Cluster size *N* determines:

 distance between co-channel cells (*D*)

 level of co-channel interference

 A mobile or base station can only tolerate so much interference from other cells using the same frequency and maintain sufficient quality.

 large *N* → large *D* → low interference → but small *M* and low *C* !

 Tradeoff in quality and cluster size.

 The larger the capacity for a given geographic area, the poorer the quality..

N = Cluster size – can be 3,4,7,12.

♦ *Frequency reuse factor* = 1 / *N*

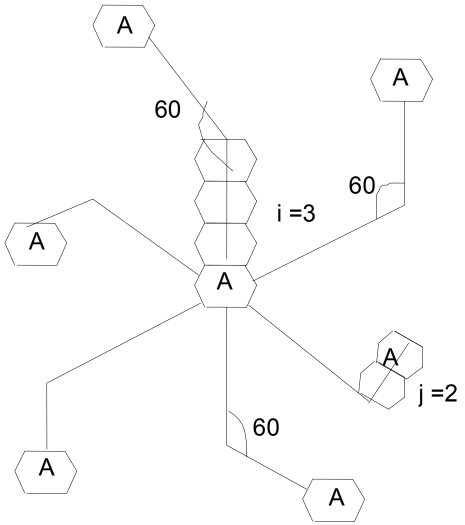
 each frequency is reused every *N* cells

 each cell assigned $k \approx S / N$

♦ *N* cells/cluster

♦ Due to the fact of hexagonal geometry
  - o has six equidistant neighbor and lines joining centers of the any cell and each of its neighbors are separated by multiples of 60°.
  - o To connect without gaps between adjacent cells—the geometry of hexagon is such that the number of cells per cluster, N, can only have values which satisfies the following equation:

$$N = i^2+ij+j^2 \text{ ; where } i, j \geq 1.$$



To find the nearest co-channel neighbor one must do the following:

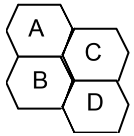
1. Move i cells along any chain of hexagon and
2. Turn 60^o anticlockwise and move j cells. Here, i = 3, j =2. N= 19.

Example: Given a Frequency Division Duplex cell system using two 25 kHz channels for frequency division duplex operation. Assume 75 voice channels are used for each cell in a cluster size of *N* = 7 with one additional voice channel used as a control channel per cell. Assume omni-directional antennas (1 antenna/cell).
What amount of spectrum is needed for such a system?

Given ,

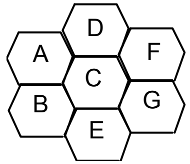
Total BW = 33 MHz = 33000khz.
Channel BW = 2 *25 kHz
= 50 kHz/duplex channels.
Total available channels = (Total BW)/ (Channel BW)
= 33,000/50
= 165 channels

(a) for N = 4.



Total number of channels per cell = 660/4 = 165 channels.
(Notes: number of channels in A = 165, B=165,C=165,D=165)

(b) For N =7



= 660/7 = 95 channels.

(c) For N = 12
660/12 = 55 channels.

Channel Assignment Strategies

♦ Goal is to minimize interference & maximize use of capacity
 lower interference allows smaller *N* to be used → greater frequency
reuse → larger *C*
♦ Two main strategies: Fixed or Dynamic
♦ Fixed

 each cell allocated a **pre-determined** set of voice channels
• calls within cell only served by unused cell channels
• all channels used → blocked call → no service
 several variations
• MSC might allow a cell to borrow a VC (that is to say, a FVC/RVC pair) from an adjacent cell
• donor cell must have an available VC to give
♦ Dynamic
 channels NOT allocated permanently
 call request → goes to serving base station → goes to MSC
 MSC allocates channel "on the fly"
• allocation strategy considers:
− likelihood of future call blocking in the cell
− reuse distance (interference potential with other cells that are using the same frequency)
− channel frequency
 All frequencies in a market are available to be used
 Advantage: reduces call blocking (that is to say, it increases the trunking capacity), and increases voice quality
 Disadvantage: increases storage & computational load @ MSC
• requires **real-time** data from entire network related to:
− channel occupancy
− traffic distribution
− radio signal strength indications (RSSI's) from **all** channels

Interference and System capacity:

♦ Interference
  - o Major limiting factor in the performance of cellular radio systems.

♦ Source of interference
  - o Another mobile in the same cell or
  - o Any non cellular system which leaks energy in the cellular freq. band.

♦ Interference on the voice channels
  - o Causes cross talks on the control channels & On the control channels
  - o Causes missed and blocked calls due to error in the digital signaling.

o Interference:
  - o More in urban areas.
  - o Has been recognized as the major bottle neck in increasing the capacity of the cellular system.

Two major types of system-generated interference:
1) Co-Channel Interference (CCI)
2) Adjacent Channel Interference (ACI).

Co-Channel Interference and System Capacity:

Using frequency Reuse concept:
 Many cells in a given coverage area use the same set of channel

frequencies to increase system capacity (*C*)

 Co-channel cells → cells that share the same set of frequencies

- Interference between signals form these cells is called co-channel interference.
- How to overcome?
  Possible Solutions:

A. Increase base station Tx power to improve radio signal reception?

 This will also increase interference from co-channel cells by the same amount

 no net improvement

B. Separate co-channel cells by some minimum distance to provide sufficient isolation from propagation of radio signals?

 if all cell sizes, transmit powers, and coverage patterns ≈ same &

BS transmits same power.

 Co-channel interference depends on:

• *R* : cell radius

• *D* : distance to base station of nearest co-channel cell

 if D / R ↑ then spatial separation relative to cell coverage area ↑

• improved isolation from co-channel RF energy

 $Q = D / R$: co-channel reuse ratio

• hexagonal cells → $Q = D / R = 3N$

♦ Fundamental tradeoff in cellular system design:

 small Q → small cluster size → more frequency reuse → larger system capacity → great

 But also: small Q → small cell separation → increased co-channel interference (CCI) → reduced voice quality → not so great

Tradeoff: Capacity vs. Voice Quality

Table 3.1 Co-channel Reuse Ratio for Some Values of 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

Small value of Q → provides larger capacity since 'N' is small. Large value of Q→ improves transmission quality due to smaller level of co-channel interference.

S/I → signal to interference ratio for a mobile receiver that monitors forward channel is expressed as,

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} \text{.......(1)}$$

S→ desired signal power.

I_i→interference power caused by i^{th} interferencing co-channel cells.

i_o : # of co-channel interfering cells

If the signal levels of co-channel cells are known,
S/I ratio for forward link can be found by sign the above equation (1).

Propagation measurement show that average received single strength at a point decays as a power law of the distance separation between a transmitter and receiver.

P_r → Average received power

d → Distance from transmitting antenna

$P_{r=} P_o (d/d_o)^{-n}$

P_o →power received at a close interference point in the far field region of the antenna at a small distance d_o.

n→ path loss exponent

D_i →distance of the i^{th} interference from mobile received power at a given mobile due to the i^{th} interfering cell will be proportional to $(D_i)^{-n}$.

Note:

- n ranges from 2 to 4 in the urban area

- free space or line of sight (LOS) (no obstruction) → $n = 2$

- urban cellular → n = 2 to 4, signal decays faster with distance away from the base station

- assuming the same n throughout the coverage area means radio propagation properties are roughly the same everywhere

- if base stations have equal Tx power (same S everywhere) and n is the same throughout coverage area (not always true) then the above equation can be used.

- When transmitting power of each BS is equal &
- Path loss exponent is same through out the coverage area.

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

Considering only 1st layer of interfering cells and all BS are at equidistant --- is equal to distant D between cell centers.

$$\text{S/I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_o}$$

 What determines acceptable S / I ?

• voice quality → subjective testing

• AMPS → $S / I \geq 18$ dB (assumes path loss exponent $n = 4$)

- Most reasonable assumption is i_o (# of co-channel interfering
  cells) = 6
- Many assumptions involved in the above equation :
  • same Tx power
  • hexagonal geometry
  • *n* same throughout area
  • $D_i \approx D$ (all interfering cells are equidistant from the base station
  receiver)
  • optimistic result in many cases
  • propagation tools are used to calculate S / I when assumptions
  aren't valid
  • S / I is usually the least when a mobile is at the
  cell edge
  - low signal power from its own base station & high
  interference power from other cells. –

More accurate picture: Fig. N =7 and $S / I \approx 17$ dB

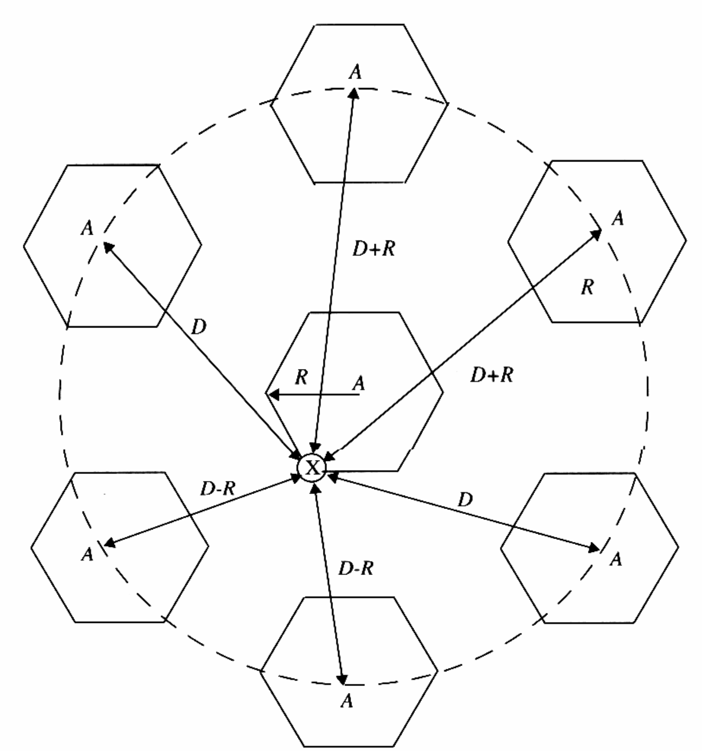


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

(S / I) for **forward** link only, i.e. the cochannel base Tx interfering with desired base station transmission to **mobile** unit

• so this considers interference @ the mobile unit

□ What about **reverse** link co-channel interference?

• less important because signals from mobile antennas (near the ground) don't propagate as well as those from **tall** base station antennas

• obstructions near ground level significantly attenuate mobile energy in direction of base station Rx
• also weaker because mobile Tx power is variable → base stations
can regulate transmit power of mobiles to be no larger than necessary

Example: 3.2

If the signal to interference ratio of 15dB is required for satisfactory forward channel performance of the 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. (b) n = 3.
Assume that there are six co-channel cells in the 1st tier, all of them at the same distance from the mobile. Use suitable approximations.

Solution:
(a) n = 4.
First consider 7 cell reuse pattern.
We know that
Frequency reuse ratio Q = D/R = $\sqrt{(3N)} = \sqrt{(3\times7)} = \sqrt{(21)}$ = 4.583

Signal to interference ratio S/I = $\frac{(\sqrt{3N})^n}{i_o}$

Signal to interference ratio S/I = $\frac{(\sqrt{3N})^n}{i_o}$

The no of co-channel cells in the 1st tier is 6.
Therefore ,
S/I = $1/6\,(4.583)^4$ = 75.3 = 18.66 dB.

Since this is greater than minimum required S/I, N = 7 can be used.
(b) n = 3.
First consider N = 7
We know S/I = $(4.5830)^3/6$ = 16.04 = 12.05dB.
Since this is less than minimum required S/I (i.e. 18 dB)
We need to use larger N.
Now, consider N=12,

$$S/I = \frac{(\sqrt{3N})^n}{i_o} = 6.0$$

$$S/I = 1/6 \times (6)^3 = 36 = 15.56 \text{ dB.}$$

Since this is greater than minimum required S/I, N = 12 is used.