

Digital Switching

EETS8304/TM-708N
SMU/NTU

Lectures April 17 & 24, 2001

Cellular & PCS

(print in PowerPoint *notes pages* format to see additional notes
below each slide)

Two suggested reference books by L.Harte and R. Levine :

Cellular and PCS: The Big Picture (1997)
GSM SuperPhones (1999)
both published by McGraw-Hill

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Print in Power Point *Notes Pages* format. Many pages have notes in this lecture. This set of lecture notes extends over two class sessions.

Cellular and PCS

General Background of Cellular & PCS

- Different Access Technologies
- System Structure
 - Physical Description Radio U_m Interface
 - Signal Description
- Call Processing
 - Initialization
 - Call Origination
 - Mobile origin, mobile destination
 - Handover
 - Release/Disconnect
- Services
 - Voice
 - Data & Fax
 - Short Message Service (SMS)
 - Packet Data (particularly EDGE and GPRS)

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This presentation is a condensed version of lectures used for people actually working in the cellular and PCS industry. It is intended for students having no particular prior exposure to radio or cellular/PCS systems. The author will appreciate notification of any errors, regardless how minor. Please send a marked copy of the relevant page(s) to the address below.

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History and Jargon (North America)

- **Analog cellular on the 800 MHz band**
 - Since 1979 (experimental), 1981 commercial; analog now being phased out
- **Digital Cellular/PCS on 800 and 1900 MHz bands**
 - Since ~1991 with immense growth rate
- **Systems on the 1.9 GHz (1900 MHz) band**
 - Usually called **Personal Communications Systems**
 - even when technologically identical to 800 MHz systems (such as IS-136)
- **900 MHz and 1.8 GHz bands used in Europe**

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There is some confusion in the industry about the similarity or distinction between the terms cellular and PCS. In some cases there is no distinction. In other cases the distinction is not technological, but is based on the frequency band of operation or on who owns the license to operate the system.

Jargon

- **Technically, a cellular system has 2 properties:**
 - Cellular frequency re-use
 - Handover (also called handoff)
- **So do most PCSs (personal communications systems)**
 - only exception is CT-2 public cordless (current implementations) without handover
- **Today the North American business distinction is mainly based on frequency band...**
 - 800/900 MHz is described as *cellular*
 - including digital cellular such as GSM, IS-54, IS-136
 - 1.9 GHz is described as *PCS*
- **Warning: jargon subject to change without notice! Beware of total confusion...**

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The jargon of the cellular and PCS industry is unfortunately not fully stable. Since not everybody agrees on the distinction between a cellular and PCS system, AT&T was criticized for calling their IS-136 roll out by the marketing name *digital PCS system*, because it operates on the 800 MHz band. From the purely technological point of view, there is no fundamental distinction between systems which operate on the two bands which justifies using a different name for each band.

This course will follow the description on the slide above just to be unambiguous and agree with what the majority of people in the industry are *currently* saying. A cellular operator is then a company which owns an 800 MHz North American cellular band license. A PCS operator has a 1.9 GHz band license.

Terminology has changed in the last 2 years, and may change again. To avoid pointless arguments, verify definitions before proceeding to argue!

Brief History of Cellular/PCS

- Manual operator-handled mobile radio (1945...)
- Automatic Mobile Radio, e.g. Secode, IMTS (1960...)
- Trunked radio (1960...)
 - cellular-like frequency re-use
 - but no handover!
- Cellular radio (1978...) required new technology:
 - control of mobile radio operation via messages from base
 - Mobile transmit (Tx) frequency and power
 - Can be changed *during* a conversation to select best base station or compensate for distance
 - *Handover* continues conversation as mobile station moves from cell to cell

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Cellular radio did not exist until the relatively simple microprocessors of the 1970s were available to provide remote control and sufficient sophistication to act on commands from the base station.

Cellular Frequency Re-use

- **Certain types of radio modulation exhibit “capture effect”**
- **When ratio of desired signal power to undesired (interference & noise) power is greater than the “capture ratio,” only the stronger signal is apparent**
- **Capture ratio depends on**
 - **Type of modulation: FM, Phase Modulation -- but NOT AM**
 - **Bandwidth of signal compared to data rate:**
 - **Analog cellular 30 kHz: capture ratio 63/1 or 18 dB**
 - **Narrow band NAMPS 10 kHz: c.r. is 200/1 or 23 dB**

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Every few years someone re-proposes some type of amplitude modulation (AM) single sideband (SSB) cellular reuse system. These proposals often include elaborate audio compression-expansion (“companding”) and audio noise reduction methods. The objective is to exploit the much narrower bandwidth of AM (only 4 kHz for a 4 kHz audio signal). These proposals ignore the fact that the C/I ratio measured at the antenna is the same audio S/N or S/I ratio that will be heard at the earphone. Therefore, the objective of a 30 dB S/I audio ratio would require something like an n=28 frequency plan. In other words, one could not reuse the same carrier frequency in the same city in many systems!

In contrast, FM and phase modulation both exhibit a fairly distinct threshold in $C/(I+n)$. When the desired signal power C is greater than the sum of interference and noise power $(I+n)$ by this ratio, the audio output (or digital bit accuracy) is almost perfect. The audio exhibits a lack of noise corresponding to 30 dB (1000/1 ratio) of S/N, although the FM C/I in an 30 kHz analog cellular system is only 18 dB (63/1). Once the C/I ratio falls below that threshold, clicks and pops are heard, and at even lower C/I, only a random noise hiss is heard. Due to widespread use of FM during World War II (the inventor, Col. Edwin Armstrong, donated his patents free of charge to the armed forces) many people got the idea of cellular reuse about the same time, but only in the 1970s was handover and remotely computer controlled radio carrier frequency selection and transmit power added.

Radio Cells

- **A cellular service area is covered by numerous smaller cells**
 - Each cell has one base station (base antenna location), usually at the cell center
 - The radio coverage in the cell may be optionally:
 - Omnidirectional (azimuthally) with one antenna group
 - Sectored (typically with 3 antenna groups, 120° each)

Warning: Some documents use the words cell/sector differently than we do
 - Each sector has **at least one RF carrier frequency**
 - A carrier frequency identification number describes two different (paired) frequencies:
 - downlink (forward): Base Tx, Mobile Rx
 - uplink (reverse): Mobile Tx, Base Rx
 - Two frequencies are used simultaneously for Frequency Division Duplex(ing) -FDD. Some technologies (DECT, some modes of 3G) use time division duplex (TDD) with alternate time interval transmit-receive on the same radio frequency

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Without cellular frequency reuse, there would not be enough spectrum for a major fraction of the population to use cellular and PCS radio systems. Without handover, calls would need to be limited to the time one dwells in a single cell. (So-called trunked radio systems do not have handover, but do have frequency reuse, and that is their limitation.) Without computer remote control of the mobile station, it would not be practical to continually select the proper frequency for a conversation or a handover, and control the mobile set transmit power accurately as the MS moves close to and away from the base station. All these complicated continual adjustments are done without the need for the user to be a technical whiz and constantly adjust dials and buttons. To quote Captain Queeg in the Herman Wouk novel *The Caine Mutiny*, the system was “designed by geniuses to be used by idiots.” The objective is to make a system which is no more complicated to use than the ordinary landline telephone. The only significant operational difference is that the user dials the desired destination directory number first, before engaging the central switching equipment and hearing a “dial tone.” Some special cellular phones such as the GTE “TeleGo” handset have even been designed so that the user hears dial tone first so it is perceived exactly like a regular wired telephone!

Cellular Frequency Plan

- **Frequency plan depends on**
 - capture ratio resulting from RF technology
 - Radio signal strength path loss or distance-related attenuation
 - Approximately: received power = $1/\text{distance}^4$ in city
 - Empirical *approximation*, not based on theory
 - Exponent in range 2 (open space) to 4 (cluttered urban environment)
- **A frequency plan is characterized by a cell cluster count in which each frequency is used in one cell**
 - Low capture ratio, high path loss requires small cell cluster (3 or 4)
 - High capture ratio, low path loss requires large cluster (7 or 12 or more)

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The major task of engineers who design and install a cellular system is the placement of the cell base stations, the choice (omni- or sectored directionality) and placement of the antennas, and the assignment of the proper carrier frequencies to each cell or sector. For proper control of handover, the threshold values appropriate to each cell or sector must be set in each cell.

The input information comprises the following factors:

Expected geographic density of call traffic in each area of the city over the planned service life of the system. This includes populations within buildings and underground in tunnels and parking garages, etc.

Topography of the ground surface and the buildings, trees, and other objects on that surface which affect radio propagation.

Relative costs of real estate for towers, building installation of equipment and mounting of antennas.

The traditional objective is to produce a plan for radio coverage of 90% of the service area which works 90% of the time. The objective of 90% of the time recognizes that, among other things, the radio path losses from overhanging foliage reduces the street level radio signal strength during the spring and summer, compared to the fall and winter seasons. The mutual interference between cells having the same reuse radio carrier frequencies (cocarrier interference) should be below the capture ratio value. External sources of radio interference (other radio systems, electrical radiation from signs, electric machinery, etc.) should be identified and properly handled.

Special Frequency Reuse Problems

- Without multi-cell frequency reuse, practical systems would not have enough traffic capacity (insufficient total radio spectrum)
- However, the possibility of co-channel (or co-carrier) interference is always of concern
- Cellular/PCS systems have various methods to prevent miscommunication with a co-channel signal from another cell:
 - Analog systems include a different Supervisory Audio Tone - SAT (above the 3.5 kHz bandpass telephone audio channel)
 - Unfortunately, the TIA-553 North American standard only provides 3 SAT choices (5970, 6000, 6030 Hz)
 - TDMA digital systems include a repeating digital identifier code in each transmission burst and associated with each control message
 - 8 synch/training code choices in GSM/PCS-1900
 - 255 CDVCC code choices in IS-136
 - CDMA systems plan to use the same radio frequency in all cells with many different uplink CDMA spreading codes in different cells. Many choices (2^{42}), but only 62 downlink code choices in each cell.

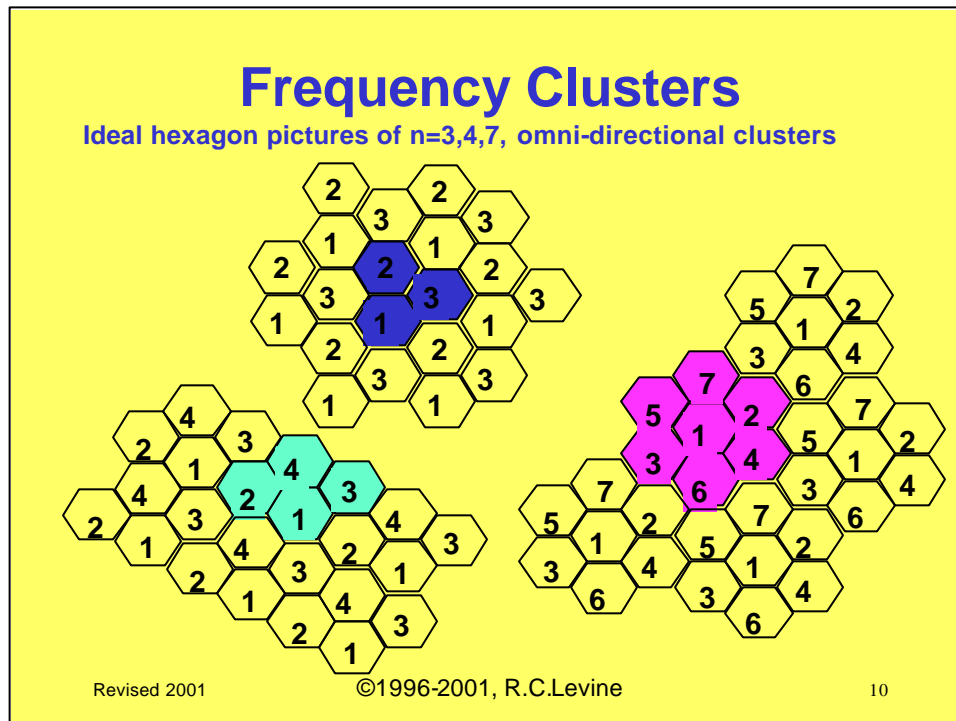
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In most systems, if a problem of reception of the wrong radio signal (or a radio signal not containing the correct identification code or signal) persists for 5 continuous seconds, the immediate way the system design deals with it is to release (disconnect) the radio link. (In the GSM/PCS-1900 system, there is an automatic reconnection following such a release, normally on another radio channel which hopefully is not experiencing such bad interference.) There is not much else to do in the short term, since the customer is either experiencing “garbage” audio, due to radio interference which is so strong that it interferes with communication, or the customer is in communication with the wrong person.

The long term solution is to identify those areas where such problems exist, and to correct the radio coverage in these areas. The correction of the radio coverage may require altering the base transmitter power, changing the height and/or the mechanical or electrical downtilt of the base radio antenna, or use of a radio repeater. In some cases, a relocation of the base antenna may be needed if other methods are not sufficient, but this is very costly so it is saved as the last measure.

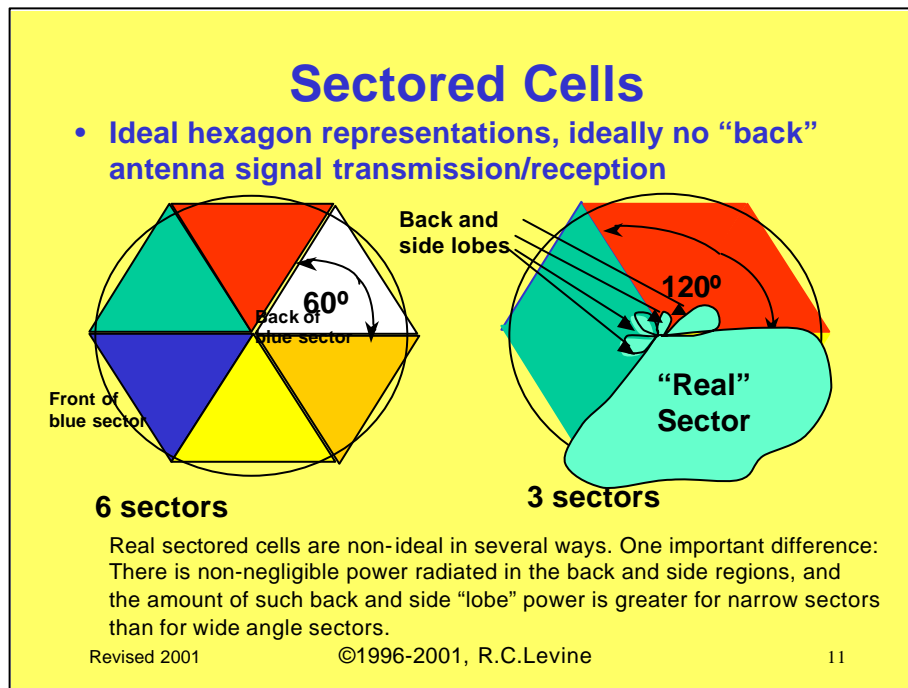


The number in each hexagonal cell represents the first (lowest usually) carrier frequency number assigned to that cell. In the $n=3$ clusters, cell 1 can also be used for carrier frequencies number 4, 7, 10, etc. so there are $1/3$ of all available frequencies used in each cell. However, the co-carrier interference frequencies are very close to that cell. Observe the many near (but not adjacent) cells also labeled with 1. In general there are 6 nearest co-carrier neighbor cells, and their centers are only 1.5 cell diameters away from the central 1 cell. There is also a second and third rank (and even more distant) of co-carrier cells, but they are not shown on the diagram and may not be significant because they are beyond the horizon.

In the $n=4$ cluster, the cells labeled 1 can also be used for carrier 5, 9, 13, etc. Thus this system does not have as high a capacity as the $n=3$ frequency engineering plan. Also, there are 4 nearest co-carrier cells (also labeled 1) but 2 of them are 1.5 diameters away and two are 2 diameters away. The next rank of co-carrier cells are about 3 diameters away.

In the $n=7$ cluster, cells labeled 1 may also be used for carriers 8, 15, 22, etc. Around each cell labeled 1 there are 6 nearest co-carrier cells (only 4 are shown in the diagram), at a distance of about 2.5 diameters.

Because of using (horizontally) omnidirectional antennas at all sites, each cell is subject to co-carrier interference from all co-carrier cells in all compass directions. A distinctive base station identity code (BSIC) can be assigned by the operator to each cluster. Three of the 6 bits are arbitrarily chosen by the operator, and the other 3 bits indicate one of 8 permitted values of the training/synchronizing sequence which is used in full TDMA bursts (explained on another page). All the full burst transmissions in this cell also use the specific training bit sequence code specified by the BSIC. The same BSIC should only be used in *very* distant co-carrier cells, if at all. This BSIC code is broadcast periodically by the base station, so the MS receives it. The BSIC is used in several places in the coding to prevent a receiver from using a co-carrier interfering signal from another base station operating on the same carrier frequency. One example relates to the random access burst, shown on another page.



Sectored cells are created by installing multiple antenna sets at the base location, each with shielding on the “back.” Each set of antennas is directional rather than omnidirectional. Sectored cells have two advantages over omnidirectional cells. First, by limiting the radio reception/transmission to the “front” of the angular sector and not transmitting or receiving a signal from the “back” they reduce the level of interference by a ratio of 3/1 or 6/1 for 3 and 6 sectors, respectively. This improves the signal quality, which is manifested as a lower BER in a digital system. Because the total interference from other cells is reduced, the cluster can be redesigned from a $n=9$ to $n=7$, or from $n=7$ to an $n=4$ plan, in some cases, thus increasing the capacity per cell.

When sectored cells are used in place of originally omnidirectional cells, but there is no change in the frequency plan, the traffic capacity actually goes down. This is a result of segregating the overall set of carrier frequencies into 3 (or 6) subsets in a sectored cell. The overall blocking probability of a number of channels is increased (and thus the usable traffic capacity is reduced) when they are subdivided into a number of exclusive subsets, and the MSs in each sector can only choose from those carriers available in that sector. The higher traffic capacity available when the same number of MSs in the cell can use any or all of the various carriers in the omnidirectional case is called “trunking efficiency.”

Sectored Cells

- **Narrow sectors reduce Co-channel interference**
 - Permits geographically closer frequency re-use
 - **Thus more carriers/cell, more capacity**
 - qualification: smaller trunk groups reduce “trunking efficiency”
- **But... back and side lobes are problems**
 - Permit “spot” co-channel interference
 - “sneak path” interference which only occurs intermittently, difficult to identify and debug
 - **“smart antennas” (adaptive phased arrays) address this problem better (but at high cost)**

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Some systems separate the carrier frequencies into subsets which operate separately in each sector. In some vendor's systems the cells are sectored but individual carriers can be “switched” from sector to sector. This capability to move channels to the sector with the most traffic overcomes the trunking limitation imposed by provisioning a fixed number of channels in each sector without regard to the changing traffic load demand in each sector.

In some systems, “smart” antennas have been proposed which permit dynamically forming the radio directionality beam for each TDMA time slot separately so that the beam points to the MS it communicates with. This requires a high degree of interaction of information between the base station signaling hardware and software and the antenna beam forming system. A limited approach to this idea using passive “dumb” antennas is to use an omnidirectional pattern for the beacon carrier (which is used to start the setup of calls), and then transfer the MS to a carrier which is used in only one sector to continue the call. The omnidirectional coverage can be achieved by either a separate antenna for that one carrier frequency, or by connecting the beacon carrier to/from all the sector antenna sets. In general, this requires a more sophisticated base transceiver (BTS) than the normal design. The special BTS must have multiple receiver inputs so it can determine which sector the MS is located in.

Uplink-Downlink Balance

- **Need equally good signal quality both directions-**
 - **two-way communications is the objective**
 - **areas covered *only* by downlink are not useful, may cause excessive co-channel interference to other cells**
- **Base Tx is more powerful (e.g. 5 to 10W/carrier) than MS (max 2W for PCS-1900, 3W for IS-136)**
- **Compensate for this via:**
 - **Base Rx diversity (equivalent gain of 2-5 dB)**
 - **Base Rx antenna gain (typ. 5-7 dB or more)**
 - **Low-noise amplifier (LNA) in base receive multi-coupler**

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The downlink limits for different samples of the same mobile station production run will differ very slightly because of minor variations in the internal noise of the MS receiver. Similarly the uplink performance will vary slightly due to minor differences in actual compared to nominal transmit power. There is also, clearly, a greater uplink operating range and consequently a larger useful cell size for a mobile station of a higher power class (a higher rated maximum transmit power level). In general this difference is much less significant in a PCS-1900 system, where all the power classes are slightly different low power levels below 1 watt, than in the case of a GSM or North American cellular system, where the power difference between the largest and smallest power class is very significant.

In general, the system operator makes a decision to support a certain power class, and by default they will also support any *higher* MS power class as well. In some cases, the operator knows that their design will not provide 90% area and time coverage to the very smallest power class MS units. Typically, system operators first design for all but the lowest power class, and then adjust the system coverage as described on another page, to eventually handle all power classes. These adjustments may take 1 or 2 years. The immediate need for many operators is to meet a legally mandated target of overall population area coverage as soon as possible.

System Design and Installation

- **System designer estimates geographical traffic density**
 - **Market, demographic, and specific geographic features such as high-traffic roads, areas of pedestrian congregation, etc.**
 - **Desirable to do this for near, mid and distant future dates**
 - **Conduct design “backward in time,” then:**
 - **Chose some cell sites for longest term usefulness**
 - so no cells need be abandoned at later date
 - **First increase capacity by adding channels at a site**
 - **Then “split” cells into smaller cells**
 - new antenna sites installed

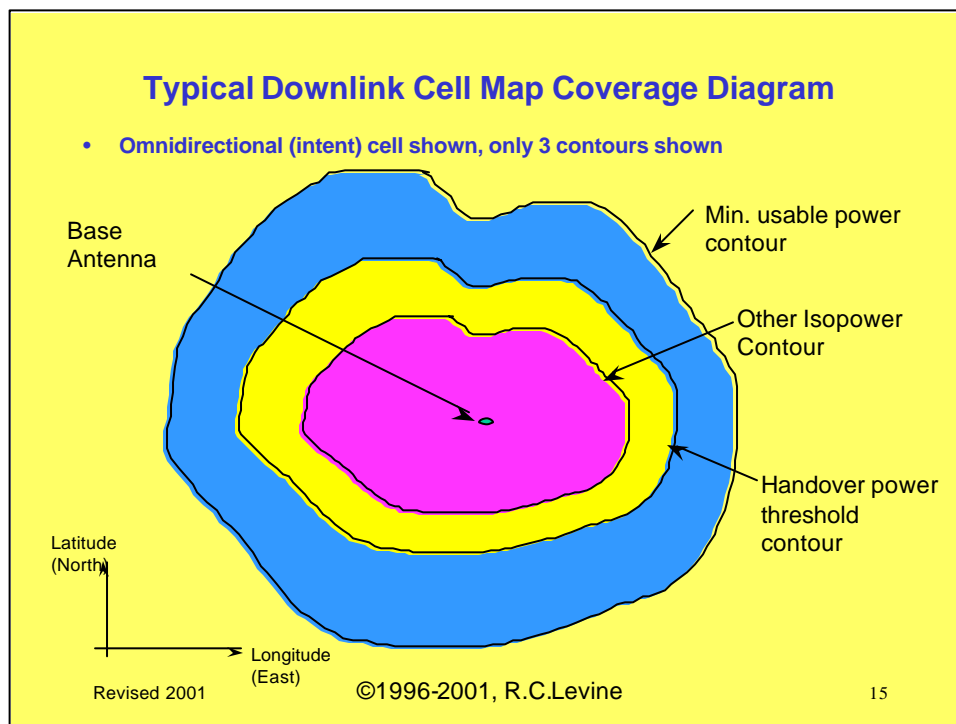
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These steps are common to all cellular system designs, regardless of the specific RF technology.

The relation between number of installed traffic channels and the traffic load which they can carry is a well understood process. Tables, charts or computer programs based on Erlang B or C probability distribution (or other statistical traffic models) are used to estimate the relationship between number of cells and expected total number of hours of simultaneous conversations per clock hour for a given probability of blocking (or grade of service GOS). For cellular and PCS systems the legally accepted GOS is a 2% probability of blocking, often expressed by the symbolic expression P02. Although a number of different statistical models are used in the industry, the ultimate refinement or fine tuning of the overall traffic handling design is best when based on actual in-service traffic measurements. As the system traffic load increases, the first stage of upgrade uses additional base transceivers installed at each cell having increased traffic demand, to provide more carriers and thus more traffic channels. When the full allotment of carriers has been installed under the frequency plan that is in place, additional cell (antenna) sites can be constructed, usually by subdividing a cell into 3 or 7 smaller cells covering the original cell area (so-called cell splitting).



The indentation in the north-by-northeast portion of this cell is probably explainable due to a hill, tall building, or other obstacle. The shorter range to the east compared to the greater range to the west and south is probably due to generally greater path loss in the eastern propagation direction. This in turn may be explainable by more convoluted terrain in the eastern part of the cell, or heavier overhead foliage (particularly in and near summer season) in that portion of the cell. We would need to see terrain data to be sure.

This picture does not illustrate the appearance of small (blue) areas of weak signal strength which will often appear in the magenta (central) area of the diagram, due to locally strong absorption or shadowing of the radio signal. If this weak signal area does not coincide with an area of population (for example, if it is in the middle of a garbage dump, or a lake not used by people) then it is of little concern. If it is in a highly populated area (a shopping center or major business district) then we need to increase the signal strength there. This may be done by any of a number of methods. One of the simplest is to increase the base transmitter power, but this may not be sufficient, and it will increase overall cell size and cause more interference to other co-carrier cells in the system. We can use a radio repeater to increase the radio illumination in the weak signal area, but this also causes some increase in multipath at the edges of the weak area where both the repeater and the direct signal appear. In an extreme case, we may choose another base antenna location during the design phase to get more complete illumination, or use a larger number of small cells. These last methods are the most expensive, in general.

Contour Map Notes

- **Transparent overlay for US Coast and Geodetic Survey (USCGS) map is typically used to display coverage**
 - (other similar government maps on other countries)
 - Positions on paper match Lambert conical projection
- **Not an antenna directionality graph**
 - Isopower curves are a result of antenna directionality *and* local site effects (terrain, etc.) as well
- **Each color boundary is a specified iso-power curve (only a few important contours shown)**
 - Like isotherms on a weather map
 - Iso-BER can also be plotted for digital systems
- **Theoretical**
 - Output from site-specific software: LCC, MSI Planet, etc.
- **Experimental (Measured at actual site)**
 - Vehicle equipped with calibrated Rx and Global Position System (GPS)

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Although an antenna directionality graph (dB on radial scale and angle on the angular scale of a polar graph) shown in a manufacturer's catalog is a good guide to the ground cover from that antenna, the final overlay showing lines of constant power (radio signal strength indication - RSSI) and constant BER value on a map is the true indication of cell coverage. One can make a reasonable estimate of ground radio coverage using any one of a number of computer software packages which estimate path loss, and utilize the actual directionality data for the antenna used at the base station, as well as data from the US Coast and Geodetic Survey (USCGS) which indicates the height of the ground above sea level at each 15 minutes of latitude and longitude. From this we get a theoretical graph of signal strength and/or BER contours. Measured data from the field indicating RSSI can be plotted as an overlay in the form of contours of constant RSSI and/or BER as well. Experimental data is even more accurate and should be gathered at each cell site before starting service. A major reason for the greater accuracy of experimental data is that most computer programs for computing radio wave propagation treat the effects of buildings, trees and other objects on the radio propagation in a very approximate and somewhat subjective way. Real measured data does not involve assumptions to the same extent that these radio coverage software packages do!

Control of Cell Size

- **Antenna height should be sufficient to cover largest expected cell via line of sight**
 - Inflexible situation to be limited by height
- **Downlink range mainly controlled by**
 - Base Tx power level adjustment
 - Antenna gain, directivity
 - Use of electrical and/or mechanical antenna downtilt
 - Electrical downtilt is preferable for omnidirectional antennas
 - Careful about back lobe effects with mechanical downtilt in sectored cells

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Cell coverage must frequently be adjusted seasonally due to the different amounts of absorption from foliage (leaves, etc.) on trees over the street and sidewalk areas where the mobile users are located. Base transmitter power must be increased slightly in the summer, and then decreased slightly in the winter. Usually no physical change is made in the base receiver usable range, except by mechanically tilting the antenna to point its main lobe at the most distant service area. The uplink is designed with adequate coverage so it is as large as the largest expected downlink coverage area. Changes in the nominal uplink (base receiver) cell size are actually mainly software changes in the handoff thresholds for RSSI or BER, which are discussed later in these notes.

Minimum Signal

- **Minimum usable signal strength must exceed total noise and interference by the appropriate $C/(I+n)$ ratio (typically 17 to 18 dB for analog 30 kHz)**
- **Noise level of receiver**
 - Fundamental physical property: thermal motion of discrete electrons
 - Calculate from temperature, bandwidth: $n=kT\Delta f$; this is 0.8 fW or -121 dBm for 200 kHz signal bandwidth
 - Noise Figure of receiver (added noise from internal amplifier) adds typ. 3 to 7 dB more noise (result: -119 to -116 dBm)
- **Interference: primarily co-carrier signals, level set by design as *low* as possible**
 - Greater Tx level in all cells works, but wastes power

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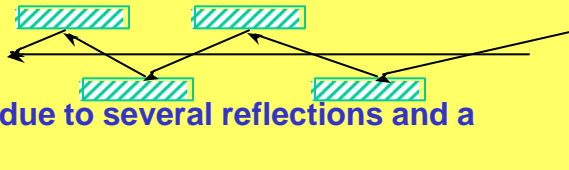
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A *noise limited* system would require a signal strength at the outer periphery of a cell to be at least -101 dBm for a receiver with a -119 intrinsic noise and using 18 dB as the desired S/n ratio for good reception. Only the the outermost boundary of the outermost cells of a system are noise limited. In all other parts of the system, the interference (primarily co-channel interference) from other cells in the system is the primary factor. Cellular and PCS systems are designed to be interference limited. Thus, the minimum usable signal strength at the periphery of an *interior* (interference limited) cell is typically about -95 dB. We design the system to use the lowest feasible transmitter power all around (bases and mobiles) so we get maximum talk time from battery powered mobile sets and minimize wasted excessive power.

Incidentally, the maximum power that a radio receiver can use without distortion or intermodulation is typically about 50 to 60 dB greater than the minimum power due to internal noise. We thus say that the receiver has a 50 or 60 dB *dynamic range*. Part of this dynamic range is the result of automatic gain control (AGC), which internally adjusts the receiver RF amplification to suit the incoming signal strength. Weaker signals are amplified to the fullest extent possible. Stronger signals are automatically amplified at a lower amplification setting. The result is that signals appear at the internal detector or discriminator stage of the receiver, where they are demodulated, at about the same voltage level regardless of their radio signal strength at the Rx antenna.

Multipath, Fading and ISI

- RF transmission is degraded by “multipath”
- Multipath propagation occurs when there are radio reflective surfaces in the environment (cliffs, buildings, earth surface)
- At the Rx antenna the total signal is the sum of
 - direct rays
 - rays delayed due to several reflections and a zig-zag path
- Multipath can cause both *fast fading* and *inter-symbol interference (ISI)*

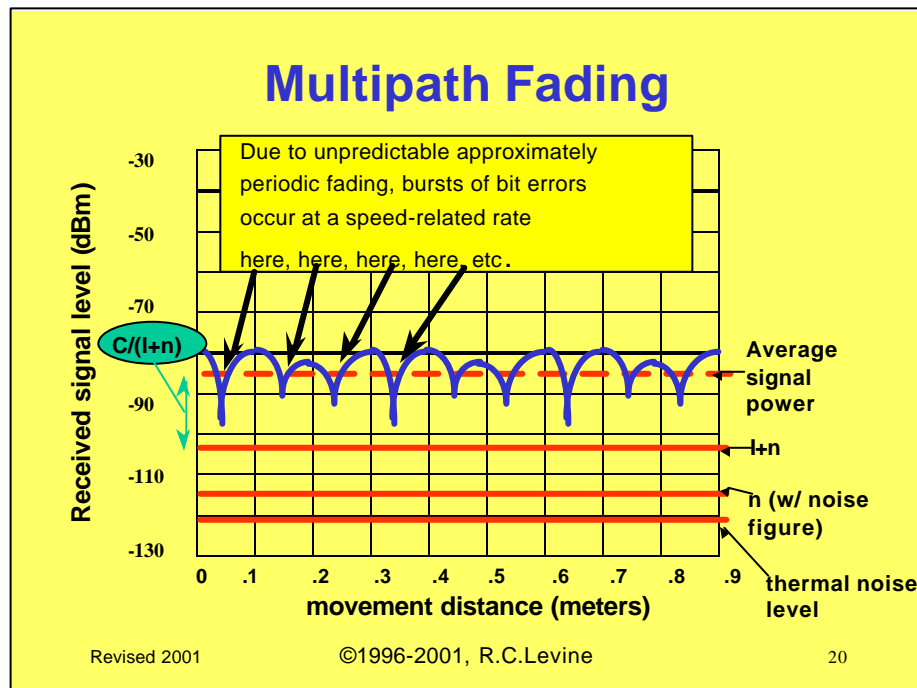


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Radio multipath occurs in all frequency bands, but the way in which it affects UHF radio for PCS systems is primarily due to the fact that the wavelength is smaller than human size, so we can move (on foot or in a vehicle) at a speed of several wavelengths per second.



Irregular but approximately periodic fades are a characteristic of multipath radio propagation. The major fades occur approximately a half wavelength apart when the various delayed radio rays are almost parallel.

When the signal strength fades, the interference and noise in the receiver dominates for a short time and the output depends on chance rather than the transmitted signal. The objective of a good design is to keep the intrinsic bit error rate (BER) below about 1%, by designing the system so the average signal strength is stronger than the combination of interference (I) and noise (n) by the capture ratio (typically approximately 17 dB) even at the outer edges of the cell. This goal is not always achieved fully, and as we approach the outer edge of the cell, the BER increases to 3, 5 or even (briefly) 8%. This can be detected due to the use of error detection codes in the digital signal transmissions, and used to initiate a handover.

The radio receiver internally produces a noise level which is the result of thermal agitation of the electrons which make up the small electric current. The power level of thermal variation in current is proportional to the absolute (Kelvin) temperature and the bandwidth of the receiver. Due to imperfections in the transistors and diodes used in the radio, there is a further increase in noise level described by a so-called noise figure, producing a total equivalent noise n. The interference, primarily from other cocarrier sources in other cells, adds to this to produce the “floor” for interference limited operation.

Fading Happens Because...

- **Direct and delayed rays are out of phase at some locations**
 - During part of an oscillation cycle, one electromagnetic wave ray is pushing the electrons in the antenna in the *opposite* direction from the other ray.
- **In the special case of two waves of equal amplitude, exact cancellation occurs at some locations**
 - Partial cancellation from rays of unequal power is more likely
- **Due to short wavelength, a very tiny delay time spread can produce significant fading**
 - ~300 mm (12 in) wavelength for 800 MHz
 - ~150 mm (6 in) wavelength for 1.9 GHz

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We almost never get two equally strong rays producing total cancellation. In most situations there are a large number of delayed rays having a variety of signal strengths. The result is a random fading pattern rather than a strictly periodic fading, although the major fades are approximately periodic. The depth of the fades in most cases is limited. The deepest fades are about 20 dB below average power level, and that does not occur very often. The strongest peak signal levels are about 6 dB above average level, but most peaks are lower than that.

To Combat Fading...

- **Fading allowance (margin) in RF coverage design**
 - Design to obtain strong enough average received RF power level so that fades are very brief (when antenna is moving).
- **Diversity: place, time, frequency**
 - Receive antenna diversity (at the base station)
 - Fading seldom occurs simultaneously at two places, particularly when they are an odd number of quarter wavelengths apart
 - Time and/or frequency diversity of the signal
 - Fading seldom occurs simultaneously at two different frequencies in the same place, so signal could be transmitted again later in time, or RF frequency can be changed intermittently, or a wideband signal is used made up of many different frequency components
- **Interleaving, a form of time diversity**
 - Initially consecutive bits of a digital signal are separated and some are sent at a later time than others, then reassembled in original order
- **Error Protection Coding (using additional digital bits):**
 - Error detection codes together with re-transmission algorithms replace badly received data (good for command messages)
 - Error correction codes allow identification and reversal of identified wrong bits (good for digitally coded speech)

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We never get perfect error-free digital radio transmission on a moving UHF transceiver, but we can achieve almost perfect final processed data rate if we design the system with adequate compensation for raw bit errors by means of error protection coding and proper use of antennas and equalizers, and always operate in regions of adequate signal strength.

InterSymbol Interference (ISI)

- When the multipath delay spread is greater than about 20% of the digital symbol duration, ISI can be a problem. To combat ISI...
- First, receivers are equipped with an adaptive equalizer
 - Adaptive equalizer (and also the similar “RAKE receiver” used for CDMA) produces delayed copy/ies of the received signal waveform and use(s) these copy/ies to cancel the physically delayed radio signals
 - This equalizer examines the effect of multipath delay on the known training sequence, and then uses this information to undo that effect on the other bits in the cell using the internally delayed replicas of the signal
- Second, the error protection codes help detect/correct errors regardless of whether they are due to fading or ISI
- ISI cannot be combated by just using a stronger signal.

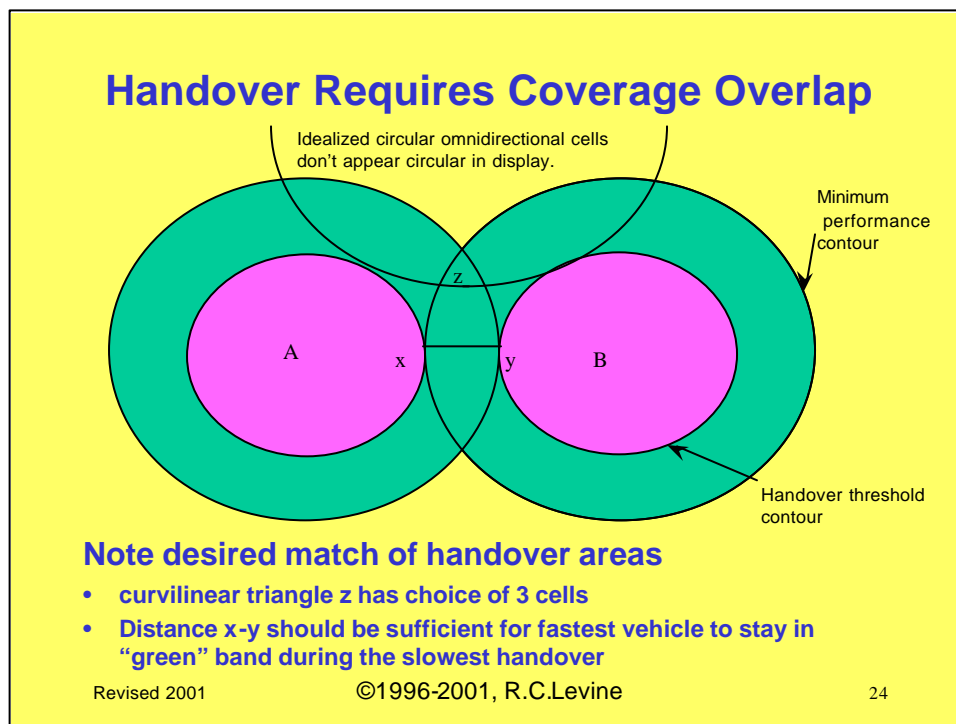
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Before the actual field tests, there was a great deal of concern that large delay spreads would make a high bit rate system like GSM impractical. Measured delay spreads in the foothills of mountains are as large as 16 μ seconds. Typical delay spreads in crowded city areas are 4 to 8 μ s. This is a larger time interval than the bit duration of the GSM/PCS-1900 bit (only 3.6 μ sec). However, the adaptive equalizer used in GSM and PCS-1900 does a more than adequate job correcting this ISI. Nevertheless, it is desirable to design the placement of base antennas so that strong delayed reflected radio signals (such as from the side of a cliff or building) are minimized by placing the base antennas so that illumination of such reflective vertical wall-like surfaces is avoided.

Similar concerns were expressed before the testing phases of the North American TDMA system, although the lower bit rate there makes the symbol duration more than twice the worst measured delay spread. Again, these concerns appear to be unwarranted based on actual system performance.



Cells are often represented by simplified abstract shapes such as a hexagon or a circle. In this diagram, a circle is used to illustrate two important contours of equal power (or more aptly, equal BER in a digital system). The MS can operate adequately all the way out to the outer circle, in both the yellow and darker areas. It is desirable that the handover threshold (usually based on BER, but also involving RSSI - radio signal strength indication in many systems) should be aligned with the outer boundary of the adjacent cell or sector.

If the handover boundary is too close in, then the handover process may start before the MS enters the valid service region of the adjacent cell. If the handover boundary is set too far out, then the system may not have time to perform a handover for a very fast vehicle moving from one cell to another. The GSM system does have a recovery algorithm to reconnect a call which is dropped because of such a problem, but the recurrence of such problems is a clue that the handover threshold should be fixed. Note when this happens on a high-speed expressway which crosses the mutual cell boundary lines.

Some areas, like region z , can receive adequate service from any one of 3 cells. When a MS enters that area from one cell, there are two possible handover target cells. If the relative signal quality or the available number of traffic channels in the two cells does not immediately settle the issue, data based on historical patterns of handover and geography of roads in area z will help to choose the best target most of the time.

Handoff Control Parameters

- For analog systems, (uplink) radio signal strength indication (RSSI) is the major measurable parameter
 - Sometimes RSSI is misleading, particularly when significant interference is present
- For digital systems, BER *theoretically* tells all...
 - Incorporates effects of weak RSSI and/or bad interference
 - BER reported for traffic channel in mobile-assisted handoff (MAHO)
- Some operators like to trigger handoff based on occurrence of either one or the other:
 - RSSI below sector-optimal threshold
 - BER above sector-optimal threshold
- Handoff process cancellation levels (of BER, RSSI) are also important
 - usually set at better signal levels than the start threshold, for *intentional* hysteresis

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One of the few things which the system operator can do to “tweak” or “fine tune” the system after all the antennas are fixed in place, is the adjustment of handover threshold values. Everyone treats this as a “magic number” and there is as much superstition as fact surrounding the methods used by various operators to set optimal threshold levels.

The objective is to hand over all calls without dropping any, and also to not start a handover (or cancel it) when it is not needed (since it consumes internal processing and data communication resources within the infrastructure). The prerequisite to meet these objectives is proper RF coverage in all adjacent cells. Then the thresholds must be set as described in the previous page so the cell boundaries line up with adjacent cell thresholds. The preferred parameter to control handovers is the bit error rate (BER). However, if you find that BER and RSSI contours which should match geographically are very separate, it is likely that there is an unsuspected source of RF interference which is increasing the RSSI but corrupting the data, and you should search for and remove it.

The “cancel” threshold is normally set at a better signal quality than the start handover threshold to avoid “ping-pong” starting and stopping of the handover process for a MS which is moving along the threshold boundary. If an MS enters the darker handover zone on the previous page, and then turns around and moves back toward the center of the cell, it is desirable that the MS can actually come in a little closer than the starting radius before canceling the handover process. More on handover later in the course.

To Add Capacity...

- **Install more RF carriers in cell (up to limit of TotalCarriers/n, where n is the cluster count)**
- **Sectorize (if originally omni) and reduce cluster group n from e.g. from 7 to 4; then install more carriers**
- **Overlay center part of cell with lower power carrier(s) [also called *tiered* cell coverage]**
 - Only adds capacity in central cell portion
 - not applicable to single frequency CDMA
- **Split cell, and install TC/n carriers in new small cells**
- **Use half-rate speech coder (if acceptable quality)**
- **Use “smart” directional adaptive antennas (when available and economical)**

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An operator will begin by installing at least one carrier supported by one base transceiver (BTS) in each cell (or each sector). In a TDMA system like GSM or IS-136, that first *beacon* carrier can support the shared channel used for call setup and related operations. The remaining 7 (or 2 in IS-136) physical channels (time slots) can support conversations. Each additional carrier can each support up to 8 (or 3) conversations. To add more capacity, just add more carriers. But there is a limit due to the number of carriers in your licensed band. If your license only permits 75 PCS-1900 carrier frequencies (A,B, or C band PCS license), and your frequency plan is $n=7$, you can only install $75/7$ or 10 or 11 carriers per cell. (Since the exact ratio is 10.714... you can install 11 carriers in about 70% of the cells, and 10 carriers in the remaining 30%.)

If your initial design was not sectored, you can change out the antennas and go to 3 sectors per cell, immediately following up with a new frequency engineering plan with $n=4$. You can then increase the number of carriers in each cell from 10 to 18 ($75/4$). Of course, most PCS systems are initially designed with sectored cells to begin with.


Overlay of some additional carriers which do not fit into the normal frequency plan is helpful only if you have a heavy concentration of traffic near the center of the cell. CDMA is not amenable to overlay carrier use.

Cell splitting is workable but expensive. You need to justify the capital cost by an almost immediate increase in traffic density.

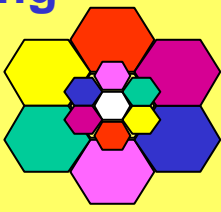
The half-rate codec and improved smart antennas have great promise for the future.

Cell Splitting

Before:



After:



- Increase of capacity by 7 in center cell (for n=7 plan)
- But there is a lower limit on cell size (due to approx. minimum 5 mW handset Tx power) so you can't split again and again without limitation
- High real estate cost of new antennas/cells is a deterrent
- Cell splitting is the last choice economically, after using methods which add capacity to an existing cell site

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Academic sources inaccurately describe cell splitting as an essential feature of cellular frequency reuse systems, which allows the capacity to be increased without limit. This is incorrect for two reasons.

First, the lower transmit power which can be controlled in a mobile set cannot go below about 5 milliwatts. This is due to leakage of RF from the internal electronic circuits, even without an external antenna. This limits the cell size to not less than about 50 to 100 meters. Attempting to use a lower design cell size will produce unacceptable co-carrier interference to other small cells.

Second, the cost of additional cell sites is very high, and must be compensated by an almost immediate increase in traffic density and revenue. If the growth is too slow, the cellular operator may lose money for months or years until the traffic and revenue increase by a factor of (typically) 7 in the split cell area.

There are several methods for adding more antenna sites without the full cost of a complete base installation. One method is to put only the base transceiver (BTS) at the antenna site, and then use one base controller (BSC) to serve several BTS locations. Another method is to feed the antenna remotely using either CO-axial cables or fiber optics to carry the RF signals to/from a central base equipment installation. A set of small RF amplifiers and electro-optic convertors is needed at the antenna location for both outgoing and incoming RF signals.

Early Cellular Systems

- **First cellular experimental analog systems (~1979):**
 - AT&T AMPS system (Chicago, IL)
 - Motorola TACS system (Baltimore, MD, Washington, DC)
- **First commercially operating systems were NMT-450 (Scandinavia) and NTT-MCS (Japan) ~1980**
- **In early 1980s, 9 incompatible cellular radio systems were in service in Europe**
 - 7 different incompatible analog technologies
 - 2 nations' technology compatible to 2 others, but no roaming service agreements!
- **Clearly incompatible with the technology unification plan for the European Union.**
 - CEPT (later ETSI) convened Groupe Spécial Mobile (GSM) meetings (1982) to develop Pan-European second generation (2G) cellular technology. Design documents issued 1989-91.

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The trade names of the first two systems later came to have slightly different meanings. Advanced Mobile Phone Service (AMPS) was originally an AT&T trade name, but later became a generic name for the North American analog 800 MHz technology, particularly when used by non-North American speakers or writers. Total Access Communication System (TACS) was originally a Motorola trade name, but became a generic name for the British 800-900 MHz analog cellular system (which is also known as E-TACS, for European-TACS), particularly when used by non-British speakers and writers. The TAC acronym survives in other Motorola products, such as the MicroTAC™ handset.

CEPT is the acronym of the Conférence Européenne (des Administrations) des Postes et des Télécommunications, an international standards body which still exists but today is more devoted to legal and tariff issues. Most of the technological standards activities of CEPT (particularly for cellular and PCS systems) have now been taken over by the European Telecommunications Standards Institute (ETSI) with headquarters in Sophia Antipolis, France (a suburb of Nice, France).

More North American History

- **Concern about traffic saturation led to experiments in digital cellular:**
 - Lucent (then AT&T) Chicago FDM demo (1988)
- **TIA TR45 Standards sub-committees formed to design digital cellular**
 - TR45.3 decision on TDMA in 1989-90 led to IS-54 “dual mode” digital cellular in 1990 (later IS-136)
 - Interest in Qualcomm CDMA proposal in '89 led to TR45.5 committee and IS-95 in '92
 - TR45.3 also designed IS-136 “all digital” TDMA in '94 (All these are also called 2G.)

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The FCC and the industry in general has followed a policy of free competition. This will eventually lead to an expected “shake-out” in a few years, since nobody really wants to continue indefinitely with so many different incompatible radio technologies. More comments on this at the very end of the lecture.

Design Objective Contrasts

- **Original first objective of GSM design was Pan-European technological standardization**
 - Secondary objective was high-technology to stimulate European production capabilities
 - Traffic capacity target nominally equivalent to pre-existing 25 kHz European analog cellular bandwidth (200kHz/8)
- **Backward compatibility was *not* an objective**
 - No “dual mode” handsets
- **Contrast this with North American TDMA (IS-54),**
 - First objective: higher capacity
 - Second objective: backward compatibility
 - These North American objectives somewhat complicated the design of an otherwise simpler system

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People frequently ask, “Why are many aspects of the designs of North American TDMA and GSM/PCS-1900 different?” Some of the reasons relate to the intended connection to the North American vs. the European public switched telephone network (PSTN), with the attendant technological and regulatory differences. Much of the fundamental difference, however, is based on the difference in design objectives. In North America, a significant amount of time (almost 2 years) was wasted arguing about the access technology, particularly FDMA (frequency division multiple access or use of narrower bandwidth radio channels for each conversation), TDMA (time division multiple access -- actually used in GSM/PCS-1900 and IS-54), and later CDMA (code division multiple access), with each side claiming that their proposed technology had inherently higher capacity than the others. In fact, all three of these access technologies have about the same inherent capacity. The most important system differences relate to secondary factors like the speech coder, DSI, or the economics of sharing common base equipment in TDMA.

The following two references both conclude that the theoretical capacity (conversations/kHz/km²) of CDMA, TDMA and FDMA are all equal, provided that all systems compared either all do (or all do not) use dynamic channel assignment (DSI) via voice activity control to fully utilize available channels during pauses in speech. Of course, there are also numerous publications which conclude that CDMA is inherently capable of greater capacity than other technologies, as well as a few papers which conclude just the opposite.

1. Paul Newson, Mark R. Heath, "The Capacity of a Spread Spectrum CDMA System for Cellular Mobile Radio with Consideration of System Imperfections," *IEEE Journal on Selected Areas in Communications*, V. 12, No.4, May 1994, pp.673-684.

2. P. Jung, P.W. Baier, A. Steil, "Advantages of CDMA and Spread Spectrum Techniques over FDMA and TDMA in Cellular Mobile Radio Applications," *IEEE Transactions on Vehicular Technology*, V. 42, No. 3, August 1993, pp. 357-364.

Access Technology Arguments

- **Many arguments ostensibly raised about access system technology comparisons actually relate to other, alterable aspects:**
 - **Speech coder can be changed, upgraded**
 - Note recent enhanced full-rate (EFR) coders (~1998)
 - **Digital Speech Interpolation (DSI) can be added, upgraded**
 - **Modulation can be changed in design stage**
 - **Features and services can be added**
 - **Are all other factors held constant?**
 - **Is inter-cell reuse interference accurately taken into account?**
 - Over-optimistic CDMA capacity estimates arose partly from mischaracterization of adjacent cell interference as RF white noise

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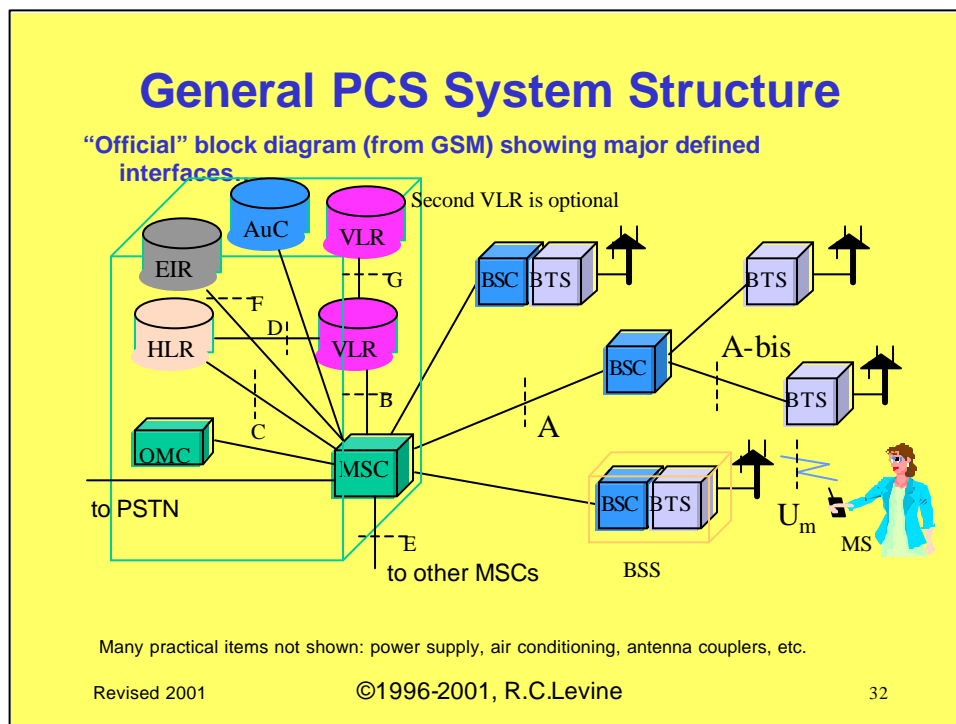
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Unfortunately the objective of some participants in the public debate about PCS and cellular technology is not always to present all the facts and evaluate them dispassionately. There is more fluff and puffery already thrown out on this subject, and the problem is aggravated by the fact that many of the people who need to make executive decisions about which technology to buy do not have a technological education or background, or when they do it is not heavily flavored with the specific technology topics which are most significant for PCS system evaluation.

I feel that the underlying technology is not mysterious, and anyone with an interest and a reasonable background can learn enough to make valid decisions based on their own understanding of the issues. Even though I make much of my income advising executives about technology, it is easier for me to work with a person who understands the technology than with someone who resists learning the technology and just wants a “go/no go” technical opinion from an expert.

You can learn what is required. You can learn the jargon and read the documents and ask questions. And don't take “expert opinion” as the only answer. The late physicist, Richard P. Feynman, said, “I finally recognized that the reason I could not explain the Pauli exclusion principle [a rule in atomic physics that certain different elementary particles never have the same energy] to my students in simple terms was because I do not really understand it!” Keep that in mind when people tell you, “It's too complicated to explain.”



This diagram and the names used with it are due to the GSM standards. A very similar terminology has been adopted for North American standards by the TIA.

AuC Authentication Center (data base). Associated with HLR.

BSC Base Station Controller

BSS Base Station Sub-system (collective name for BSC + BTS)

BTS Base Transceiver Station

EIR Equipment Identity Register (data base). Associated with HLR.

HLR Home Location Register (data base). Can be located with the MSC, or may be distant. In some implementations, multiple MSCs share the same HLR.

MS Mobile Station (or Set)- includes portable handsets

MSC Mobile-service Switching Center. In some cases an MSC can also serve as a gateway MSC (GMSC) to the public network. In other cases, it is only connected to other MSCs. The almost synonymous term Mobile Telephone Switching Office (MTSO) is frequently used for this switch in older cellular systems.

OMC Operations and Maintenance Center. In some implementations, one OMC serves multiple MSCs and other equipment.

PSTN Public Switched Telephone Network

VLR Visited Location Register (data base) - includes both visiting and active home subscriber data.

Usually built into the MSC. In some implementations, HLR and VLR are the same physical data base, with records active in the VLR specially/temporarily marked as required.

 Interface names (A, Abis, B, C, etc.) were arbitrarily assigned in alphabetical order. The U_m label is taken from the customer-network U interface label used in ISDN. Although mnemonics have been proposed for these letters, they are after-the-fact.

VLR Data Base

- **Misleading name- “Visited” Location Register**
- **Data needed to communicate with a MS**
 - Equipment identity and authentication-related data
 - Last known Location Area (LA) [group of cells]
 - Power Class, other physical attributes of MS
 - List of special services available to this subscriber [e.g. circuit-switched FAX, etc.]
- **More data entered while engaged in a Call**
 - Current cell
 - Encryption keys
 - etc.

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Data from the VLR is used to set up a call and maintain data about the call, including the generation of the detail billing record for billing purposes. All the physical, radio and electronic information needed for setting up a call is available in the VLR.

HLR Data Base

- **Home Location Register**
- **Need not be part of the MSC**
 - One HLR can be shared by several MSCs
 - Some operators plan a single regional HLR for shared use by several MSCs
- **Contains “everything” permanent about the customer**
 - IMSI, IMEI, Directory Number, classes of service, etc.
 - Current city and LA
 - particularly when not in home system (when “roaming”)
 - Authentication related information
- **In some implementations HLR and VLR are the same physical data base**
 - VLR records distinguished logically via “active in VLR” bits

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The HLR contains all the “background” information about each subscriber needed to “reload” the VLR when that particular subscriber appears in the service area of the appropriate VLR.

In the GSM or the IS-136 systems, when the customer is roaming to another city or system, the HLR contains the system identification number and the most recent LA in which the MS was located. This occurs automatically when the MS enters a new LA or new system area. A series of transactions take place in the cell and on the carrier frequency which the MS identifies as new (different from the System ID and LA of the previous carrier frequency just used before that). The visited MSC notifies the HLR by means of messages through the signaling network which connects all the MSCs and their associated VLRs and HLRs. In the European GSM network, the signaling messages used for this purpose form a part of a vocabulary or set of messages described as MAP (mobile application part), which is a special subset of Common Channel No. 7 signaling. The MAP was developed just for GSM. In North America, a similar (but not identical) set of messages, also called MAP, are described in TIA standard IS-41. These messages can be transmitted via Common Channel 7 signaling associated with a telephone network, or they can also be transmitted via other types of data communication networks such as TCP/IP or X.25 packet data networks. Each operator and his vendors make a choice about the specifics among these implementation choices.

Base Station Assembly

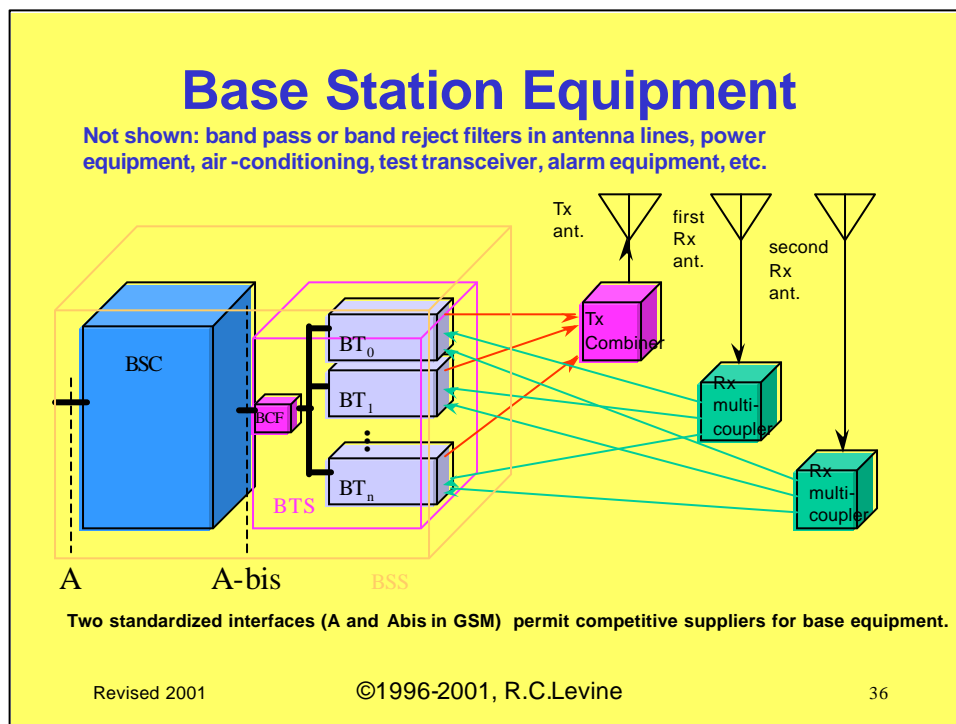
- **Antennas**
 - Transmit Combiner Processing
 - Receive Multi-coupler/Low Noise Distribution Amplifier
- **Base Transceiver**
 - Transmitter Section
 - Receiver Section
 - Antenna Diversity Processing in Receiver
- **Base Station Controller**
- **Support equipment: power, air conditioning,**

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Many aspects of the base station design are specifically intended to make the cost lower than analog systems. For example, the use of only one base transceiver is feasible in a low traffic cell (compared to at least two transceivers in an analog system). Eight channels on one carrier in one transceiver implies that less transmit combiners (or none for a one carrier base installation) are used, reducing the cost and space for equipment, and the power wasted. The ability to operate several BTS units off of a common BSC, even when they are geographically separated, is a major cost saving compared to the need to fully equip each base station with its own control equipment installation in analog technology. The multiplexing and the low RF power level used in PCS systems also makes the equipment smaller and less costly to install. The cost of smaller building space is lower, whether you rent or buy.



Readers who are familiar with analog cellular equipment will note that there is no locating receiver here.

Carrier number zero is associated with Base Transceiver zero, and the common shared channels such as broadcast, dedicated, reverse access, etc., are on this carrier and transceiver. In a GSM system, at least 6 of the time slots on this carrier zero are used for customer traffic. The other transceivers devote all 8 (3 for IS-54 and IS-136) of their time slots to customer traffic.

Standard industry jargon replaces part of many words with the letter x. Some examples:

Tx = transmitter

Rx = receiver

Xtal or Cx = crystal (used in some oscillators, etc.) (not on this slide)

Other abbreviations:

BCF Base Control Function

BT Base Transceiver (with one carrier, 8 time slots in the case of GSM)

Inside the Boxes

- **Transmit Combiner contains**
 - Tunable resonant cavity filters
 - Directional couplers
- **Its purpose: feed *most* Tx power to Tx antenna, *not* to other transmitters**
- **Receive multi-coupler is RF low-noise pre-amplifier**
 - similar to TV community antenna distribution system
 - distributes Rx signal to all receivers at same level they would get from an *unshared* Rx antenna

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The receive multicoupler can compensate for splitting the receiver antenna signal between several receivers, and it can add a little bit of gain to the signal, but like all amplifiers it also introduces more noise of its own.

Transmit combiners normally discard half the power from the transmitter in the form of heat, because they use a directional coupler which splits the power so half of it goes on to the antenna and half to a suitable power-absorbing resistor with cooling fins. The important part of its operation is that (almost) none of the power gets into the output of other RF transmitters which share the same antenna, to cause overheating and damage there! A transmit combiner typically has 4 (or for some units, 8) inputs and one output. If more than 4 transmitters must be combined onto a single antenna, then two stages of combiners are used, and 75% of the power is turned into heat. This situation is better with a digital system having less stages of combiners than for an analog system, but it is still a significant consideration in the overall power budget. Most combiners contain frequency filters which must be manually retuned when the carrier frequency of the associated input is changed. Many vendors make combiner filters which can be remotely tuned by means of a precision remotely-controlled stepper motor which rotates the tuning axle, thus facilitating changes in the carrier frequencies at a cell site without dispatching a technician to the site.

Why 2 Base Rx Antennas?

- **Dual antennas diversity improves base reception sensitivity by as much as 2 to 5 dB vis-à-vis a single antenna**
 - **Spacing of antennas should be *odd* multiple of $\lambda/4$, preferably $>8\lambda$ apart**
 - **Several methods for diversity combining:**
 - **Switching/selection**
 - **Equal gain**
 - **Maximal ratio**
- vendor design choice, not standardized**

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Early (ca. 1978) analog cellular mobile stations used two antennas for *mobile* diversity reception as well. Most customers were unwilling to pay the extra installation costs for a two-antenna system, and single antenna mobile sets have since dominated the market. System designers must design with a single antenna mobile set as their objective, which implies *at least* 3 dB more signal strength must be delivered on the street compared to the “old” mobile diversity sets.

From time to time, various manufacturers have shown special mobile antenna units with two individual antennas mounted one above the other in a slender tube which is no more difficult to install than a single antenna. However, vertical separation diversity is not as effective as horizontal separation diversity, which is universally used at base stations.

Receiver diversity using two antennas improves receive signal/noise ratio by 2 to 5 dB. The amount of improvement depends on the placement and separation of the antennas and the technology used to combine the two diverse signals. Diversity usually gives at least 2 dB improvement or more in $C/(I+n)$ even for selection diversity. Use of a more sophisticated system such as equal gain or maximal ratio combining can improve that by as much as 2 dB more. Use of more than 2 antennas, or a properly constructed adaptive phased array, can improve the signal/noise even more, but is rarely done in cellular and PCS systems due to increased cost.

Diversity Combining

- **Switching/selection**
 - Stronger of two signals instantaneously selected
 - ~1 dB hysteresis in selection
 - Causes random phase shifts
 - a problem for phase modulation like IS-136, IS-95, where switch times between antennas is restricted to the boundaries of data bit fields
 - Simplest, about 1.5 to 4 dB C/(I+n) increase in signal/noise
- **Equal gain**
 - Adaptive phase shift hardware used to phase shift one channel to match carrier phase of other, then added coherently
 - about 1.5 dB better than switching diversity
- **Maximal ratio**
 - Like equal gain, but weaker signal is dynamically amplified to same average level as stronger signal as well
 - Most complex, but typically 2dB better than switching diversity

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The random phase shifts which occur as a result of switching/selection diversity restrict its use with phase modulated (as opposed to frequency modulated) signals. The switching instants must be restricted to the beginning or end of a TDMA time slot when phase modulation is used, and thus the effectiveness of this form of diversity is further reduced if the fading rate corresponds to time intervals generally shorter than a time slot.

Test Transceiver

- **Not required in standards, but available from most vendors**
- **A remotely controllable transceiver which mimics a mobile set**
 - Controlled from operation-maintenance position (OMP)
 - Temporarily uses a voice channel in the A interface
- **Permits many useful tests without sending a technician to the site:**
 - Place or receive a call
 - Talk over the radio link
 - Check RSSI independent of BSS equipment
 - etc.

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A test transceiver at each cell is an invaluable piece of equipment. Don't omit it if you are designing or provisioning an installation!

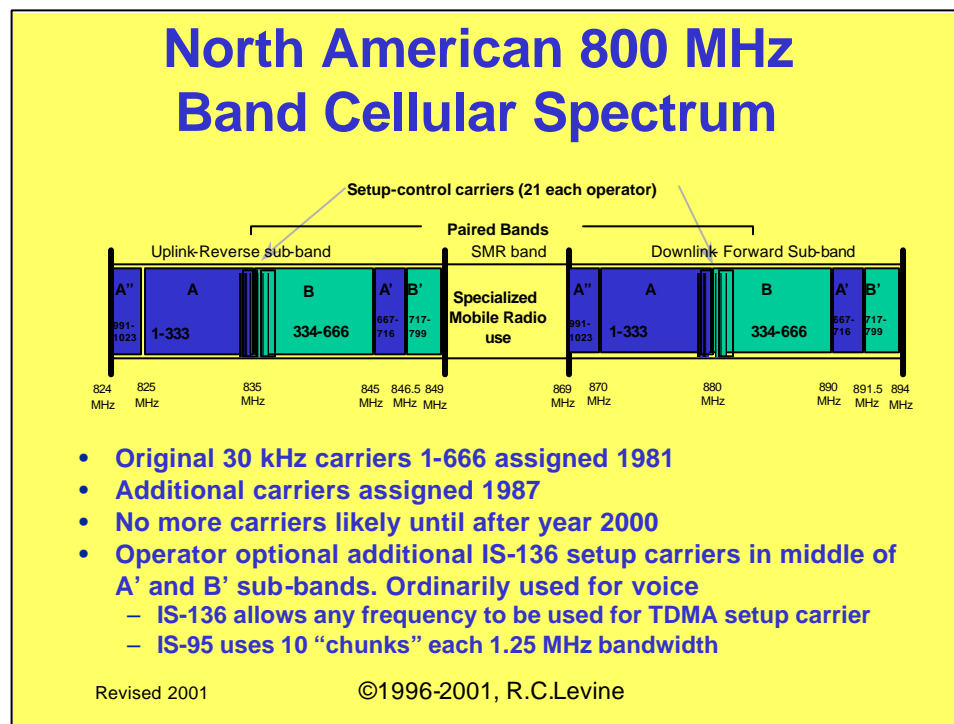
Why UHF Bands?

- “Because they are available” is a legal/historical reason only, although very significant...
 - VHF and below, absolutely no available bands!
 - Former point-point microwave and military bands were made available around 2 GHz band
 - Still some incumbent microwave systems
 - Government auctioned bands to highest bidder in 1990s
 - Strong financial motive to move quickly
- Technological reasons:
 - UHF follows “line of sight” propagation
 - Little/no over-horizon or “skip” radio propagation
 - MF, HF short-wave bands would be impractical for cellular
 - SHF bands require much more costly components, and some bands are used for extensive installed microwave or have strong atmospheric attenuation

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In radio frequency band jargon, terms like medium, high, ultra high, etc. have very specific meanings. This chart shows the terms and shows a typical use of each band:

MF- Medium Frequency (AM Broadcast band)	100-1000 meters (0.1-1 km) wavelength	30-300 kHz (0.3- 3 MHz)
HF- High Frequency (Short Wave Bands)	10-100 meters wavelength	3- 30 MHz
VHF - Very High Frequency (TV Ch. 2-13 North America)	1-10 meters wavelength	30-300 MHz
UHF- Ultra High Frequency (800 MHz cellular, 900 MHz GSM, 1.9 GHz PCS-1900)	0.1-1 meters wavelength	300-3000 MHz (0.3- 3 GHz)
SHF- Super High Frequency	0.01-0.1 meters wavelength	3-30 GHz

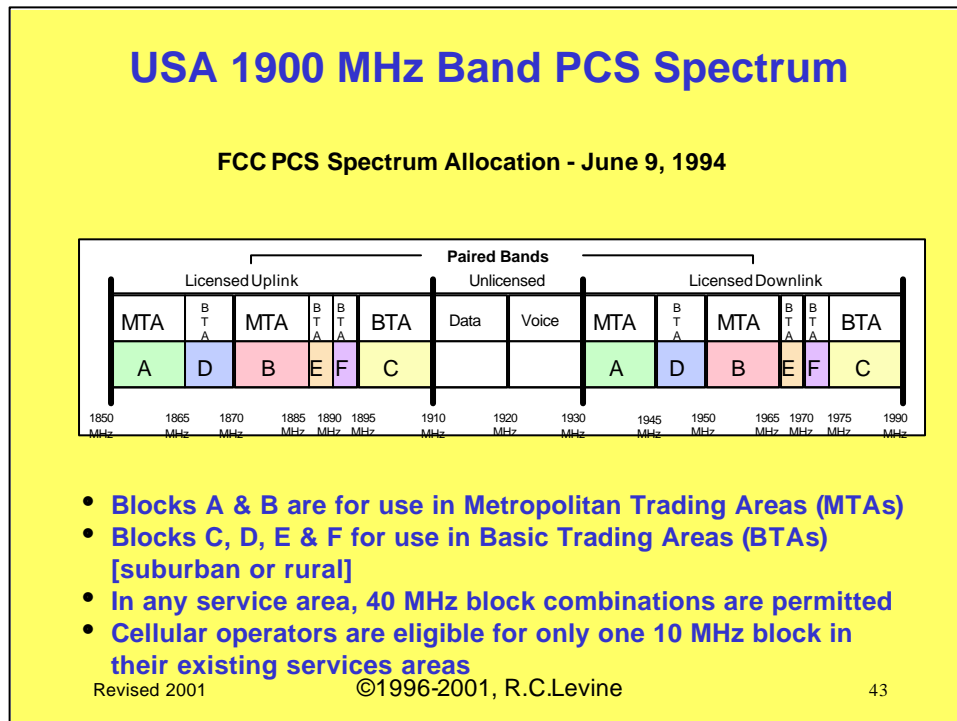


The North American 800 MHz cellular spectrum consists (at present) of 832 RF carrier frequency pairs. Each pair is called a channel, although this term is also used in different ways when a carrier can carry multiple TDMA channels. The 832 carriers are divided legally into two subgroups of 416, each subgroup allocated to one of two competitive operating companies (also called “common carriers” in the legal sense arising historically from railroad terminology). Within the 416 carriers, 21 are legally designated as primary control channels, and are prohibited from use for voice. There are also 21 secondary control channels (used only by IS-54 TDMA dual-mode radios) which may be used for voice instead, at the option of the system operator.

The “A” operating company is legally restricted to not have a financial interest in the local telephone operating company. The “B” operator in general also operates the local “landline” telephone service in the same city. As a memory aid, many “A” licenses are owned by AT&T wireless (formerly McCaw), although many are held by others, and most “B” licenses are owned by former Bell System operating companies, although a few are not. A landline telephone operating company can own a financial interest in an “A” license, so long as it is not in a city where they also own part or all of the landline operation. For example, Southwestern Bell owns a portion of the “A” license in New York, but is prohibited from owning even part of an “A” license in Dallas, where they already own the “B” license.

Analog cellular systems can perform adequately with a 63/1 (18dB) carrier to interference ratio. In a typical analog cellular system frequency allocation plan, the total number of carriers in use are divided into 7 subgroups, with each subgroup (of about 60 carriers) operating in a cell. The 7 subgroups are arranged in a cluster consisting of 7 cells, and the geometric pattern of this cluster is repeated throughout the service area (typically a city and its suburbs). In most systems, the cells (particularly in the high-traffic areas of downtown) are further subdivided into three sectors, each covering about a 120 degree wedge of the circular cell, by means of three sets of directional base station antennas. Each sector then uses about 20 carriers, of which only one is a control carrier (channel) in analog cellular systems.

In systems using such a modulation and coding technology that the radios can perform adequately with a lower C/I ratio, four cell or three cell clusters, with proportionately higher numbers of carriers per cell, may be used. This produces greater capacity in conversations per square km, using the same cell size as comparable systems.



This shows only a portion of the 1.8-2.2 GHz spectrum which has partly been auctioned for voice and data PCS. Other sections of the spectrum are reserved for later auction. Certain bands are reserved for women and minority owned businesses, to be politically correct in allocation of the spectrum resources.

MTA- Metropolitan Trading Area

BTA- Basic (rural, suburban) Trading Area

(these names come from Rand-McNally commercial atlas maps of business districts in the USA).

Access Technologies

Name	Technology	Modulated Carrier Bandwidth	conversations/ carrier	speech coding	Modulation
Analog (AMPS) TIA-553, IS-91, 94	Analog FM	30 kHz	1	analog FM (telephone 3.5 kHz audio)	analog FM (FSK for control signals)
N-AMPS IS-88 (Motorola)	Narrow Band Analog FM	10 kHz	1	analog FM	analog FM (subcarrier AM for control signals)
TDMA IS-54, IS-136	Time Division Multiple Access	30 kHz	3 [6]*	VSELP 8 kb/s + 5 kb/s FEC; ACELP	Differential P/4 offset DQPSK
CDMA IS-95 (Qualcomm)	Code Division Multiple Access	1280 kHz	62 planned [typically 12 to 18 achieved]	QCELP 9.6 or 13 kb/s; ACELP	Binary and Quad. Phase Shift Keying
GSM and PCS-1900	TDMA	200 kHz	8[16]	REL P 13 kb/s +9.4 kb/s FEC; ACELP	Digital FM GMSK

* 3[6] refers to 3 conversations at present, planned 6 in the future with half rate speech coder.

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ACELP	Algebraic CELP, an enhanced full rate speech coder.
AM	Amplitude Modulation
AMPS	Advanced Mobile Phone System, originally an AT&T trade name.
DQPSK	Differential Quadrature Phase Shift Keying.
FEC	Forward Error Correction code.
FM	Frequency Modulation
GMSK	Gaussian Minimum Shift Keying, a special type of digital FM with controlled gradual transitions between the two frequency extremes for the purpose of producing an optimal combination of narrow bandwidth and low susceptibility to interference.
GSM	Global System for Mobile communication, originally Groupe Spécial Mobile
NAMPS	Narrow-band AMPS
QCELP	Qualcomm Code Excited Linear Predictive speech coder.
PCS-1900	North American version of GSM on 1.9 GHz band.
REL P	Regular Pulse Excited Linear Predictive speech coder.
VSELP	Vector Sum Excited Linear Predictive speech coder.

Radio Design Objectives

- We want a signal which has small bandwidth in proportion to the information bandwidth transmitted
 - Relatively high “spectral efficiency,” the ratio of data rate, in bits/sec, to bandwidth, in Hz (cycles/s)
- At the same time, we want high resistance to interference
 - Usability at a low $C/(I+n)$ [capture] ratio is desired
 - Initial C/I used for GSM was 17 to 18 dB (63/1)
 - Now operating at about 14 dB (25/1) even 9 dB(8/1)
 - permits $n=4$ clusters with 60° sectors
 - Theoretically we can approach 9 dB (8/1)
 - theoretically permits $n=3$ clusters with 60° sectors
 - requires optimum performance from antennas, frequency hopping, etc.

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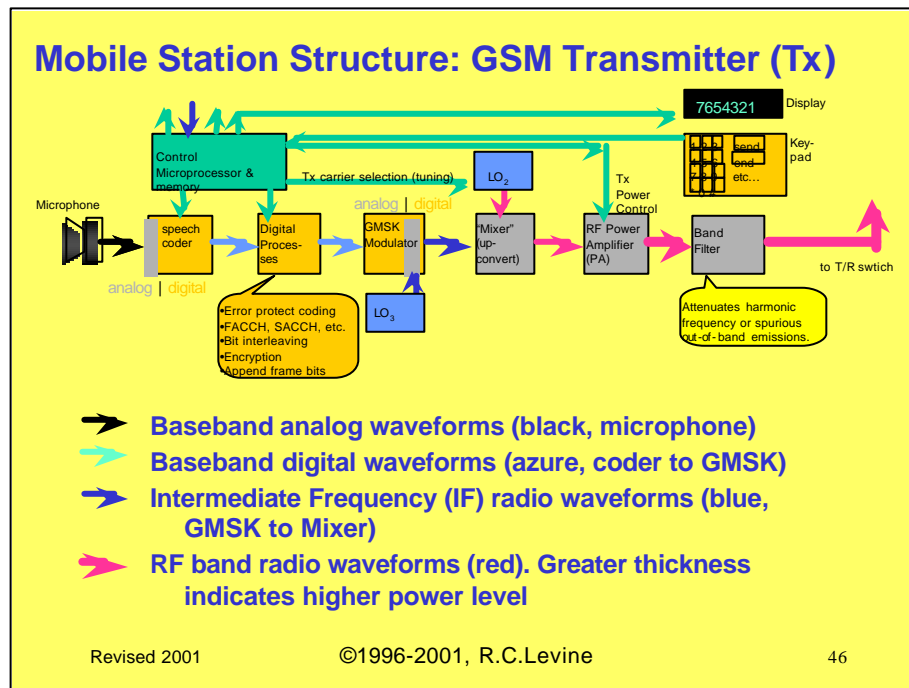
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The term “spectral efficiency” is only part of the story. The term is sometimes loosely used to describe overall capacity of a PCS system when comparing two technologies. In that case what is actually needed to make a fair comparison is the *geographic* spectral efficiency, conversations/kHz /km² (or other appropriate measure of area). In a system used in an office or multilevel building, the space aspect of this comparison should rightly be based on *cubic* meters rather than land surface area.

Many types of modulation have high spectral efficiency, but rather poor ability to operate error-free in the presence of interference. One can demonstrate this by merely increasing the number of discrete levels used in many existing types of modulation. For example, increase from a 2-level FM signal to a 4 or 8 level FM signal (this is actually done in some radio paging systems). The bit rate increases (4 bits per symbol can be encoded using a 4-level FM signal), but (with the same signal level) the effect of interference is much worse (that is, a higher C/I ratio is required). Our objective is an optimum combination of the two properties.

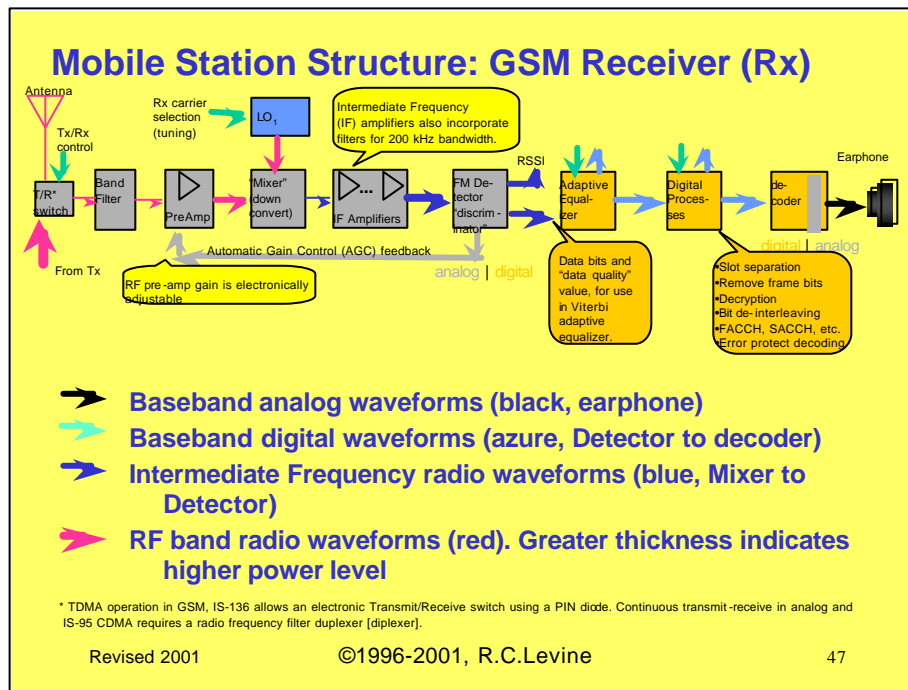
Improvements in the fading performance by use of frequency hopping, use of improved antennas, and adaptive equalizers, ultimately permit the operation of the system at a truly lower $C/(I+n)$ ratio (for example, 9 dB C/I for GSM), and thus allow more carrier frequencies and more capacity in each cell.



This is a “generic” block diagram of a PCS-1900 Tx section in a handset transceiver. The base Tx is similar, but produces higher RF output power levels, and multiplexes 8 different channels onto one carrier. A particular manufacturer’s design may differ in many details, such as performing more or less of the operations in digital form by means of a digital signal processor (DSP) computer chip.

Both the Tx and the Rx use the “super-heterodyne” technique devised by pioneer radio inventor Col. E.H. Armstrong. Complicated signal processing such as modulation in the Tx and amplification and Rx filtering are performed at a relatively low frequency using less precise and less expensive components, which are optimized for use at only one frequency. A replica of the desired signal can be produced at a lower (for the Rx) or a higher (for the Tx) frequency by effectively multiplying it with a local oscillator signal. This multiplication of the two waveforms produces two new frequency components, one at a frequency equal to the sum and the other at a frequency equal to the difference of each signal’s frequencies, respectively. In the Tx, the modulator is design to work at a so-called intermediate frequency (IF) from LO₃ which is typically 70 MHz (although some designers use 10.7 or 26 MHz). The desired transmit frequency signal can be produced by multiplying the modulated signal with the adjustable LO₂ which is set to 70 MHz below the desired Tx frequency (for example, to transmit at 1850.2 MHz, LO₂ is set at 1780.2 MHz). The “image” signal also produced at 1710.2 MHz is removed by filters and/or a dual mixer which subtracts the image signal. In the Rx (next page) LO₁ is adjusted to 70 MHz below the desired carrier frequency.

The RF power amplifier (PA) has adjustable power output level, aside from ramping the power up and down at the beginning and end of each Tx burst. All the major functions of the handset are controlled by the microprocessor, including the initial scanning of the RF spectrum to find and camp onto a broadcast channel so the handset can be initialized to work with the local base system.



This is a "generic" block diagram of a PCS-1900 Rx section in a handset transceiver. The base Rx is similar, but has duplicated modules from the band filter up to the FM demodulator for implementing Rx diversity. Also, the base transceiver uses separate Tx and Rx antennas (no T/R switch) since it transmits and receives continuously on all 8 time slots.

The T/R switch uses a positive-intrinsic-negative (PIN) semiconductor diode to prevent high transmit power from getting into the Rx. A PIN diode switches from the ON to the OFF condition very quickly. The band filter attenuates radio signals from out of the 1.9 GHz band so that the Rx will not have "image" signal reception (from antenna signals which are *below* the LO₁ frequency by the IF value).

Most GSM and PCS-1900 Rxs use a Viterbi adaptive equalizer, named for Andrew Viterbi, who incidentally is one of the developers of CDMA, a competitive technology. Other digital technologies such as IS-54 and IS-136 or the RAKE equalizer in CDMA IS-95 mostly use a multiple delay line adaptive equalizer, a different method altogether. The Viterbi equalizer corrects for ISI by encoding an XOR of two time-adjacent bits in the GMSK modulator (see other page), and then evaluating the overall quality of a *sequence* of three or more received data bits, with regard to a numerical measure of the signal accuracy. If the frequency of the received signal is not exactly on the expected value for one bit symbol interval, a measurement of the amount of frequency error is passed to the equalizer along with the binary bit value (0 or 1). The Viterbi algorithm saves bit and accuracy data and checks all combinations of previous bits to find the sequence which has the smallest total error. Typically, it uses the last 3 or 4 bits, and thus has a corresponding 3 or 4 bit delay.

The amplification of the RF pre-amplifier is adjusted continually by means of the AGC feedback signal to provide extra amplification for very weak signals, up to the noise limited minimum receivable signal level. The received signal strength indication (RSSI) is used in the MAHO reports send to the BS.

Mobile Station Power Classes & Control

- **Mobile sets are manufactured in various power classes**
 - Large high-power RF output for vehicle mounting typically 3 W (up to 40 W in GSM)
 - Medium “bag phones” typically 1.8 W max
 - Handsets typically 0.6 W max
 - Handsets are by far most popular for “use anywhere” convenience
 - Some “low tier” PCS systems use 0.1 or 0.2 W tiny handsets with limited range to base station
 - Many vendors make a vehicle adapter for handset which gives RF power amplification to ~3W level.

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High power class MSs, like the 20 watt vehicle mounted mobile unit in GSM, must have a final PA which can be adjusted for the full range of 16 power steps. They use the lowest power step when they are very close to a base station, or when they are in a small cell.

The high power MS can operate much further from the base, and is valuable for large rural cells.

In the PCS-1900 system, only hand held Mobile Sets of relatively low power are contemplated. Since GSM operates on a different radio band entirely, there is no possibility of someone bringing in a MS with power capabilities in excess of the PCS-1900 design limits and causing technical problems in the system. The PCS-1900 system is designed overall to work with lower power at both the base and mobile transmitter, and to use smaller cells than GSM, most likely in urban areas rather than in the open country.

The system operator has the option in PCS-1900 to adjust the base transmit power on a moment by moment basis, to use only the amount of power needed to communicate with the particular MS now connected. When it is close in to the base, turn down the base transmitter power, reduce co-carrier interference in other cells, and save some electric power cost.

Logical Channel Taxonomy

- Some communication is via *shared* common physical channel (time slot)
 - While idle, to get general system information
 - broadcast, paging, etc.
 - first access on uplink
- Some communication via *dedicated* channel/time slot
 - continuation of call setup
 - conversation, data communication
- Logical inconsistency regarding logical channels:
 - some documents categorize various types of messages which can appear on the same physical time slot as different *logical* channels
 - in other cases, different types of messages are just categorized as different *message types* in the *same* logical channel
 - part of the “computer science mystique”

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Today the concept of layered and structured description is generally applied to packet type digital communications systems. There is great merit in defining the software structure so that it can be divided into relatively independent programming tasks to allow parallel simultaneous development and testing of the software by different programmers. It is also valuable to define different parts of the data message (headers, etc.) so that changes in one portion do not affect other portions. However, the general concept of layered description of data communication systems sometimes reaches such a level of complexity that one can spend more time learning the terminology and jargon than in actually understanding how the system works. Some observers have accused the GSM standards of approaching this extreme level of self-imposed documentation complexity. In this course, we use the logical channel names because they are necessary to refer to the existing documentation effectively, but we do not dwell on them. From your point of view, it is actually sufficient to know only that certain types of messages are only allowed to be transmitted during certain scheduled time intervals on certain permitted time slots. The rest is jargon!

Every profession seems tempted to exalt jargon above meaning. If you try to read most textbooks on group theory applied to such topics as error protection coding or atomic physics, you will note that the first 60% of the book is learning jargon, then 10% is the actual concepts of group theory, and the remaining 30% is application of the theory to the topic at hand!

Analog Cellular Channels

- **Specified frequencies (one per cell or sector) used for setup or control**
 - All MSs in cell (except those in conversation) share this frequency
 - Digital Signaling via binary FSK modulation
 - Repetitive 5x transmissions (majority logic) with BCH* error detection code
- **Individual frequency (FDM) used for each conversation in the cell**
 - To make optimum handover choice, RSSI is measured by locating receivers in adjacent cell
 - Handover begins when RSSI falls below acceptable level
 - Handover is a co-ordinated change in MS frequency and a switchover of the base channel to another base station and selected frequency

*Bose, Chaudhuri, Hocquenghem error protection code

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BCH Bose, Chaudhuri, Hocquenghem code, one type of block code with extra error detection bits appended to the end of the message block.
RSSI Radio Signal Strength Indication

TDMA Cellular Channels

- **Several (3, 8, etc.) multiplexed conversation channels (time slots) on each frequency**
- **A specified time slot on one frequency used for setup or control in a cell**
 - All MSs in cell (except those in conversation) share this channel
 - Digital Signaling via same modulation used for coded voice
 - Mostly convolutional FEC* error protection coding used
- **Individual scheduled time slot used for each conversation in the cell**
 - RSSI and BER of adjacent cell transmitter measured by MS receivers during otherwise idle time slot(s) (mobile assisted handover -MAHO)
 - Handover when RSSI falls below (or BER rises above) acceptable levels
 - Handover is a co-ordinated change in MS frequency and time slot with synchronized base switchover
 - Proper TDMA handover is “seamless”

*Forward Error Correction code

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BER Bit Error Rate, ratio of erroneously received bits to total received bits.

MAHO Mobile Assisted Hand Off. Mobile set measurements on adjacent cell RSSI and BER provides data for MSC and BSS to decide which is optimum target handoff cell.

Use of BER in addition to RSSI prevents false indication from unduly strong co-channel interference, which can fool RSSI measurement but which produces more detectable bit errors.

MAHO simplifies the system structure and reduces the cost and the data communications traffic load at base stations.

TDMA *Logical Channels*

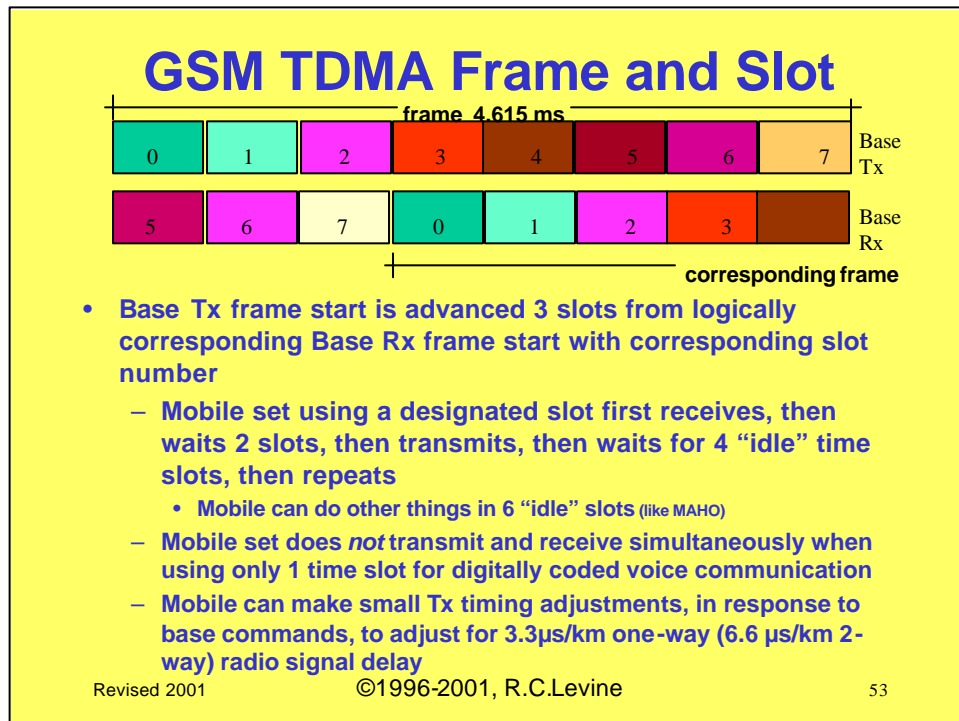
- **Some logical channels are pre-scheduled uses of the same physical time slot**
 - GSM examples: Broadcast Channel (BCCH), Paging Channel (PCH), Slow Associated Channel (SACCH), etc.
- **Others are un-scheduled, although for some a time is reserved where they may (or may not) appear**
 - examples: Fast Associated Channel (FACCH), Access burst,
 - When signals do *not* appear, physical reserved time is either unused or devoted to a continual background task (such as continuous transmission of digitally coded speech)

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One of the objectives of this course is to learn the jargon so you can read and understand the documentation on a cellular or PCS system. The names and abbreviations originated for GSM are frequently used in the industry. In some cases the authors of the standards may be accused of slight logical inconsistencies, but in general the name for a logical channel is a useful thing to know, because it indicates unequivocally the physical, scheduled timing, interleaving, and other properties of the information transmitted via that logical channel.



Now we get into the time sequence details of the time division multiple access (TDMA) system. The basic GSM TDMA frame has 8 slots; the IS-54 and IS-136 frame has 6 slots. You will note that all GSM/PCS-1900 documents number sequences in time by starting with 0 (zero) rather than 1, which is the practice in North American standards documents. Remember that the “first” number in a GSM sequence thus is most often 0 rather than 1.

When the future half-rate coder comes into extensive use, an alternative numbering identification counting a double frame as one, and thus labeling the slots from 0 to 15 decimal is also used for some documents.

TDMA Time Slot Structures

- **Two types of burst duration:**
 - **Full duration (normal)**
 - Used for Communication of Data
 - **Shortened burst:**
 - Used for a first access RF burst when the distance (and thus the signal delay) between MS and BS is not yet known
- **Many different types of information content for Normal Burst**
 - **Most 2-way exchanges of information**
 - **Some 1-way (paging, broadcast, etc.)**

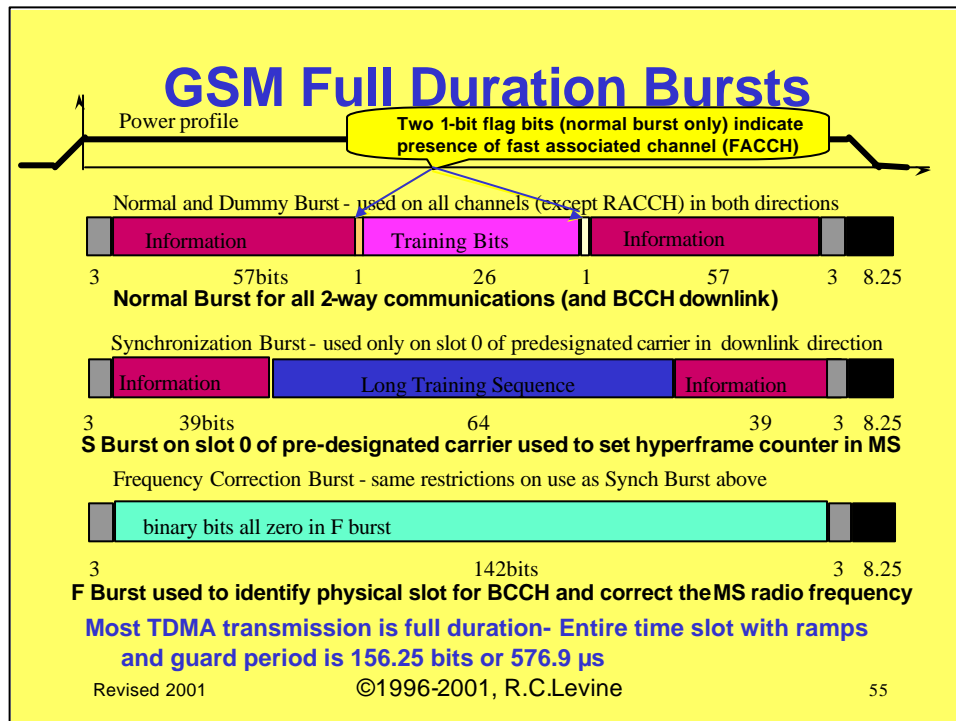
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The shortened burst is only transmitted by the mobile set, *never* by the base station.

The special full duration bursts (frequency correction and synchronization) are only transmitted by the base station, *never* by the mobile set.

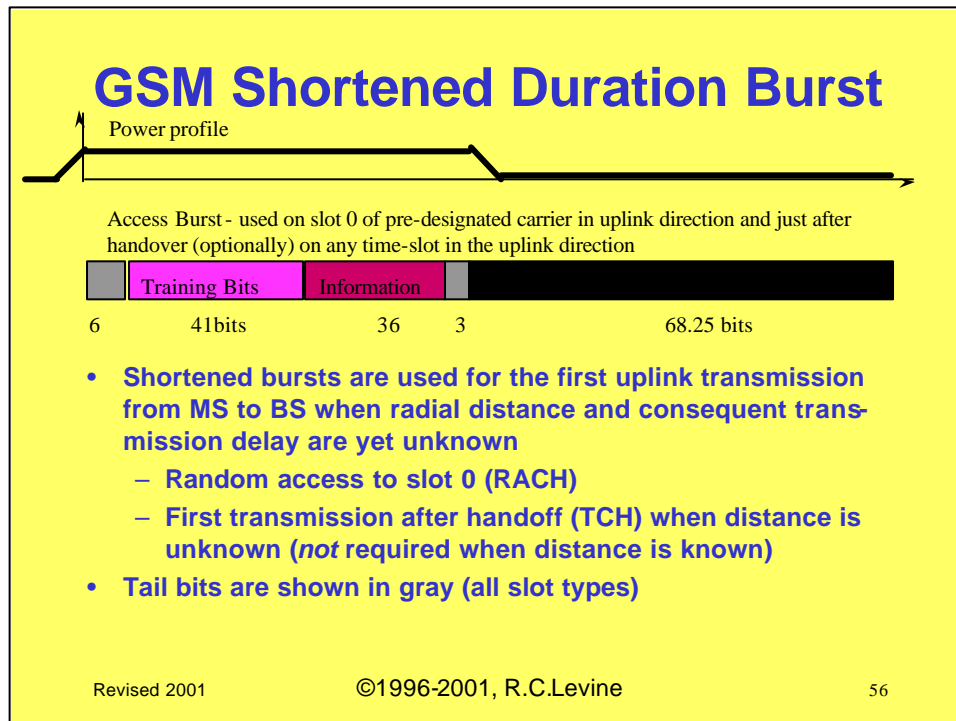


Mobile stations must have transmit power off except for the particular time slot which they use, and therefore they must follow these transmit power profiles.

Base stations on the so-called beacon carrier (the one containing FCCH and SCH bursts) must transmit on all 8 time slots at the same power level, even if some of them are reserved for traffic and there is no traffic at that particular time. They use a so-called dummy burst to fill in on the unassigned traffic time slots in such a case.

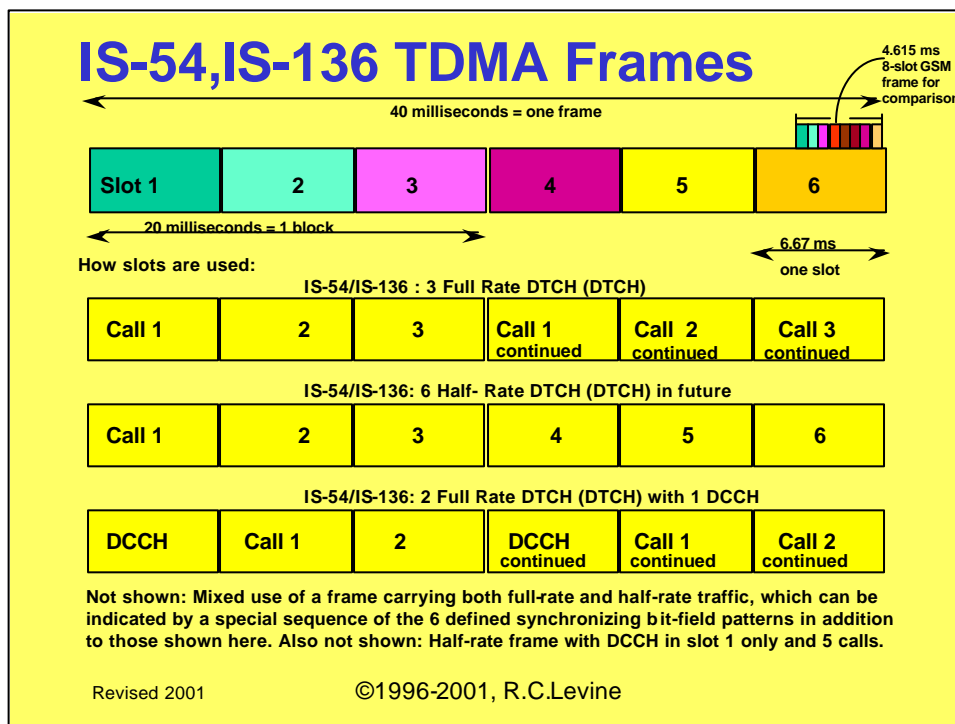
The standard does not require the BS to ramp its transmit power down between immediately consecutive time slots, leaving this choice to the various makers of base equipment. The use of a constant envelope transmit signal, even during the guard times (black intervals on the slide) at a base transmitter makes the RF adjacent carrier frequency emission from the transmitter a little better than required by the standards, and thus lowers the overall interference level to other frequencies in the system a bit.

The base transmitter may adjust the transmit power level separately in each time slot, except on the beacon frequency. Thus, a higher power may be used in a time slot which is transmitting to a MS in the outer part of the cell, while a lower power may be used in a slot transmitting to a MS which is close in. This is optional, but again improves the overall interference level with other cells in the system.



When the MS makes its first transmission to a “new” BS the range and consequent time delay for radio propagation is not yet known. Therefore the MS transmits a shortened burst. The BS measures the time of arrival of the burst and then immediately sends a command message to the MS to adjust its timing so that it can subsequently send full duration bursts.

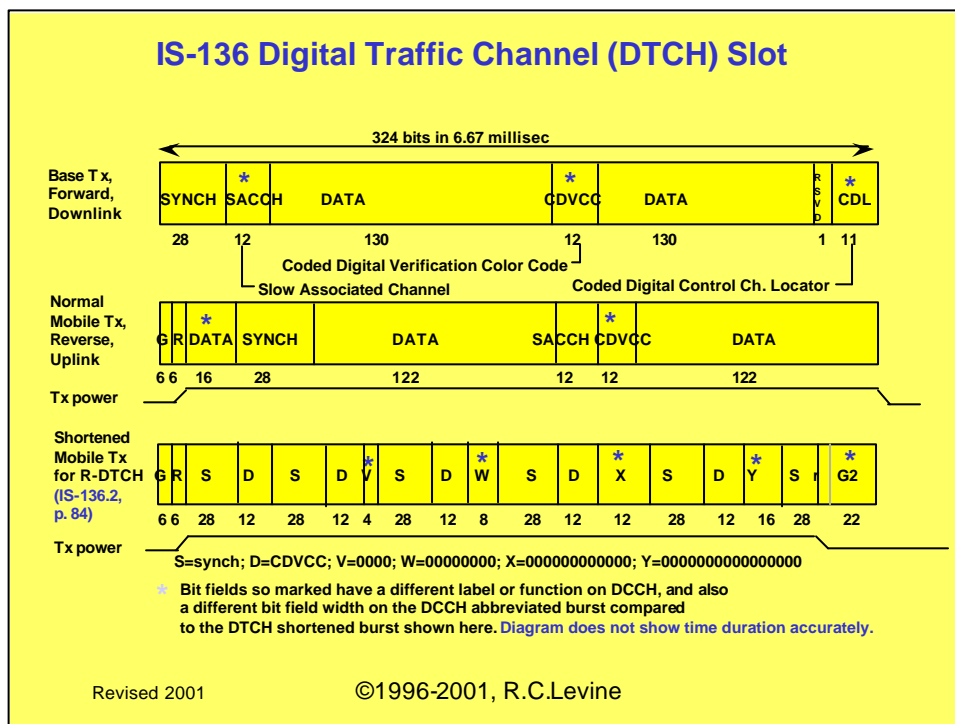
A “new” BS situation occurs when a MS begins a call or location update, or it could occur when it makes a first transmission after a handover while in a connection. In many cases of handover, the geography of the cells is known to the MSC/BSC and the use of a shortened burst can be omitted when the size of two adjacent cells is the same within about a km, or when an MS makes a handover between two angular sectors originating from the same BS so that the distance is unchanged. Thus we can achieve a so-called “seamless” handover with no interruption in the TDMA bit stream of the traffic channel. In the case where the two base stations are frame synchronized and, just for discussion, the same time slot number is used on the new carrier, the last time slot burst from the old BS is followed by 7 time slots of receiving and other operations, including re-tuning to the new carrier, and then the next time slot used originates at the new target BS. When the corresponding time slots are not synchronized at the two base stations (but the timing offset is known) or the handover also involves a change in choice of time slot, a similar process occurs and in general there is no “lost” digital data or at worst one time slot of data lost, during the handover. Even when there *is* lost data, the LPC -type speech coder can bridge over one missing time slot reasonably well.



At this time, IS-54/136 voice traffic is always “full-rate” digitally coded speech at a gross bit rate of 13 kbit/s, which requires 2 out of 6 time slots. Present low bit-rate data traffic (<6.5 kbit/s gross rate) and planned future support of a half-rate speech coder, can be supported by using only one time slot out of 6. The GSM standards cover one type of accepted half-rate coder, but it is not popular today because of relatively lower quality, and is seldom used because the capacity of most GSM systems is adequate.

There are 6 defined synch patterns for IS-136, each one is 14 symbols in duration (IS-136.2, Table 1.2.4-2). In most cases, the six symbols will be used in the six time slots of a frame in “normal” consecutive order, Synch pattern 1 through 6. This normally designates the use of 3 traffic channels in IS-54, and is permitted for use with 3 traffic channels in IS-136. However, IS-136 prefers the use of all 6 consecutive synch patterns for a 6-channel all-half-rate frame/carrier, and the use of only 3 of the synch patterns, repeated in the sequence 123123etc., when only 3 full-rate traffic channels are supported on one frame/carrier. Various other special sequences of the 6 synch symbols are designated in IS-136.2 Table 1.2.4-1, for a frame/carrier which handles a mixture of full-rate and half-rate traffic. In addition, there are future plans for multiple rate traffic channels which carry more bit rate than the full rate channel by using more than 2 of each 6 time slots, and which also can have special synchronizing sequences. This would allow fax or data service at higher bit rates, or superior quality digitally coded speech.

As examined at the MS, a specific time slot such as mobile transmit slot number 1 immediately precedes mobile receive (and thus base transmit) time slot number 1. Stated another way, mobile transmit time slot number 2 coincides with mobile receive time slot number 1. This permits time division duplex operation (in addition to use of different Tx/Rx frequencies) in fully digital mode.



The DTCH was historically used initially in IS-54, which retained the ACH for call setup purposes. The IS-136 DTCH is backward compatible with the DTCH of IS-54 with the following two modifications:

The IS-54 forward channel has a 12 bit reserved field, all zeros, where the 1 bit reserved field (always set to 1) and the 11-bit CDL field are at the right of this figure.

The Abbreviated Burst used on the RACCH (reverse DCCH) is shorter than the Shortened Burst shown here (used only on the reverse DTCH). Also, the bit fields in the Shortened Burst convey no data or information other than synchronization. The Shortened Burst (not always needed) was designed to be used optionally immediately after a handoff for one (or more) frames to control the proper burst timing delay via messages from the BMI (BS) to the MS.

The digital verification color code (DVCC) is an 8-bit code value assigned by the system operator with a unique value in each cell. The coded DVCC (CDVCC) is the 8-bit code augmented with a 4-bit Hamming code for error protection. The purpose of CDVCC is to detect false reception of co-channel interference from another cell in the system and thus prevent using the wrong signal. It has no connection with “color” which is a word used here for historical reasons.

The SACCH is used for slow messages between the BS and MS. The fast associated control channel (FACCH) is not shown explicitly because it uses the same 260 bits in the slot labeled for DATA. The FACCH is created by preempting the DATA bit fields when there is a FACCH message to transmit. FACCH messages are distinguished from coded speech data because of using different error protection code methods.

CDMA: Qualcomm IS-95

- **How CDMA works**
 - **Speech is digitally coded by a LPC-type codec**
 - **The original codec (QCELP) had excellent quality, but is rivaled or exceeded by two later enhanced full rate codecs, (one codec based on ACELP* used also in other TDMA systems)**
 - **voice activity detection (VAD) is used to control transmit power and lower the data bit rate when no voice detected at microphone**
 - **Coder bits (at ~10kb/s) are multiplied with PN code (at ~1000 kb/s) to get spread spectrum**
 - **Correlation of received signal with duplicate synchronized PN code is used to extract original data**
 - **Multiple users can theoretically share the same RF spectrum by using orthogonal PN codes**
 - **Up to 100 in this following example (64 in actual IS-95 design)**
- *Algebraic CELP

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CDMA was first developed for military point-to-point communications. It converts a low bit rate (narrow bandwidth) digital signal into a high bit rate digital signal, thus spreading the spectrum of the resulting RF signal.

To support multiple users each user must have a distinct and separate PN (pseudo-noise) code sequence. All of the PN codes used produce minimum mutual interference if they are orthogonal to each other. This means that, when one code waveform is multiplied by another (in a NRZ bipolar waveform embodiment) the product is positive and negative in value for equal numbers of PN bit intervals during one data bit interval, and thus the average value of the product is zero. Although use of a PN bit rate at 100 times the data bit rate provides 100 mathematically orthogonal PN codes, some are unsuitable because they are too obviously periodic (like 10101010...) or contain long sequences of 1s or zeros.

When multiple transmitters send signals with different PN codes to a common receiver, the RSSI of all the signals must be very close to equal, or the strongest one will dominate all the others and only it can be decoded without errors. This was a major problem which caused malfunctions of a trial CDMA system used in tests by the Groupe Spécial Mobile in 1986 in Paris. Qualcomm revived the idea of CDMA for cellular in 1989 with an improved closed-loop feedback power control to keep all the received signals from deviating in individual power levels. They are the main proponents of CDMA and the IS-95 standard is based on their design. CDMA is also the basis of some “third generation” (3G) system designs.

CDMA Cellular Channels

- **Multiple code-multiplexed conversation channels on one carrier frequency**
 - Theoretically up to 62 (usually a maximum of 10 to 18 in use simultaneously in one cell/sector)
 - Also pilot, paging, access codes in each cell for setup channel use
- **Each conversation supported by combining 9.6 kb/s coded speech (CELP) with 1.28 Mb/s chip code**
 - Each chip code chosen for separability (orthogonality)
 - Desired received signal separated from others by multiplying with properly synchronized replica chip code sequence
 - Requires approximately equal RSSI at base receiver from all MS transmitters
- **Soft handoff supports one MS with multiple BSs**
 - Except when near the center of a cell, the MS is in communication with 2 (or 3) Base Stations all using the same chip code
 - Better (lower BER) base receiver signal is chosen for each speech block
 - Internal adaptive equalizer (RAKE receiver) combines all differently delayed base transmit signals at MS receiver, giving stronger signal and better performance
 - However, this design approach greatly increases the number of BS-MS links and system complexity
 - Cannot correct for simultaneous bad RF signal to *all* base stations

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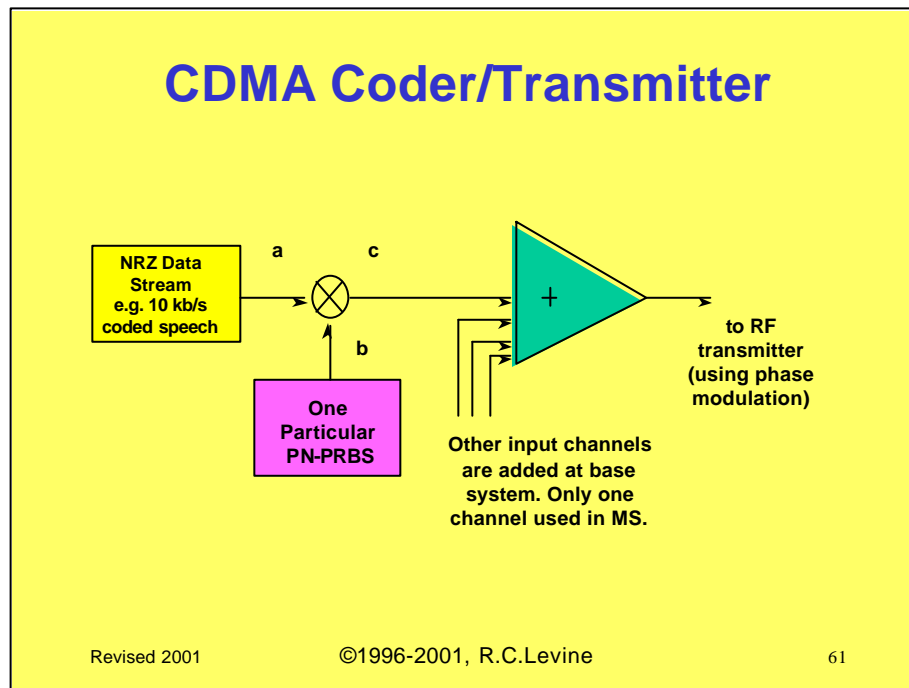
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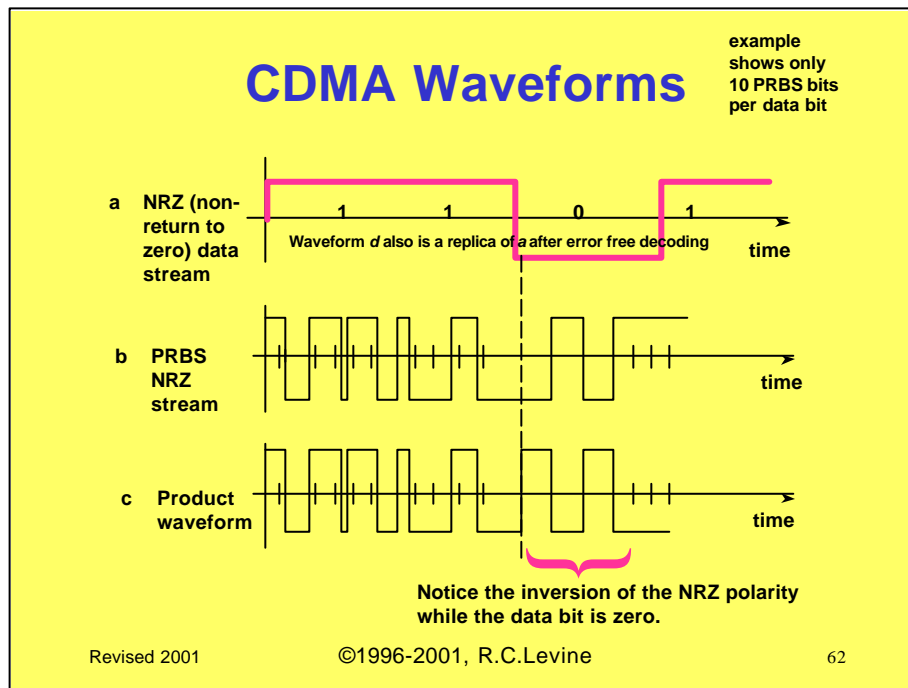
chip A high bit rate pseudo-random (random appearing but actually deterministic) binary bit sequence used to “chop” or “chip” each signal bit into many intermediate bits. Each MS in a cell has a unique chip sequence code which is generated by combining a unique repeated 64 bit code sequence (called a Walsh code) with a very long code unique to the particular MS. The objective of this design is to give each MS a chip code which can be separated from the combination of all other signals with almost complete randomization of the other signals. The chip code is also called a pseudo-random or pseudo-noise binary code or sequence (PN-PRBS or PRBS)

RAKE receiver. This is a type of adaptive radio equalizer which compensates for multipath propagation or for use of multiple base transmitters (at different distances from the MS) by internally delaying and then combining the several delayed versions of the signal which arrive at the receiver antenna.

A major design objective of CDMA is that all the radio signals arrive at the base receiver with about the same instantaneous RSSI (typically a tolerance of only ± 2 dB is permitted). Tight control of MS transmitter power is achieved by a combination of self adjustments (based on MS receiver signal from the BS transmitter) and periodic feedback control signals coming from the BS.



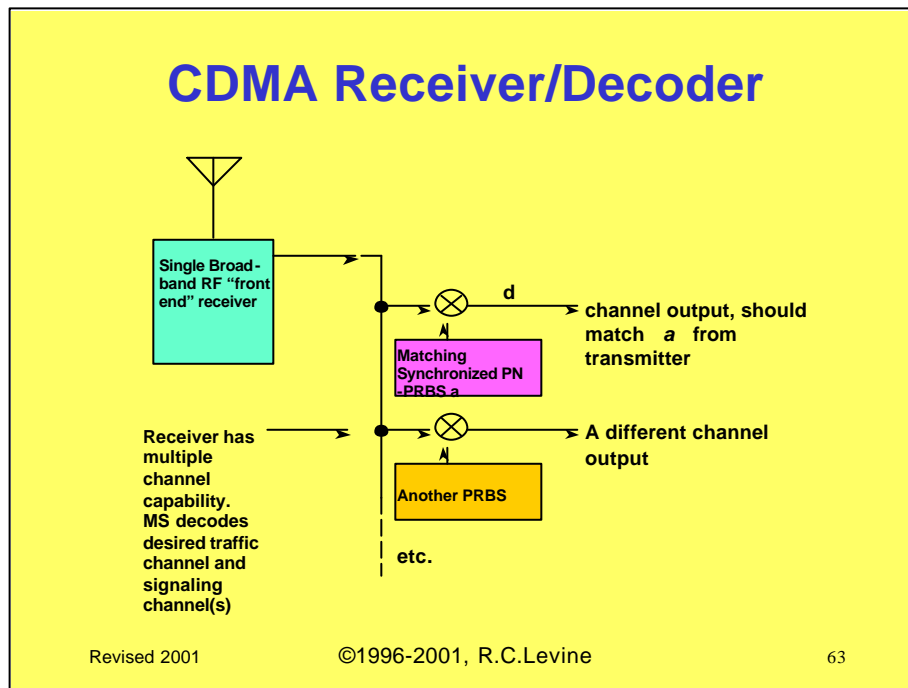
This simplified block diagram shows the essential parts of the CDMA process. The low bit-rate data signal is multiplied by a much higher bit rate signal. Both signals are in NRZ (non-return to zero) form, meaning that the two binary levels are implemented as 1 and -1 volts, for example. At the base transmitter, several different orthogonal PN-PRBS (Pseudo Noise - Pseudo Random Bit Stream) patterns are used, one for each separate data (digitally coded speech) signal. At the mobile transmitter there is only one signal and one PRBS pattern. The actual data bit rate of the Qualcomm IS-95 system is 9.6 kb/s and the actual PRBS bit rate is 1.28 Mb/s.



In this illustration, the PN bit rate is drawn at only 10 times the data bit rate to simplify the illustration, rather than the 100 described before. To decode a CDMA signal, one must have available at the receiver a replica of the encoding PN-PRBS bit stream, properly synchronized with the received waveform. This local matching PRBS is again multiplied with the received NRZ waveform, and the result is to restore the original low bit-rate signal. It is very similar to encryption, which is the basis of CDMA's original military application.

If other orthogonal PRBS coded data streams are also present, they will produce zero *average* disturbance to the decoded waveform. However, if there are so many of them that they produce a very large random fluctuation of the total signal, or if some of the PRBS codes are not orthogonal to the desired PRBS code, then the result will not average out to zero over a full data bit interval. Also, if one signal is much much stronger (greater amplitude) than all the others, it will be the dominant output signal. This latter problem is the one Qualcomm has addressed with their closed loop feedback power control.

In the actual IS-95 system, there are 64 allocated PRBS codes per cell. The proponents claim that another full 64 codes can be used in all adjacent cells, on the same carrier frequency as the central cell. This has proven to be a problem, because the other codes are at least partially correlated (non-zero time average product waveform) with the codes in other cells, thus causing unexpected high levels of BER. There are other IM problems as well.



The process in the baseband part of the receiver is similar to that at the transmitter. The presence of additional signals causes the decoded waveform to fluctuate about its intended mean/average value, but in a properly designed and not overloaded system, it should be clear whether the data bit value is +1 or -1 volt in each bit interval so the bit error rate (BER) should be low.

Major advantages of CDMA

- **Voice activity control increases capacity without need for coordinating messages between mobile and base**
 - **This is the only distinct source of high spectral efficiency compared to other access methods**
 - **Frequency Hopping in GSM also averages silent DTX intervals from other co-carrier cells, thus producing a lower average interference and higher system capacity**
 - **Proposed DSI methods for TDMA (such as Hughes Network Systems proposed E-TDMA) has also closed this “capacity gap.”**
- **Relatively easy to configure different data rates for different users**
- **MS transmitter is constant envelope phase modulation Class C (high power efficiency)**

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Using VAD (voice activity detection) to turn off the transmit signal during voice silence intervals is the “gimmick” which actually gives CDMA a greater capacity. The use of CDMA alone is *not* more efficient in its use of radio spectrum or in terms of the recommended figure of merit: the number of conversations/unit-area/kHz of spectrum. The use of VAD improves capacity by about 2 to 1 compared to continuous transmitting, because a speaker is normally silent for about 40 to 60% of the time. By lowering other transmitters’ radio power during this interval, we can load the system with more speakers without producing the same level of instantaneous radio interference that would occur if they all transmitted continuously. (This would not be useful for continuous data transmission, of course, but the vast majority of cellular/PCS users use voice.) Furthermore, in a CDMA system it is not necessary to send additional signals between the base and mobile to coordinate channel assignment when a particular user falls silent for a short while. This is the most significant feature of CDMA. Other systems have demonstrated VAD and dynamic channel assignment (satellite, undersea cable and fiber, and Hughes Network Systems’ E-TDMA digital cellular system) but they all require added coordinating signals.

CDMA Aspects

- **RAKE receiver, similar in complexity to adaptive equalizer, corrects multipath**
- **Extra cost of soft handoff when only usable with under-capacity installation**
 - Soft handoff requires $n=1$ frequency configuration, which requires that each cell be under-populated to avoid adjacent cell interference
 - Soft handoff design incorporates extra processing capacity, trunking capacity, etc.
- **Frequency diversity benefits of CDMA are similar to FH in GSM/PCS-1900**
 - Very dependent on specifics of each site; multipath statistics, etc.

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In early claims, CDMA was said to be immune to the effects of multipath propagation because the delayed signals arrived later than one chip interval, and merely looked like another un-correlated PRBS signal, which would supposedly not affect the decoding. In fact, it raised the equivalent noise level and had to be controlled by means of a RAKE receiver which is, in effect, another type of adaptive equalizer. A RAKE receiver adds about as much complexity, in terms of integrated circuit hardware inside the receiver, as does an adaptive equalizer in a PCS-1900 or GSM receiver, but consumes more battery power because it operates at a higher bit clock rate.

IS-95 prescribes a process called soft handoff, during which the MS is temporarily in simultaneous communication with two different base stations in two adjacent cells. This requires both BSs to be on the same carrier frequency, and both must transmit the same voice signal with the same PRBS coding, and both receive and decode signals from the MS. The better voice signal is chosen for each 20 ms speech coder time window. Although this improves the quality of audio if there are many bad radio coverage spots in the handover region, it greatly adds to the complexity and cost of the CDMA system (both capital cost and monthly recurring operating cost for renting more T-1 links between cells and the MSC). Even using Qualcomm's most optimistic capacity estimates, the cost per customer projected for CDMA is at least 30% higher than PCS-1900, and much of the difference can be attributed to soft handoff hardware. In addition, when different carrier frequencies are used in adjacent cells, soft handoff cannot be used.

A great deal has been made by proponents of CDMA regarding the benefits of a wideband signal, since it has less fading, etc. Not to be outdone, PCS-1900 proponents (particularly Ericsson) have claimed that fast frequency hopping in GSM/PCS-1900 works over 15 MHz or more, rather than the "measly" 1MHz of IS-95. Well, the benefit of a wide band signal is significant for both systems, and is indeed somewhat better for FH PCS-1900, but it is a second order problem, mostly very dependent on particulars of site geography, and should not get one embroiled in controversy!

CDMA's Main Disadvantages

- Higher cost and complexity of base station (particularly due to soft handoff and its extra needed switch links)
- Somewhat higher MS cost and receiver power consumption
- Early promises of 40x or 20x or even 15x analog cellular capacity are not demonstrable in the field. Actual dependable capacity is likely to be ~6x to 8x analog (comparable to TDMA)
- Sensitivity to narrow band IM from strong signals
 - Every receiver has a dynamic range bounded by two power limits
 - Low power limited by noise effects
 - High power limited by non-linearity
 - CDMA receiver has small dynamic range to receive low level CDMA signal
- Availability of contiguous spectrum is sometimes a problem. Strong narrowband carriers often exist in band:
 - On PCS bands: pre-existing point-to-point microwave systems
 - In 800 MHz cellular: IM products from other cellular carrier frequencies

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The wide band receiver used in CDMA can be adversely affected by a strong narrow band radio signal within the pass band. This type of non-linear distortion is called inter-modulation (IM).

InterDigital, a firm which was primarily in the military electronics fields, has also proposed a Wideband CDMA system based on the inventions of Prof. Donald Schilling. Although they have presented their technical proposals at various standards meetings, they appear to be stalled by lack of capital and there is no announced delivery date for a product. Their system uses approximately a 4 MHz PRBS spreading code, and is consequently much wider bandwidth than IS-95. They also have the problem noted regarding pre-existing microwave signals in the middle of their proposed band.

Several 3G system proposals involve CDMA at approximately a 5 MHz chip rate. There are also some TDMA 3G proposals as well, so there is not yet a single accepted third generation technology for cellular and PCS.

PCS-Primeco started commercial 1.9GHz CDMA PCS service in 14 cities during November, 1996. Commercial use of CDMA on the 800 MHz band started in several cities in early 1997.

Types of Handoff

- **Break-before-make handoff**
 - “Hard” analog handoff interrupts audio for about 200 millisecon while MS re-tunes to new carrier frequency
 - “Seamless” TDMA handoff has no perceptible interruption in audio. MS quickly re-tunes between two normal TDMA bursts.
 - Only in a case of two adjacent cells with extremely large difference in radius is a re-timing adjustment needed (using shortened mobile Tx radio bursts). When this occurs a 20 millisecon loss of digitally coded speech occurs, which is normally “bridged” over by the digital codec and is still usually imperceptible.
 - When timing adjustment for distance to new base station is pre-commanded, TDMA handover is truly “seamless”
- **Make-before-break handoff**
 - “Soft” and “softer” handoff in CDMA. MS is in temporarily in communication with more than one base station for some time interval during handoff.
 - Soft handoff cannot compensate for bad RF coverage or insufficient target cell traffic capacity affecting both cells. Dropped calls can, and do, still occur.

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Both CDMA and TDMA systems produce a much better perception of continuity during handoff than analog. There are pros and cons for the way each digital technology does handoff. Both analog and TDMA require a brief interruption of the speech prior to handoff to give the command to the MS regarding the new frequency (and time slot in TDMA). However, this command requires only 20 ms in TDMA, and this loss of one speech coder frame of speech bits is normally interpolated over smoothly by the TDMA speech codec, giving no perception of audio loss. In a CDMA soft handoff system, there is no similar command, since the MS never changes frequency.

Large scale TDMA systems provide for a command to allow the MS to temporarily transmit shortened radio transmission bursts when handing off to a new cell which is very different in size than the old cell, to allow for adjustment related to the time delay for the radio signals to travel between the BS and MS. However, in most real systems the difference in radius between two adjacent cells is either very small (less than 3 km, corresponding to a 9 microsecond time interval) or it is known in advance and can be adjusted without sending shortened bursts. Thus, in real systems there is seldom any loss of the bit stream at handoff. Even when one or two short bursts must be sent for re-adjusting the time advance of the MS, only 20 or 40 ms of bits are lost, which is again covered by the normal interpolation capability of the LPC-type digital speech coder.

At one time, soft handoff proponents implied that soft handoff somehow compensated for flaws in the radio coverage, and thus there was an implied promise that the system design and installation could be accomplished more rapidly or with less detailed coverage measurements than for other technologies. This has proven not to be true in practice. Good RF coverage is necessary for *any* type of RF technology to prevent dropped calls, bad signal areas, etc. If you need a team of 32 RF engineers and technicians to install, test and monitor an analog or TDMA system, you need the same size team for CDMA as well.

Call Processing

Initialization
Call Origination
Mobile origin, mobile destination
Handover
Release/Disconnect

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The signaling over the radio link (Um interface) to accomplish these operations will be described at a general level. Then later we will show the form of the messages used, with one specific example.

MS Initializes

- A non-conversation-state MS “looks” for a control or setup frequency (and time slot for TDMA or pilot code for CDMA) when:
 - Power is turned on
 - Signal on the present control channel is weak or has bad bit errors (usually when leaving a cell)
 - A periodic timer in MS initiates a re-scan
- Then the MS scans *all* relevant carrier frequencies looking for a control channel, however...
 - A “brand new” MS scans *all* the frequencies
 - Scans all carriers when turned on in a “new” area and can’t find the “old” control channels
 - Only 21 carriers to scan in 800 MHz analog cellular
 - IS-136 base stations transmit the carrier number of the setup channel on all frequencies as a CDL “helping pointer”
 - A previously used MS saves the last known control frequencies found in the city in its memory
 - Usually provides faster initialization (seconds v.s. minutes to be ready to operate). Particularly helpful for GSM, IS-136

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Unlike analog cellular systems, the “beacon” carrier (containing the control channel time slot in a TDMA system) may be *any* frequency that the operator wants to use for that purpose, so long as there is only one (for GSM designs) carrier per cell/sector which is used in that way. (IS-136 permits multiple control channels in the same cell/sector.) This gives the operator great flexibility. For example, if there is a particularly low traffic cell/sector, it may be provisioned with only one carrier frequency (compatible with the overall frequency plan, of course) and that frequency may be used as a beacon frequency without restriction. There are no frequencies which are legally reserved for voice traffic only, nor any reserved for beacon use.

Remember that a *GSM* beacon carrier can be configured to use one time slot for the broadcast and other generally used channels, and then several other slots may be optionally configured for the stand-alone channels used for the intermediate messages during call setup. Then at least 4 of the remaining 7 time slots may be used as traffic channels, and as many as all 7 if there is minimal call setup, location update, and SMS activity.

An IS-136 control channel always uses slots 1 and 4 (for full rate configuration) or slot 1 only (for half rate configuration). The other slots on that carrier *must* be used as traffic channels.

Idle MS in a cell

- When a power-on but non-conversing MS is in a cell, it normally locks onto the control channel of that cell
 - automatically scans and finds new best RSSI, best BER control channel as it moves from cell to cell
- MS could start a call if user dials a number and presses START/TALK button
- MS could “ring” if it is “paged” by means of a message broadcast on the control channels of all cells in the vicinity
 - User can then answer, and MS can be commanded to change to a voice or traffic channel for a conversation
- Analog systems normally page all cells in city
- Digital systems have multi-cell “location areas” (LAs) which broadcast distinct identification numbers periodically
 - MS identifies when it crosses a boundary from one LA to another
- MS eventually tunes to a “voice” or “traffic” channel (commanded by the BS) after the preliminaries above

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The MS must find the nearest (or more accurately, the best signal) beacon carrier rapidly, so it can stay in contact with the base system in case of a page, or so that the end user can originate a call.

Preliminary Registration

- In current cellular and PCS networks, the MS must register or “attach” to the network (identify itself via a radio transmission on the uplink control channel)
 - At first power up for the day
 - When entering a new base system
 - When entering a new LA
 - Conversely, just before power-down it “detaches”
 - In some of these cases, the MS “authenticates” to prevent fraud
- This leads to infra-structure network messages which eventually update the home HLR and the current VLR
 - After authentication of the MS, then:
 - MS can originate calls
 - HLR and active VLR know where the MS is currently
 - HLR can cause “call forwarding” (in North America) to other cities if pre-arranged

In *original* 1980 analog cellular network designs, much of this did not happen. Fraud was rampant. Call delivery was not easily done.

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No notes on this page.

Registration Process

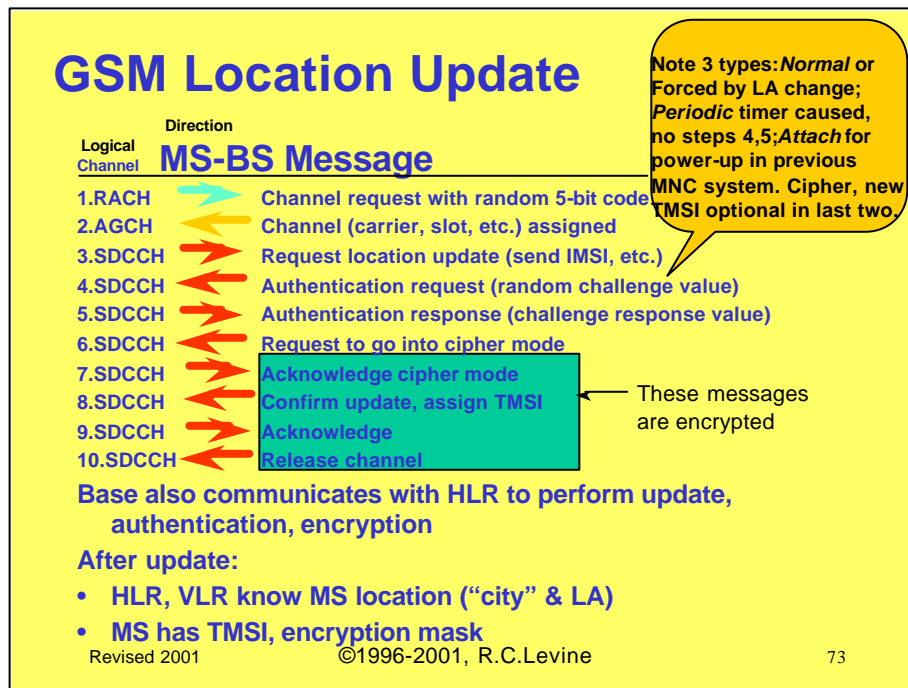
- A number of transactions occur during a modern digital cellular or PCS system Registration
- Next example is from GSM, which performs each operation with a separate message
- North American IS-54 and IS-136 combine several data message elements into a smaller number of longer messages
 - Also encryption is not done on everything at IS-136 registration time, but rather optionally at calling time

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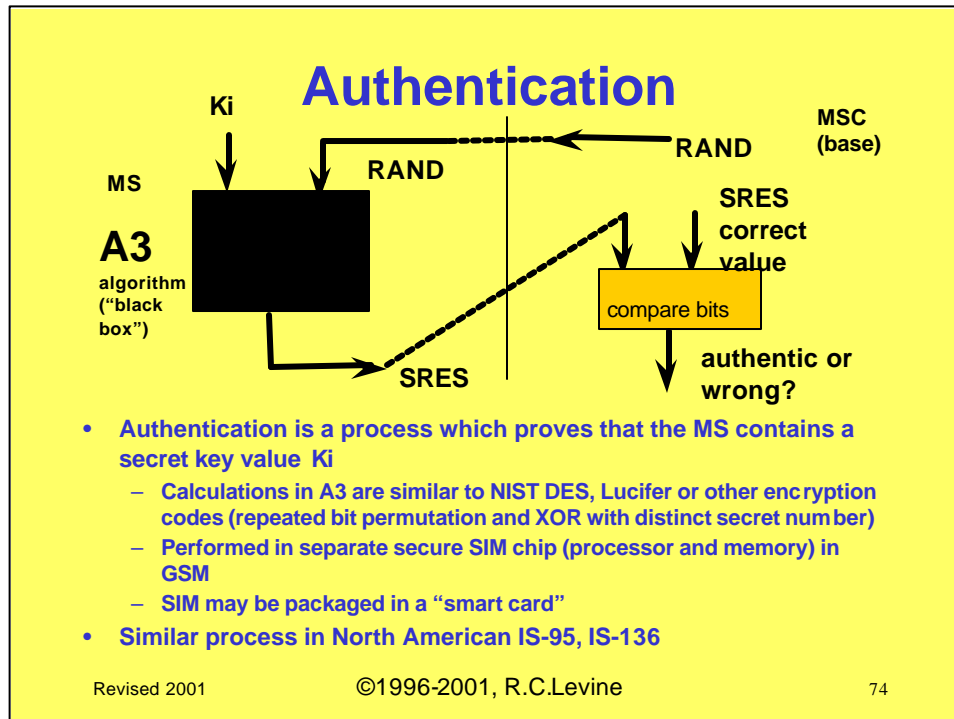
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In the North American cellular system, there was originally no firm plan regarding networks of MSC equipment. Specific features were designed and added as required, in the various releases of the IS-41 standard. In contrast, the GSM system was designed from the beginning with all its network features pre-specified.



Details of cipher mode are explained on another page. In a GSM system, when cipher mode is established, a ciphering key sequence number (CKSN) is set in the base and mobile. On subsequent contacts by the MS with the BS (for further location updates or to begin a call), the MS sends a message with the CKSN value as a data element. If the MS CKSN value agrees with the corresponding value in the base system, the messages and data elements required for establishing ciphering need not be repeated. In that way a new cipher key need not be established just because the MS is doing a location update. However, the practice of most operators is to establish a new cipher key for each telephone connection. In summary, all the steps to establish new cipher keys in other operations following this should be viewed as optional operator choices without explicitly labeling each one thus.

Please note also that there is a GSM SACCH channel associated with the SDCCH channel used for location updating and other pre-connection type exchanges of information, such as short message service (SMS). This SACCH permits the MS to receive a list, from the BS, describing which nearby beacon frequencies to scan, and then report back the signal quality on each such beacon frequency (about one report per second). The purpose and result of this is that a handover can be done, if required, during a location update, call setup or short message transmission. This is not possible in older analog cellular systems.



PCS-1900 authentication involves a two-way transaction. The base station transmits a random "challenge" number $RAND$ (different value on each occasion when authentication is to be performed for any reason) to the mobile set. The mobile set performs a calculation using that number and an internal secret number K_i and returns over the radio link the result of the computation $SRES$. The base system also knows what the correct result will be, and can reject the connection if the mobile cannot respond with the correct number. The A3 algorithm used for the calculation is not published, but even if it is known to a criminal, the criminal cannot get the right answer without also knowing the internal secret number K_i as well. Even if the entire radio link transaction is copied by a criminal, it will not permit imitation of the valid set, because the base system begins the next authentication with a different challenge value $RAND$.

This transaction also generates some other secret numbers which are used in subsequent transmissions for encryption of the data. Therefore, nobody can determine which TMSI was assigned to the MS, aside from not being able to "read" the coded speech or call processing data.

This process has proved to be technologically unbeatable to date, and there is no technological fraud similar to the major problem with analog cellular. There is still non-technological fraud, such as customers presenting false identity (e.g., a stolen driver's license) to get service but never paying their bill (subscription fraud).

The mathematical processes involved in DES and Lucifer encryption consist of two repeated operations. One is the permutation or rearrangement of the data bits. The other operation involves XOR (ring sum or modulo 2 sum) of the data bits with an encryption mask or key value. These operations are repeated a number of times (rounds) to thoroughly scramble the data, but they can be reversed by a person who knows both the algorithm and the secret key value.

The April 1998 reported "cracking" of A3 by U.Cal Berkeley group indicates no flaw in the algorithm, but rather intentional assignment of only small number values as K_i key values when longer constants are feasible. The question "why was this done by the GSM system operators?" remains to be answered, since it reduced the security of their system.

Call Setups

- **A mobile destination call is the most lengthy to set up because the MS must first be paged and then respond**
- **A mobile origination call is simpler, since the MS begins at a point corresponding to the middle of the previous case**
- **Following example is from GSM**
 - **Again, IS-54 or IS-136 perform similar functions, but using fewer (multi-parameter) messages**
 - **GSM uses an “intermediate” standalone SDCCH channel for these processes (8 MSs scheduled to use one time slot for lower average bit rate)**
 - **IS-54, IS-136 use only the control channel for these processes**

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With regard to authentication, in the North American systems (IS-54, 91, 94, 95 and 136) there is an authentication transaction very similar to that shown on the previous page for GSM. A random challenge number is transmitted from the BS to the MS, and the MS performs a calculation using it and an internal secret number called SSD-A, and then returns the result in a reserved data field which is part of the paging response or call setup message (for mobile destination or mobile origination respectively).

The secret number SSD-A is derived from a second internal number called the A-key. If the operator suspects that the SSD-A in the MS has been compromised, it can be changed by means of radio messages to a new value. Only a base system which knows the proper value of the A-key can perform these operations. The A-key can be set at the factory or entered by the end user via the keyboard of the mobile set.

Authentication and encryption setup in North American systems are more often performed at call setup time rather than at registration time, as shown for the GSM type system on these pages.



The steps involved in setting up a connection are similar in all cellular and PCS systems. For a mobile destination (also called mobile terminated or answered) call, the base stations in the last known LA must page the MS. In GSM/PCS-1900 the paging for certain IMSI numbers occurs during pre-scheduled time windows only. Therefore, the MS can "sleep" (operate with several internal modules turned off) in a low power-consumption state until a paging window time, thus prolonging the interval until battery recharge is needed for the MS.

Following the receipt of a paging message (which contains the TMSI for identification of the proper MS), the MS must make radio access to the base system, and then an exchange of messages leads to directing the MS to the correct TACH. To do this, most of the messages are exchanged using a SDCCH channel, which is used for short intervals by each MS in turn which is involved in a call setup, location update or short message transmission.

A mobile originated call involves primarily the same operations as a mobile destination call. Only messages 1,3,4 and 9 differ in any details. After the connection on the TACH is established, the call is processed for all subsequent steps (handover, release, etc.) in the same way regardless of whether it is mobile originated or mobile destination. Other sequences of call setup are possible in a system with SS7 signaling to the PSTN, so the voice channel does not need to be connected until the called person answers, but are not feasible with present MSC to PSTN signaling which do not have SS7 signaling.

Handover Control

- **Operator has generally 4 measurable parameters to control handover (2 each on uplink, downlink channel)**
 - 1.Threshold handover start RSSI**
 - 2.Threshold handover start BER**
 - Note that either of above could start handover independently
 - “Delta” of above parameters to cancel handover
 - In general these delta parameters are used to minimize “ping-pong” effects via intentional hysteresis
- **Values may be set to independent and distinct values in each sector of the system, and different for different MS power classes**

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Setting these handover thresholds is one of the few parameters which the operator (as opposed to the manufacturer of the base system) has under control. A lot of experimentation is used to “fine tune” the value of each threshold in each cell or sector.

Why A Too Slow Handover?

- **Handover may be unintentionally delayed due to:**
 - **Locating receiver measurement delay in analog systems**
 - **Fix: install more base station locating receivers (costly!)**
 - **Queuing of MSC-BS data link control messages**
 - **Fix: More total bit rate on these channels**
 - **No available traffic channels in destination cell(s)**
 - **Temporary Fix: traffic leveling handovers where feasible***
 - Delay waiting for a cascade of traffic leveling handovers may drop the call!
 - **Permanent Fix: increase cell capacity (e.g. more carriers in a cell)**
 - **Data processing delays (unusual!)**
 - **Install more (parallel) processing capacity**

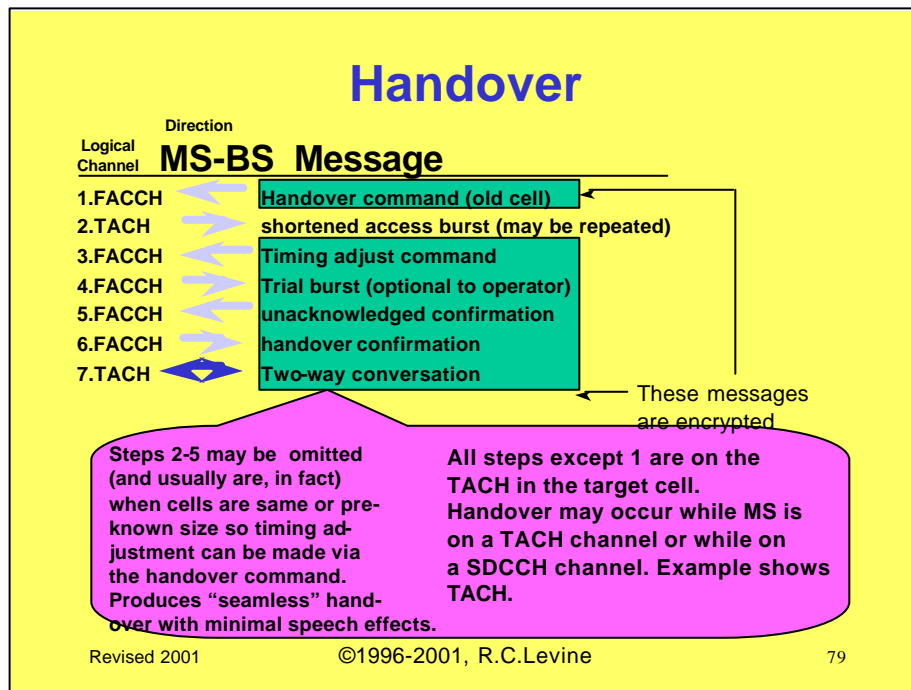
*Dependence on traffic leveling implies need for extra cell overlap

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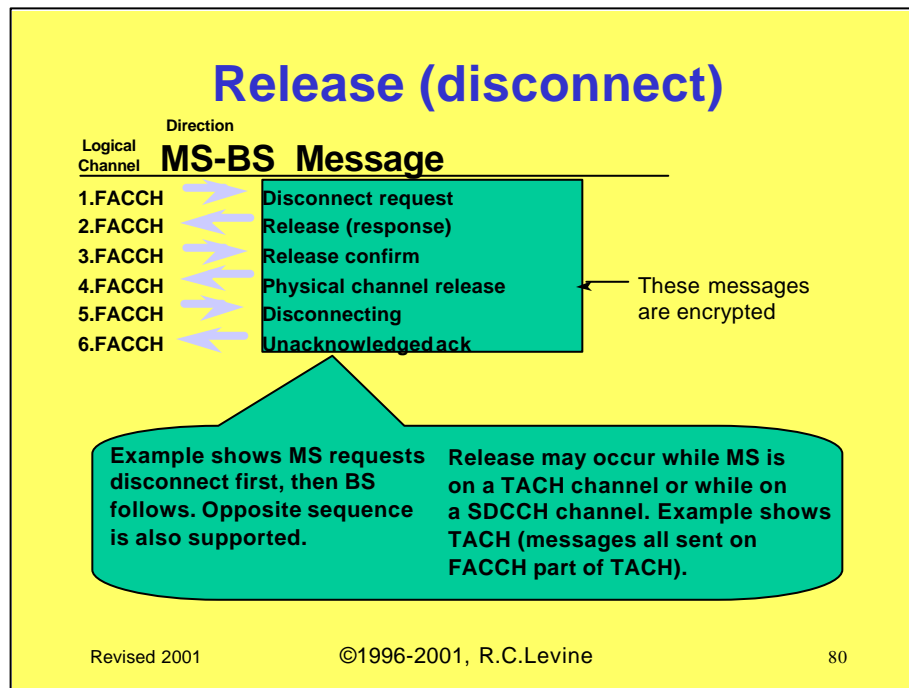
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In most cases, although analog cellular systems suffer from problems arising from handoff delay, a properly provisioned digital cellular system should not have any unexpected delays in performing a handoff.



This shows the commands which are sent AFTER the system has already determined that a handoff is necessary and which cell (and carrier frequency and time slot) should be the target of the handoff.

In a TDMA system with adjacent cells of approximately the same size, it is not necessary to make timing adjustments for the transmission delay, so a "seamless" handoff can usually be accomplished with no lost coded speech. CDMA systems also have continuity of speech during a "soft" handoff. Of course, both of these systems may have a brief interruption of the digitally coded speech data in order to send the handoff command (which requires about 0.2 seconds), but the missing data is interpolated over because of the design of the speech coding process. Analog systems always lose about 0.2 seconds of speech during a handoff since they have no designed-in way to save and repeat prior speech during that time.



The number of confirming acknowledgments used in this exchange leading up to a disconnect is testimony to how important it is to never, *never* disconnect a call already in progress. If you have to drop *something* due to an uncontrolled situation (bad signals, lack of channel capacity, etc.), it is better to drop a call attempt which is still at the dialing stage, since the customer will not be so irritated (and often needs to only press the SEND/TALK button again). In addition, and not shown explicitly in the diagrams, there is a whole procedure designed for GSM/PCS-1900 to automatically *re-establish* a call which was accidentally or unintentionally disconnected due to bad radio channel errors or other problems. This does not exist in the design of other non-GSM systems -- you must manually redial if you are accidentally disconnected.

Circuit-Switched Data or FAX

- In addition to voice, digital cellular systems provide for circuit-switched data and FAX
- Special connectors (Terminal Adapters) are provided on some MSs for a FAX or data terminal
 - The FAX adapter contains a FAX MODEM which extracts the binary FAX information
 - Other devices (laptop PC, etc.) use a simple serial data (RS-232) connector
- The MSC contains a modem pool for PSTN connection*
- GSM data was originally limited to 9.6 kbit/s since significant amount of error protection code must be added and available total bit rate is 22.4 kb/s in GSM or 13 kb/s in IS-54, IS-136.
 - Today GSM standards provide for 14.4 kb/s by linking two time slots.

*Modem at MSC is an example of inter-working functionality (IWF)
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The actual PCS-1900 system data throughput for the low bit rate data streams allows some extra bits for data overhead used or originated by the terminal. Although 9.6 kb/s is the present maximum customer data bit rate, 14.4 or more kb/s (such as 19.2 kb/s) is also supported using 2 or more time slots for the same TDMA connection. CDMA systems also support a so-called “Rate 2” connection with 14.4 kb/s data. This linking of two channels for higher bit rate is described in the IS-130 standard, used with the IS-136 North American TDMA standard.

Packet Data in 3G, 2.5G

- **3G and 2.5G technology enhancements of cellular and PCS technology support packet data**
- **Subject of later lecture in EETS8304/MS-708N**
- **Packet data allows efficient use of a logical channel by numerous bursty data flows to/from distinct subscribers.**
 - **Unlike circuit switched connections, which dedicate a channel to one subscriber even when there is no data to be transmitted**

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Error Protection Codes

- **Convolutional codes**
 - Similar to multiplication*
- **Cyclic Redundancy Check (CRC)**
 - Similar to transmitting long division*
remainder, recalculating it and comparing at Rx end
- **Block codes**
 - Similar to matrix multiplication*
 - Fire code used for call processing messages in GSM/PCS-1900

* Binary arithmetic is performed without usual carry or borrow for these codes (so called modulo-2 or ring-sum arithmetic)

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Now we have an idea how a message is put together. When the message or some speech coding bits are ready for transmission, they need to have error protection applied to them. Several different types of error protection codes are used in GSM. The major types are listed above with examples on following pages. There are also some specific types not explicitly listed which are used only in one context such as the shortened burst. IS-54 and IS-136 systems use convolutional and CRC codes as the GSM system does, but *not* block codes like the Fire code. In addition, interleaving of the bits over a number of consecutive time slots is used in both GSM and IS-54 and IS-136. After the bits are re-assembled in the order they had before interleaving, the number of *consecutive* bit errors due to a radio channel fade is thus reduced. This allows various error correction codes to work more effectively since they have a limitation on the number of consecutive errors which they can correct.

Convolution Code

- Analogous to multiplying* by a pre-determined constant before transmission
- $10110 \bullet 10101 = 100101110$, transmit product
- Divide* received bit string by the pre-determined constant at receiver
 - Non-zero remainder indicates errors
 - Some patterns correspond to limited numbers of bit errors at identifiable bit positions
 - correct error(s) by reversing those bits (0 <->1)
 - Other patterns correspond to more than one error condition
 - errors are detected but not correctable

* Ring sum or modulo 2

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The two binary numbers shown in the example correspond to decimal 22 and 21, respectively. If we did ordinary arithmetic multiplication with carry, the product would be decimal 462. Examination of the result above shows that it corresponds to decimal 302, because we did not carry in cases where there were two or more binary 1 values in a bit column at intermediate stages of the multiplication process. The convolutional code is used on most (but not all) of the bits from the speech coder, and on *all* of the bits from data sources, but (in GSM and PCS-1900 only) in conjunction with a Fire block code as well for call processing messages.

Cyclic Redundancy Check Code

- Analogous to dividing* by a pre-determined constant and appending the remainder (the CRC) to the data before transmitting
- The division* is repeated at the receiver, and the computed and received CRC compared
 - Non-zero difference indicates errors
 - Some patterns correspond to limited numbers of bit errors at identifiable bit positions
 - correct error(s) by reversing those bit values ($0 \ll 1$)
 - Other patterns correspond to more than one error condition
 - errors are detected but not correctable

* Ring sum or modulo 2

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CRC is a good error detecting code, and can fix a very limited number of errors as well. The exact properties depend on the length and type of divisor used to calculate the CRC. Of course, a longer divisor will produce a longer CRC remainder as well. The CRC is used on only some of the most important bits in the speech coding, in combination with a convolutional code.

Block Code (only in GSM)

- Data is matrix multiplied* by a pre-defined matrix to generate parity check bits, which are appended to data and then transmitted
- Matrix process is repeated at receiver, computed parity bits are compared to received parity bits
 - Non-zero difference indicates errors
 - Some patterns correspond to limited numbers of bit errors at identifiable bit positions
 - correct error(s) by reversing those bits (0 \leftrightarrow 1)
 - Other patterns correspond to more than one error condition
 - errors are detected but not correctable

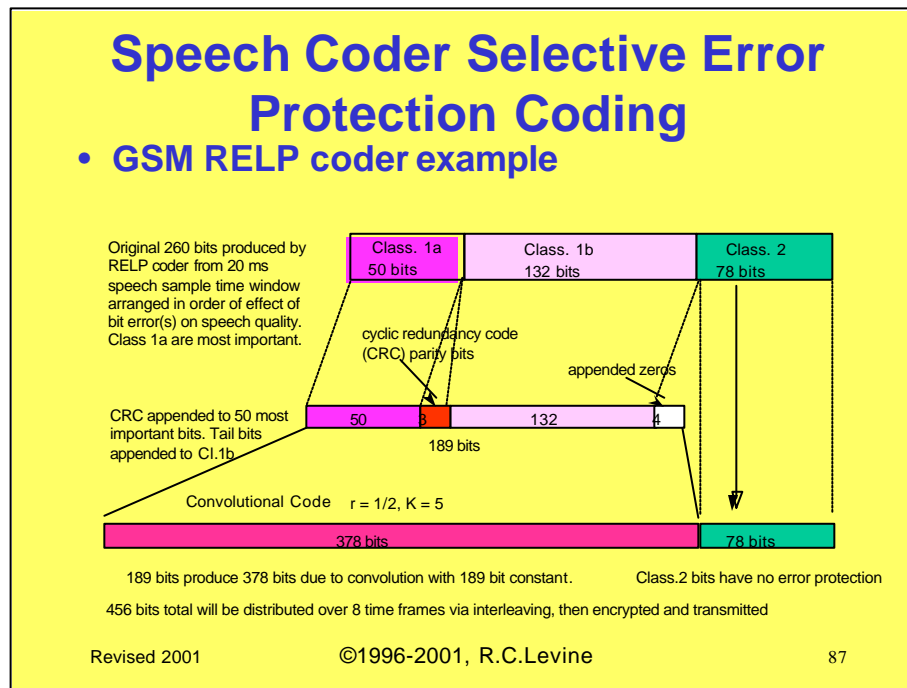
* Ring sum or modulo 2

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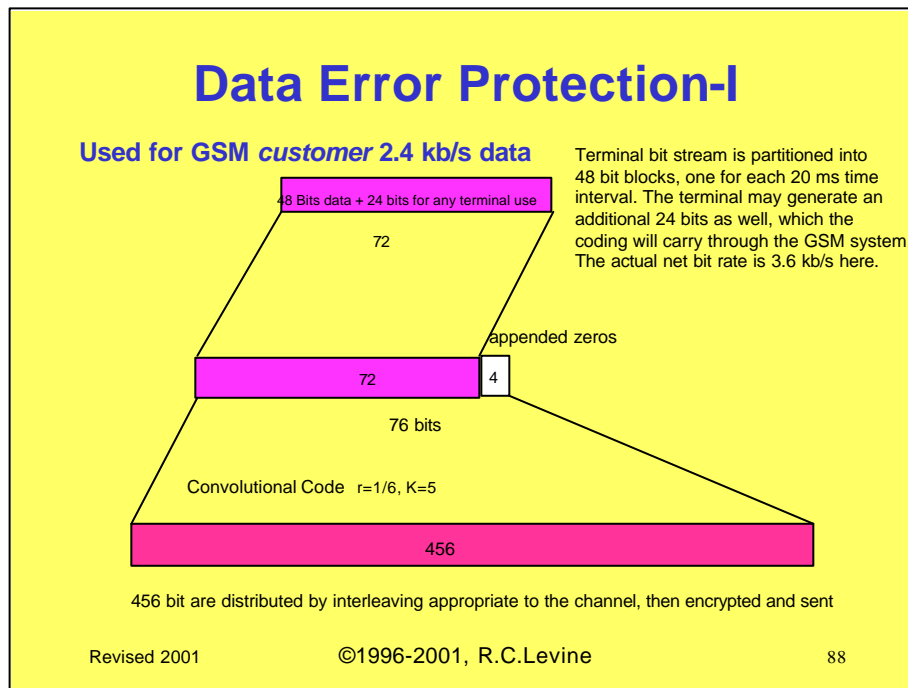
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The particular block code, used only in GSM and PCS-1900, is the Fire code, named after its inventor P.E. Fire. It is a very good error *detecting* code, and is used only for data which can be retransmitted with some delay, by means of an ARQ protocol, without affecting the system too adversely. It is not a forward error correcting code and is not used for speech coding or customer data. ARQ (automatic request to retransmit) protocol uses an acknowledgement signal from the receiver back to the transmitter to prevent automatic re-transmission of each message packet. In this way, an incorrectly received packet is retransmitted repeatedly until it is received error free and is successfully acknowledged.



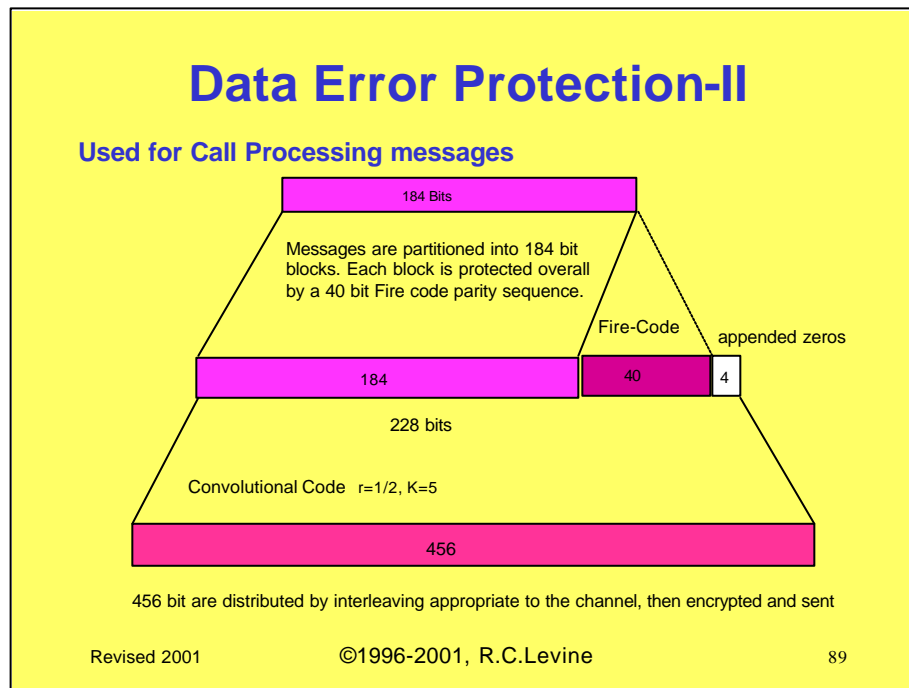
The bits are arranged in order of importance to speech quality by the simple but tedious method of intentionally introducing 50% BER into one selected bit in a recorded voice sample, and comparing the subjective quality with a similarly processed recording which has 50% BER introduced into *another* bit. By ranking the quality of all such samples, the bit with the most importance to good quality is placed at the left in Class 1a, and the bit with the least importance to quality is placed at the right in Class 2. The bits are then divided into three *classes* of importance, since there is a observed larger change in quality between having errors in the last bit in Cl.1a and the first bit in Cl. 1b, and likewise with the last bit in Cl. 1b and the first in Cl.2, compared to the difference between consecutive bits within the classes. (Don't ask me why the three classes are not labeled as Classes 1,2, and 3 !?!)

The 3-bit CRC permits correction of single bit errors in the 50 most protected bits all by itself. The convolution code can correct several bit errors, and detect any bursts of errors which are within a consecutive group of 5 bits. Most of the bits in Classes 1a and 1b are most significant bits of filter coefficients and other numerical bit quantities which have an obvious significant effect on the sound output if they are wrong. Most Cl.2 bits are least significant bits of numeric quantities and some bits describing the excitation waveform.



This a method only applicable to 2.4 kb/s data. Such data could be from a FAX machine (running slower than normal, of course!), or a data terminal with a keyboard and display, or a point of sale terminal, etc. When higher bit rate data such as 4.8 or 9.6 kb/s is used, a different rate convolution code is used, and the interleaving method is different from the interleaving used for digitally coded speech. The 2.4 kb/s example is shown here because its interleaving method is exactly the same as the one used for speech, FACCH and SACCH data bits on the TACH channel.

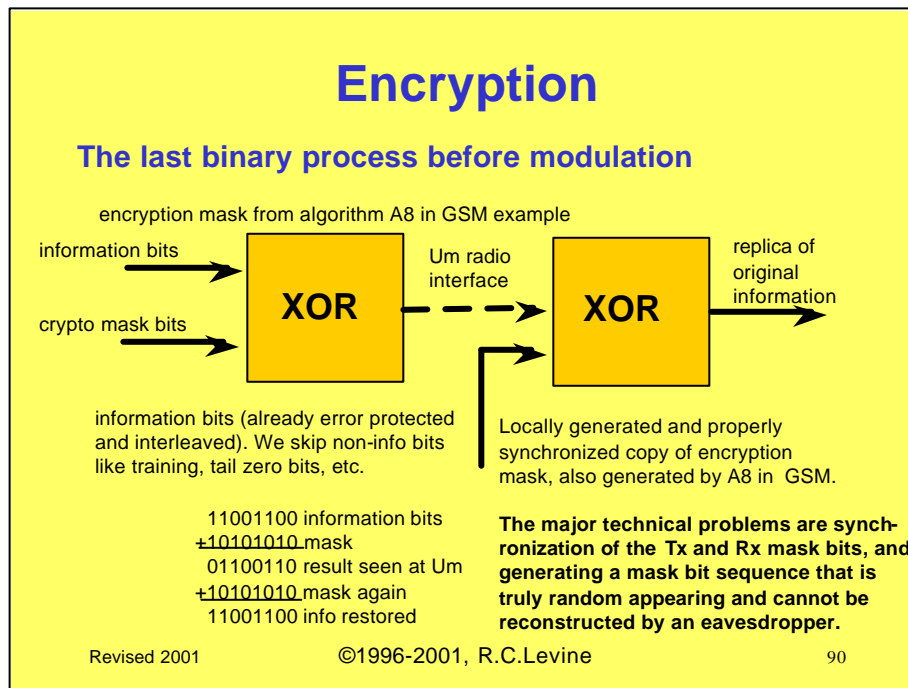
The 24 extra bits allowed in each 20 ms time interval in addition to the 48 data bits, may be used by the terminal equipment for packetizing the data (header and terminal-related error protection codes) or any other purpose desired by the terminal. The gross data throughput (due to the extra bits) is really 3.6 kb/s, and the terminal can use this in any way desired. The GSM/PCS-1900 system is designed to eventually deliver the entire 72 bits at the other end.



The GSM call processing messages may be of any length, in principle, but they are transmitted in blocks of 184 bits, and if necessary are reassembled at the other end. The Fire code using this particular implementation can detect any combination errors of up to 11 bits total in error, regardless of their arrangement (consecutive or otherwise).

The description of the convolutional code on each figure shows its rate r and its constraint length K . The rate is merely the ratio of the number of bits of data to the total number of resulting bits. The predetermined multiplier contains a number of bits equal to the difference between the two bit string lengths. Thus, in the $r=1/6$ code used previously for customer data, the 76 bit data block is “multiplied” by a 380 bit predetermined constant, to produce a 456 bit result. This is similar to the general rule in decimal arithmetic that the number of digits in the product is the sum of the number of digits in the two numbers which are multiplied. Of course, there is no carry used in this modulo 2 or ring sum multiplication, so it is not *true* multiplication in the everyday sense of that word.

The constraint length K is the longest cluster of error bits that this particular code can disclose as an error. A longer cluster of errors will not be properly detected, although multiple error bursts separated by a section of good data *will* all be detected properly.



This same method is used in both GSM/PCS-1900 and IS-54,136. However, the encryption mask is generated by different algorithms in these two families of system designs. The European A8 algorithm is not known to be “crackable,” but the algorithm used in the North American systems was intentionally designed to be simple and can be “cracked” by analysis of samples of data using a reasonably powerful computer. It was only designed as a low level privacy method in order to meet US export restrictions on cryptography. In practice, most North American system operators have not implemented even optional encryption yet, depending instead upon the digital coding of the speech to protect the conversations against interception by undesired listeners who only have an analog radio receiver or “scanner.”

Short Message Services (SMS)

- IS-136, IS-95, GSM, PCS-1900 are capable of sending a short message (up to 160 characters in GSM -- 7-bit ASCII code characters)
 - Individually addressed or broadcast
 - Appears (scrolls) on alpha display of handset
 - MS can send short messages as well
 - Select from menu of “canned” or “cliché” messages
 - “Let’s have lunch,” “Your message understood,” etc.
 - Arbitrary message from keypad or attached PC, etc.
 - Messages can be broadcast to all, or to a class of recipients
 - Automobile traffic reports, weather warnings, etc.

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SMS makes a MS into both the functionality of a pocket alpha-numeric message pager along with its voice telephone capability. SMS has the promise of lower overall cost than the use of two separate services using separate customer units for each purpose and separate infrastructure for each type of signal. It is viewed by many industry observers as a very important customer motivator to change over to or begin IS-136, IS-95 or PCS-1900 service.

SMS Connections

SMS messages may originate in many ways

- Call-back number, coming from calling line ID of PSTN, or caller-entered touch tone
- Alphabetic message from many sources
 - E-mail to MS user
 - Internet messages to SMS server
 - Dial-in MODEM for SMS messages
 - Attendant typist transcribes verbal telephone messages into text of SMS message
- MS may reply to any of these specifically
- But SMS is not a real-time 2-way dialog

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While digital PCS systems offers many sophisticated ways to deliver short messages to an MS, these are all data network infrastructure developments which are beyond the scope of the GSM or IS-xx standards documents. The only direct interaction is the transmission of these messages via the MAP common channel signaling message set, which is a subset of common channel number 7 signaling. CCS7 (which also has numerous other abbreviations) is almost universally used for telephone networks in North America and most other industrialized nations.

All of the methods described here are equally applicable to GSM and competitive services such as IS-136 (which was openly modeled after GSM), CDMA, and also the so-called NPCCS (narrow band PCS) paging systems recently licensed on the 900 MHz band.

Network Interactions with Public Switched Telephone Network (PSTN)

- **Until the present, connections between the PSTN and MSC switches for PCS & cellular used signaling originally developed for PBX (private branch exchange)**
 - The best version of this is primary rate interface (PRI), which provides better answer supervision
 - The “vanilla” signaling system is A,B bit signaling, which has lower cost!
- **Roamer call delivery can be provided by forwarding calls through the home MSC**
 - This is part of the IS-41 infrastructure signaling standard used by North American cellular operators

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The “vanilla” PBX signaling uses so called “in band” signals to indicate when a call is originated and disconnected. It does not indicate specifically when the distant called destination answers the ringing call attempt. PRI does better on that score, but some operators feel that otherwise it costs a lot of money for no additional capabilities. Both systems can provide caller ID by means of different signaling mechanisms.

Neither system gives the MSC access to all the network capabilities which are designed into the European implementation of MAP, the set of messages for handling mobile customers via the SS7 signaling network. It is likely that the advent of landline local service competition from companies which also own long distance (inter-exchange carrier or IXC) networks as well, like AT&T, MCI-Worldcom, etc., may change this and give MSCs full access to SS7 signaling and provide MAP implementation on the PSTN (or at least on part of it). Local Number Portability (LNP), which has been mandated for cellular/PCS telephones as well as wireline telephones by the FCC is another reason why SS7 signaling will eventually be available to cellular switches.

The objection by the public telephone companies to using SS7 all the way to the MSC has been that it opens up possible methods of fraud such as placing calls which are not billed because they are identified as test calls, etc. There *have* been some cases of fraud with existing PBX signaling which lead to this concern.

Promises of MAP

- **MAP (mobile application part) is an extension of SS7 signaling for mobile services**
 - Uses the same SS7 network to carry MAP messages as other telephone signaling
 - Compare IS-41 which normally requires a separate parallel data network as well as the public telephone network for voice
- **Allows calls to be routed directly to the present MS location**
 - NOT via the home MSC, as IS-41 does
- **Adoption of MAP in North America is a business/political issue to be settled in the future**
 - FCC requirement for local number portability by cellular/PCS carriers ultimately make SS7 signaling interworking between MSC and the PSTN mandatory

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MAP and SS7 signaling were specified in detail as a part of the GSM standards and are being implemented in Europe. In principle, with a fully developed MAP system, a call placed from Boston, to an MS which is visiting Boston from a home location in Los Angeles, will be routed entirely within the city of Boston, and the voice channel in the PSTN will never get out of the city, although some MAP data messages go back and forth to Los Angeles as part of the call setup. As the number of roaming cellular and PCS users increases, the traffic load on the long distance networks using the IS-41 call forwarding method will increase exponentially. And the customer annoyance at paying for unnecessary long distance connections when calls actually originate and are answered in the same city will also increase exponentially!

In addition, there is a possible saving in air time, since with positive answer supervision the call could be connected on a TACH only after it is answered by the called destination. One would not need to use the TACH channel to listen to busy or ringing tone.

TDMA vs. CDMA vs. FDMA

- Access technology debates between FDMA, TDMA (and later CDMA) are also called the “religious wars”
- My own conclusions: “Levine’s Laws of RF Access Technologies”
 1. The *inherent* traffic capacity of all 3 technologies is about the same
Proper Measure= conversations/kHz/km²
 2. Significant differences in implemented system capacity arise from secondary *non-access* features, for example:
 - Speech coder
 - Voice activity control (DSI combined with Frequency Hopping, TASI)
 Corollaries: a) there is a corresponding technological problem in every technology for each technological advantage. b) A good engineer can make *any* access technology into a working system
 3. The decisions regarding competing technologies depend on overall performance and economic criteria:
Measure: conversations/kHz/km²/\$ (equiv. capital or recurring costs)

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A lower bit-rate digital speech coder of equal quality obviously permits more conversations to share an overall link digital data transmission capacity having a fixed number of total bits per second.

Voice activity controlled channel assignment (also known as Digital or dynamic Speech Interpolation -- DSI -- or, in an older analog version Time Assignment Speech Interpolation -- TASI) is a technology which re-assigns a physical channel to a different user when the current user pauses during speech. Aside from silence on the part of one participant in a two-way conversation when the other participant is speaking, a typical “continuous” stream of speech is actually about 50 to 60% silence, due to pauses between syllables, phrases, etc. In theory, an increase in capacity of almost 2.5 could be achieved by completely utilizing all these silent intervals. In actual systems, the very shortest intervals are not always utilized effectively, so the improvement is under a factor of 2. The application of DSI also requires a large number of conversations to choose from, so the probability of all channels being in actual use instantaneously is very low. Otherwise there will be “clipping” of the beginning of syllables because an idle channel is not always immediately available.

DSI is used extensively on both undersea cable and satellite telephone channels. It is also effectively part of the design of the Qualcomm CDMA system (IS-95) and the Hughes Network Systems E-TDMA system, which is an enhancement to IS-54 and which can also be applied to GSM/PCS-1900 as well. When optional frequency hopping and discontinuous transmit is used with GSM, an increase in capacity similar to that achieved with DSI is also apparent, since the average RF interference is reduced in proportion to the amount of audio silence.

Note that DSI is not useful for digital data communication of long data transfers, in general. It is only helpful for speech or highly bursty data.

TDMA (GSM) Advantages

- **Economy of TDMA Base Station**
 - 8-channel transceiver costs about twice the cost of a single channel *analog* transceiver
 - Therefore, about 1/4 the cost/channel
- **Mobile Assisted Handoff**
 - Mobile station can tune to nearby RF carrier frequencies during idle TDMA time slots, report signal strength to system
 - No extensive “locating receiver” system as used in analog cellular
- **No simultaneous receive/transmit**
 - Bulk, Cost, Power Savings of RF antenna switching in MS
 - Better compared to duplexer filter

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Truly TDMA handsets, as used in GSM, PCS-1900, or IS-136 (digital mode only) can use an electronic antenna switch (usually implemented with a PIN diode) rather than a filter-type antenna duplexer. The PIN diode is smaller in size, somewhat lower in cost, and slightly more power efficient than a filter. The IS-54 dual-mode cellular mobile sets must be able to operate in a simultaneous Tx/Rx mode for the analog-type control channel and the analog voice channel, so they do not use any type of antenna switching.

In the debate between TDMA, CDMA and FDMA, no *major* systems currently use FDMA in the form of one conversation per narrow-band carrier. There are two systems in existence which meet this description, but their respective manufacturers appear to be supporting them to a much lower degree than other standardized approaches of the TDMA or CDMA variety.

One FDMA system is CT-2, and its Canadian second-generation version, CT-2+. The slow roll out of features leaves this in question. CT-2+ uses digital speech coding, and is intended as a low-tier (short range) semi-public PCS system. Its main advantage arises from the present relatively low cost home cordless base station available with the private/public handset. However, the cost of base stations for other technologies which provide public/private service is dropping so that this advantage is eroding. In addition, the full public capability of CT-2+ is only realized when there is an infrastructure of switching software which can provide both mobile destination calls as well as mobile originate calls. This is not yet available for CT-2+, although the handsets are designed to be capable of this when it is available. Meanwhile, systems like IS-91 (GTE Telego, etc.) provide both public and private answering and origination of calls, and thus have this feature before CT-2+.

Motorola's N-AMPS technology uses narrow band analog FM voice, and it has been installed in the 800 MHz cellular system in Las Vegas, NV. It is apparently not being promoted as a general cellular or PCS system. Several MicroTAC™ handsets are N-AMPS capable.

Is GSM the Future “winner?”

- In the instructor’s opinion, GSM is the most likely candidate for 2G worldwide adoption as an ultimate “universal” cellular technology standard
- GPRS/EDGE is most easily co-supported in the same base system with GSM
- EDGE Compact strategy, if carried out, will migrate GSM technology into the North American 800 MHz band, as well as other GSM radio bands elsewhere
- 3G technology, discussed in later lecture, theoretically able to provide up to 2 Mbit/s, may prove to be too costly to be popular.
 - 3G allows you to view a movie like “Gone With the Wind” on your handset or mobile PC, or download a large data base.
 - GPRS/EDGE allows you to see a complicated web page with no perceptible delay on your handset or mobile PC.
 - GPRS/EDGE is likely to be more cost effective for users needing higher bit rates up to ~384 kbit/s

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Low-tier Systems: DECT/DCT/PWT, WACS/PACS, CT2+

- **Historical Outgrowth of British CT-2 systems**
 - Short Range due partly to low RF power
 - Short range also implies simpler design
 - No timing adjustment in TDMA
 - Little or no error protection code
 - No adaptive equalization in handset
- **CT-2 was *not* a business success**
 - But main problems were not technology
 - Late development of a common air interface (CAI) contributed to demise in UK
 - Bad marketing, pricing, timing
 - Still in limited use in Singapore, Hong Kong, France, Germany, etc.

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Low tier systems are presently sold now only for limited range use, such as wireless PBX in an office, or limited use in special areas like the airport or a shopping center. However, due to the significantly lower cost of their infrastructure, they can be a direct competitor to PCS-1900 if sufficient number of networked closely spaced base stations are installed to cover the public areas of the city. They have the advantage that the handset is then a dual-use public/private handset for both office/home and also for public networks.

The original British CT-2 system had the limitation that one could only originate calls in the public domain, but not answer calls, because there was no network facility for call delivery. The original CT-2 handset could both originate and answer when used with a special base unit as a home cordless telephone *only*. All the new low-tier technologies have designed in capability to both answer and originate calls in the public domain, and all but CT-2+ have already demonstrated network capability to locate the handset and deliver calls to it.

Low-tier Technology survey

- **Objective is low cost, with intentionally less comprehensive service than cellular or high-tier PCS**
 - **Use of same handset as both home/office cordless set and public low-tier handset**
 - **Shorter range of coverage, incomplete geographical coverage in some systems**
 - Service only in heavily used public areas: airports, shopping malls, etc.
 - **Most low-tier systems have theoretical handoff capability, but some installations do not support it at this time**
 - **Most low-tier systems have theoretical originate-answer capability, but some installations (CT-2+) do not support public domain answer at this time**
- **Vendor support for low tier systems comes and goes. Currently (2001) on the “back burner”**
- **Several Low-tier systems use Time Division Duplex (TDD)**

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Low tier systems are generally designed to provide limited coverage for a high geographical user and traffic density at lower cost than public domain or high tier cellular or PCS systems.

Advantages of time division duplex (TDD)

- **TDD utilizes short RF bursts in alternate directions**
 - Digital storage buffer at each end produces continuous output
 - Burst digital bit rate is twice the continuous bit rate for single channel
 - 8 or 12 times for TDMA/TDD with 8 or 12 channels respectively
 - Paired spectrum channels (as in FDD) not required
 - any adequate contiguous single spectrum chunk will work
 - Use of same frequency in both directions permits use of a base station diversity method only
 - shared base duplexer for multi-channel system is less costly than an equalizer in every handset
 - Handset receiver benefits via base transmitter diversity, but...
 - quality of performance dependent on excellence of base diversity methodology
 - Tx diversity parameters based on prior time slot Rx properties
 - **Most low tier systems consequently limited to pedestrian handset speeds**
 - ~5 km/h (3 mi/h) is fast walking speed
 - Low tier systems perform well up to about 40 km/h (24 mi/h)

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TDD has many beneficial properties. Its most notable negative property is a limited ability (in existing implementations) to make timing adjustments for changes in propagation distance, and some mutual interference between base and mobile stations, since they both transmit on the same frequency. These problems can be overcome in future designs. Note for example that the ETSI W-CDMA system includes TDD as one feature.

Fixed wireless systems and related technologies:

- Too costly via most existing high-tier technologies
- **Some business exceptions:**
 - special short-term or interim uses
 - legal protection of service area to prevent loss of exclusive franchise
- **BETRS and other rural-radio-telephone systems (Ultraphone, etc.)**
- **Possible use of low-tier systems (DECT, PWT?)**
- **Specially designed fixed wireless systems (Ionica, DSC-Alcatel, etc.)**
- **Telephone service via cable TV facilities**
 - could be serious economic competitor

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Many other technologies have been proposed for general public PCS use. Some involve radio, others are alternative methods of wire transmission. Most of the radio systems based on cellular or other higher cost technology cannot compete reasonably with ordinary wire landline telephone. Only in special short term applications is high cost wireless useful. It is often installed only to temporarily provide service (such as after a hurricane or other widespread disaster) until replaced permanently by wired telephone service.

Review of technical and economic points of comparison:

- **Remember Geographic Spectral Efficiency: *conversations/kHz/sq.km***
- **And more important *Economic* geographic spectral efficiency: *conversations/kHz/sq.km/\$***
 - \$ represents equivalent capital or equivalent total recurring cost of all operations
- **Delivery calendar and product roll-out are very important: availability beats theoretical advantage in this game**
- **When heavy price competition breaks out, the most economical system with adequate capacity will ultimately dominate**
- ***Perhaps* the industry will gravitate to one main PCS technology *after* the year 2001**

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Remember these figures of merit for comparison of different systems, or even for comparison of two vendors selling the same technology! What counts is the proportional cost per conversation (and ultimately per customer, although that depends in turn on the amount of traffic load offered by each customer, which is beyond the scope of this presentation).