8 Cellular Networks -- From 1G to 5G

Case Study: Remote Stroke Diagnostic Center[1]

University of California, San Diego (UCSD) needed to diagnose and administer a specific life-saving drug remotely to counter and nullify the debilitating effects of a stroke. The drug is effective only if administered in the first three hours from the onset of the stroke symptoms. The main challenges for this remote drug administration were:

- Only a handful of physicians were sufficiently trained to perform the required diagnosis to determine prescription of the drug.
- The trained physicians were available at only one site. This prevented patients at remote locations from taking this life-saving drug.
- The diagnosis is based on the performance of certain physical routines/movements, so transmission and analysis of sheer numerical results accumulated from tests is not sufficient when the physician is at a remote location.
- The drug is suitable only for a very specific type of stroke: the one caused by a blood clot. Administration of the drug in any other situation would heighten the stroke and make subsequent treatment extremely difficult.

The hospital administration started examining different solution technologies. Conventional videoconferencing was not suitable because it required both parties to be at the ends of a single, dedicated wire; the doctor had to be on one end of the wire at a TV console and the patient had to be at the other end. Getting each party to these fixed ends of the wire often proved almost as difficult as getting a stroke expert to the patient on time. A new system was proposed with the following components:

- A camera that could be controlled remotely so that the distant physician could pan and zoom the lens. This would allow the neurologist to look at what she wanted, just as if she was in the room.
- In addition, the camera would be connected to a laptop that could go anywhere and would connect instantly via a cellular connection with another laptop. Either laptop could

---

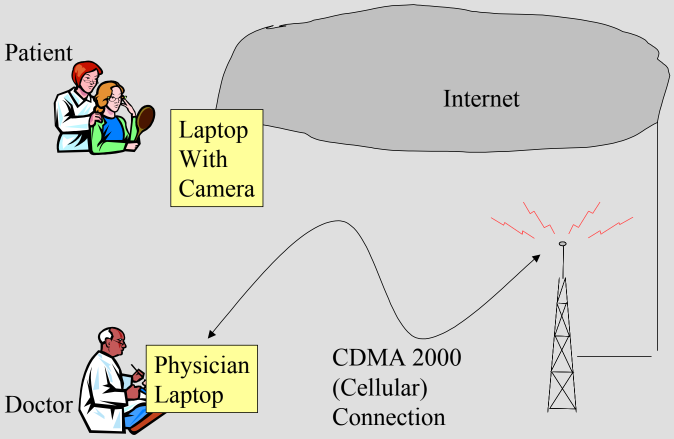
[1] Suggested by Sonal Gandhi

be at any location – an airport, a hospital, or a living room. Thus, in case of a stroke the camera and the laptop could be moved to the site where the patient was available.

- A data transmission rate of 10 megabits per second – the speed needed by the existing hardwired telemedicine systems in order to get the kind of video quality necessary for a correct diagnosis by the physician.

This system needed to integrate technologies in three distinct areas – video processing, real-time cellular packet-data transport, and medicine – to create a platform for remote diagnosis and treatment of acute medical conditions. The deployed system, shown in the figure below, provided an emergency room or clinic with access to medical specialists through a common laptop computer connected to the Internet via a QUALCOMM CDMA-2000 cellular network. It combined video compression and synchronization technologies for real-time video and medical telemetry over IP networks.

The data transmission requirements of the system were the most difficult to satisfy. The commercially available software was targeted toward transmitting video clips. For the video quality necessary to make a correct diagnosis, physicians needed a data transmission rate of 10 megabits per second on the existing hardwired telemedicine systems. Using a cellular system would need extensive compression. The engineering team wanted to reduce the data rate to one megabit per second so that then it could be carried over a 3G cellular network. This part of the challenge was met through collaboration with Path 1 Network Technologies, a company that had been independently developing a system to transmit DVD-quality video over a cellular network.



The UCSD staff developed its own software for encoding and transmitting high-quality video images. Shortly thereafter, the project team placed the new cellular telemedicine stations in five hospitals, as part of a study of the system's effectiveness. The method of operation consisted of the following steps:

- A suspected stroke patient arrives in the emergency room.
- The local physician activates the diagnostic tool, which essentially consists of a camera that can be controlled remotely (as mentioned above).
- Once a clear link is established, a live video of the patient is transmitted to a wireless laptop computer operated by the on-call member of the UCSD stroke team.
- The UCSD stroke specialist conducts the physical exam, consults with the community physician, and advises on whether the patient should be administered the drug or not.

The system is currently in operation and has already saved some lives. Eventually all community hospitals will participate in UCSD clinical trials that will utilize enhanced, broadband wireless Internet technology, dubbed the Multi-Media Telemedical Diagnostic

System.

Sources:

[1] Presentation by Dr. Ramesh Rao, UCSD, at University of Pennsylvania (Feb. 2004)

[2] http://www.cdg.org/news/events/CDMASeminar/031016/padovani.pdf

[3] http://health.ucsd.edu/news/2003/06_05_NINDS.html

8.1 Introduction

Cellular telephones and residential cordless telephones (wireless systems) were introduced in the mid-1980s. These technologies are enjoying widespread public approval with a rapidly increasing demand that has exceeded all early predictions. For example, AT&T predicted in the mid-1980s that there would be about 1 million cellular telephone users by the year 2000 [Ziegler 1993]. However, the number of cellular telephone users exceeded 12 million way back in 1994. The Cellular Telecommunications & Internet Association (CTIA) estimated that there were over 90 million cell phone US subscribers in 2000 and about 140 million in 2002. The CTIA predicts a yearly increase of about 10%. At a global level, the number of estimated subscribers exceeded 1 billion in 2003. This number is also expected to keep growing for several years to come.

The cellular networks are evolving through several generations (see Figure 8-1). The older generations (1G and 2G) provide lower data rates, while the new and future ones (3G and beyond) offer higher data rates. Although the cellular networks are going through rapid evolution, there are some common principles to all cellular networks. Section 8.2 discusses these principles that are the foundations of cellular networks. Sections 8.3 through 8.8 review the 1G through 4G systems and Section 8.11 introduces some cellular network engineering issues.

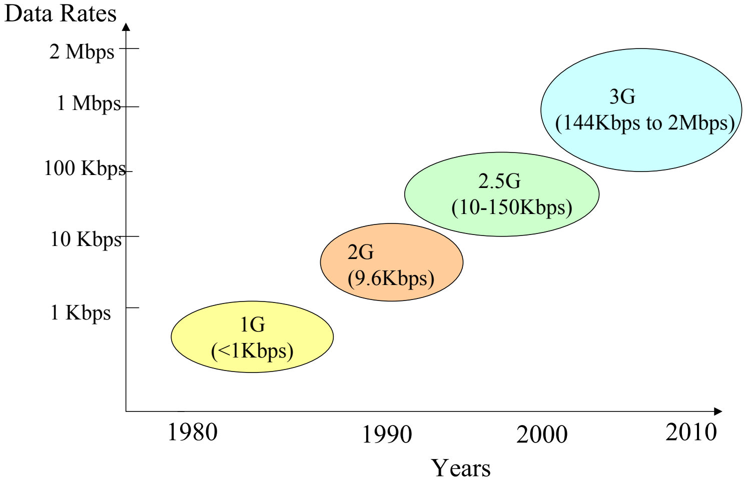


Figure 8-1: Evolution to 3G – A Technology-Independent View

Chapter Highlights

- The cellular network consists of many "cells," where each cell is managed by a Base Station (BS). A Mobile Switching Center (MSC) controls the entire cellular network**.** Frequency allocations and location management are two of the most important issues in cellular networks.
- **1G (First generation)** wireless cellular systems, introduced in the early 1980s, use analog transmission, and are primarily intended for voice. These networks are very slow – less than 1 kilobits per second (Kbps).
- **2G (Second generation)** wireless cellular systems, **i**ntroduced in the late 1980s, use digital transmission and are also intended primarily for speech. However, they do support fax and email services at low bit-rate (8 to 9 Kbps) data transmissions. The high-tier 2G systems use GSM (Global System for Mobile Communications) and the low-tier system is intended for low-cost, low-power, low-mobility PCS (personal communication systems). These systems, most prevalent at present, operate at 9.6 Kbps.
- **2.5G Systems** are essentially 2G systems that have evolved to medium data rate (around 100 Kbps). A popular example of the 2.5G initiative is the General Packet Radio System (GPRS), an extension of GSM, that supports data rates of 112 kilobits per second. Generally, 2.5G technologies have been developed for third generation (3G) networks, but they are applied incrementally to existing networks. This approach allows carriers to offer new high-speed data and increased voice capacity at much lower cost than deploying all new 3G networks. Plus, they can do so using their existing spectrum.
- **3G Systems** represent the completely digital cellular facilities that can operate at 2 million bits per second. 3G systems have evolved from 2G – thus dual-mode terminals to ease migration from 2G to 3G are commercially available. In addition to conventional voice, fax and data services, 3G promises to offer high-resolution video and multimedia services on the move. 3Gs are very complex systems intended to deliver many more services faster.
- **4G systems** are the next generation of cellular networks that promise to deliver up to 20 Mbps. 4G is mainly a marketing buzzword at present, with some basic research underway. The implementation target for 4G is around 2010, although some early implementations have been promised. For example, NTT Docomo is planing an implementation by 2006.
- Development and operation of cellular networks involves cellular network design, traffic engineering, and power engineering. Specifically, the allocation of frequency ranges, the number of users to be supported per cell based on traffic patterns, and adjustment of transmission power to assure that all users get strong and clear signals are discussed.

The Agenda
- Principles of Cellular Networks
- 1G, 2G, and 2.5G Cellular Networks
- 3G, 3G+, Cellular Engineering and Examples

8.2 Principles of Cellular Networks

8.2.1 Overview

Cellular networks are wireless WANs that establish a connection between mobile users. Figure 8-2 shows a high level view of a cellular communication network. The cellular network is comprised of many ***"cells"*** that typically cover 2 to 20 miles in area. The users communicate within a cell through wireless communications. A ***Base Transceiver Station (BTS***), also known as a ***Base Station (BS),*** is accessed by the mobile units in each cell by using wireless communications. One BTS is assigned to each cell. Regular cable communication channels can be used to connect the BTSs to ***the Mobile Switching Center (MSC),*** also known as ***Mobile Telecommunications Service Center (MTSC)***. The MSC is the heart of cellular networks – it determines the destination of the call received from a BTS and routes it to a proper site, either by sending it to another BTS or to a regular telephone network. Keep in mind that the communications are wireless within a cell only. The bulk of cell-to-cell communication is carried through regular telephone lines (wireless local loops can be used but are not essential). The MTSC uses two databases called ***Home Location Register (HLR)*** and ***Visitor location Register (VLR)*** to locate the mobile users. We will discuss location services and roaming support in a later section.

.

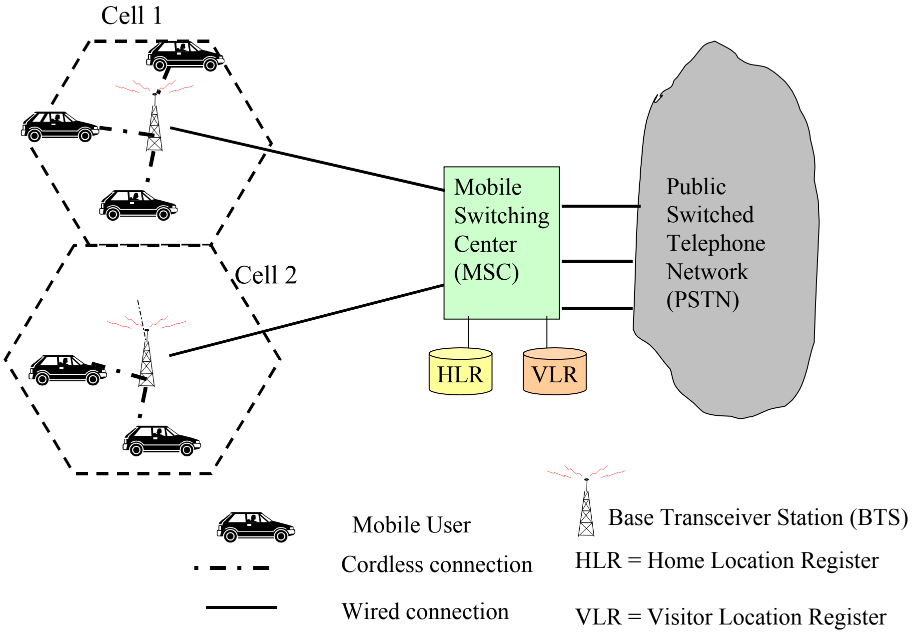


Figure 8-2: A Cellular Communication Network

The current cellular networks use many different and incompatible standards which rely on different frequency modulation techniques. The focus of the ***third generation wireless systems (3G Networks)*** is on a single network which combines a variety of wireless services. We will discuss 3G networks in Section 8.7.

Many initial cellular networks were predominantly analog because mobile communications were primarily targeted for voice users (e.g., cellular phones). However, the use of cellular networks to support digital applications is increasing rapidly due to the emphasis on mobile computing. In particular, as the use of laptop computers, palm pilots, PDAs, and sophisticated mobile devices increases, the need to communicate from these mobile devices to access the Internet and remote databases is also increasing. A collection of technologies have emerged to provide analog as well as digital services over cellular networks to support mobile users and applications. Although many of these technologies have found their space in the cellular space, GSM (Global System for Mobile Communications) and its upgrade (GPRS) are the most popular at present.

8.2.2 How Cellular Phones Work – A Quick Look

Each cell in a cellular network is assigned a band of frequencies. In general, 10 to 50 frequencies are assigned per cell. The allocated frequencies are divided into two types of channels: **control channels** that are used to set up and maintain calls, and **traffic channels** that are used to carry voice and data traffic. For the sake of simplicity, let us assume that each channel is assigned a unique frequency and that one user can only use one channel. For example, if the frequency band of a cell is subdivided into 30 traffic channels, then only 30 users can talk simultaneously. User 31 is blocked and gets a busy signal. This model changes somewhat, as we will see, when we use CDMA systems. The user of a phone goes through the following steps (see Figure 8-3):

User Initiation:

- The user turns on the phone and scans for the strongest control signals from the various BTSs.
- It detects and selects the BTS with the strongest control signal as its “home cell.” In most cases, a user is assigned to the closest BTS.
- The selected BTS informs the MSC about location of the user. The MSC then “registers” the user in a directory to indicate its location.

Cellular to Cellular Call:

- The cellular user places a call; the BTS finds a free traffic channel and then routes the call to the MSC for call-setup.
- The MSC finds and pages the called user by using the location services (see Section 8.2.5).
- The called user’s BTS receives the page and uses its setup control channel to be scanned by the mobile units.
- The called mobile unit detects its number when it scans the setup channel and responds to its BTS to accept the call.
- The BTS now informs the MSC of the call acceptance. The MSC determines that a free traffic channel is available on both sides and enables the call. If free traffic channels are not available, the user gets a busy signal.

Cellular to PSTN Call:

- The cellular user places a call; the BTS finds a free traffic channel and then routes the call to the MTSO for call-setup.
- The MTSO finds that the called user is not part of the cellular network (by looking into its directories – HLR and VLR).
- The MTSO directs the call to the PSTN, used for regular telephone calls.
- The called phone responds to the telephone switch to accept the call.

- The telephone switch now informs the MSC of the call acceptance. The MSC determines that a free traffic channel is available on the cellular side and enables the call. If a free traffic channel is not available, the user gets a busy signal.

PSTN to Cellular Call:

- The PSTN user places a call; the PSTN determines that the called number is not part of the PSTN and routes the call to an appropriate MSC for call-setup. This implies that PSTN and cellular network operators have to know about each other and route calls between them.
- The MSC finds and pages the called user by using the location services (see Section 8.2.5).
- The called user's BTS receives the page and uses its setup control channel to be scanned by the mobile units.
- The called mobile unit detects its number when it scans the setup channel and responds to its BTS to accept the call.
- The BTS now informs the MSC of the call acceptance. The MSC determines that a free traffic channel is available on both sides and enables the call. If free traffic channels are not available, the user gets a busy signal.

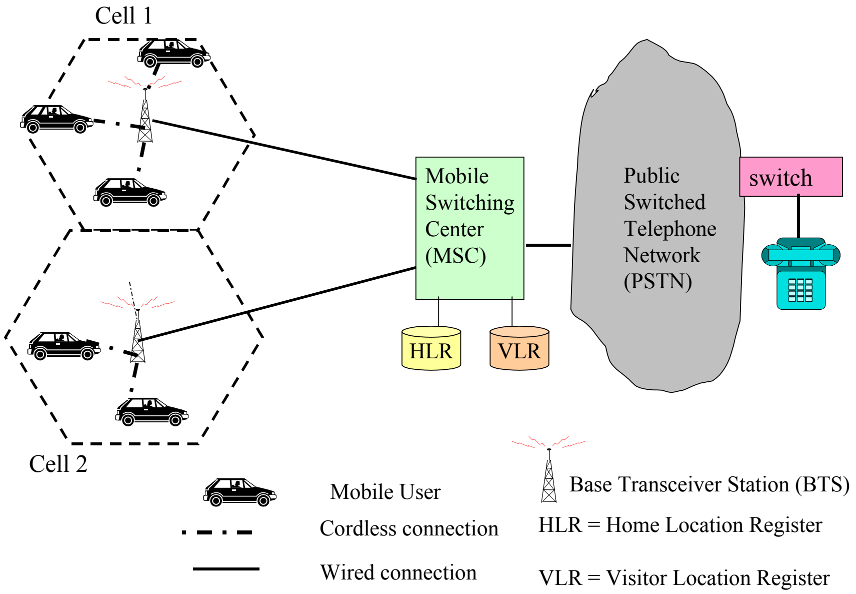


Figure 8-3: A Cellular Network

Handoffs:

- If one of the mobile units moves from one cell to another during the call, then handoff processing takes place.
- The mobile unit detects and selects the BTS with the strongest control signal as its "home cell."
- The selected BTS informs the MSC about location of the user. The MSC then "registers" the user in a directory to indicate its location.
- The user is assigned a new channel in the new cell and now the calls are routed to the new cell.
- All this processing takes place without any interruption.

Call Termination:

- The two users communicate by using the traffic channels.
- When the user hangs up, the traffic and control channels are freed.

Special Situations:

During the aforementioned procedure, the following situations can occur:

- Calls can be blocked if no free traffic channels are available. As a result, the user is given a busy signal.
- Calls can be dropped if the quality of signals is too low or the noise is too high on the traffic channels for the BTS to keep a conversation going.
- Calls can be routed from the PSTN to the cellular network and vice versa.

8.2.3 Highlights of Cellular Networks

Let us capture the highlights of cellular networks by using our, by now, familiar framework of data rates/distance covered, target applications, frequency allocation, location management, and physical communications shown in Table 8-1.

8.2.3.1 Data Rates and Distance Covered

Data rates range from 9.6 Kbps to over 1.2 Mbps depending on 1G to 3G. Distance covered in a cell ranges from 5 miles to 20 miles (newer systems have smaller cell sizes). For example:

- 1G networks provide less than 1 kilobits per second (Kbps) data rate that can go over 20 miles.
- 2G networks operate at 9.6 Kbps with distance between 20 to 15 miles. .
- 2.5G networks support data rates of 112 kilobits per second over 2G distances (these systems are built on top of 2G).
- 3G networks can theoretically support data rate up to 2 Mbps cover distances in the 5 mile range.
- 4G and 5G cellular networks are planning to support data rates between 30 Mbps to over 50 Mbps, but over very short distances (less than a mile).

8.2.3.2 Target Applications

The applications targeted for cellular networks differ dramatically from the data-centric applications of WLANs and WPANs. In contrast to LANs where the primary application is data and Internet access, voice is the predominant application in cellular networks. It is, after all, voice that made the cellular phones popular. The 1G cellular networks were primarily used for voice applications. The 2G networks started supporting fax and SMS (Short Message Services) in addition to voice, and the 3G networks are intended to support the MMS (Multimedia Messaging Services). This difference in application emphasis drives many of the design decisions we will discuss.

8.2.3.3 Frequency Allocations

The cellular networks operate in licensed frequency bands roughly between 900 MHz and 2 GHz. There are several implications of this. First, the cellular operators compete with each other for frequency allocations because the bandwidths, and consequently data rates, of communication channels are restricted by government regulations. Because of this, cell design for efficient frequency utilization is a major concern (see Section 8.2.4). An additional implication is that universal adoption of cellular technology is contingent upon international agreements between various licensing agencies. For example, 2G and 3G networks operate at different frequency bands in the US and Europe due to the differences in FCC versus

European regulations. This creates interoperability problems. As another example, one of the main roadblocks to 4G cellular is that the major participating countries cannot agree on a frequency band. Thus progress to new technologies can be also blocked.

8.2.3.4 Location Management

It is important to keep track of cellular users, since the location of a sender/receiver is unknown prior to the start of communication and can change during the conversation. In particular, rapid changes in location can occur because the cellular users can be traveling in cars and trains. Due to this, handoffs between cells must be handled very efficiently.

The cellular systems have to keep track of the users as they move around rapidly through the cells. As discussed in Chapter 5, a wide range of techniques for location management have been introduced in cellular networks. Examples of the techniques include:

- **Cell ID-based location**. Each user is assigned an ID for the cell that he is in. This Cell ID is stored in a database. As the use moves from one cell to another, he is assigned a different Cell ID and the location database is updated. This technique is most commonly used in cellular networks.
- **Angle of arrival (AOA).** The angle at which radio waves from your device “attack” an antenna is used to calculate the location of the device. This is somewhat similar to the police work where they can tell the location of a suspect by studying how the bullet entered a body (a horrible but illustrative example).
- **Estimated Time and Signal Strength.** The time taken between the device and the antenna is used to calculate the location of the device. Alternatively, the signal strength can be also used to estimate the distance (the signal gets weaker with distance).
- **Network-assisted Global Positioning System (GPS)**. A GPS chip is installed inside a phone and thus the location of the user is tracked. GPS-based location services are quite accurate but require some time to set up. This time may be too much for an emergency call such as 911.

These and many other techniques yield different location accuracies (typical ranges are 50 meters to over 700 meters). The most commonly used location-management schemes in cellular systems are based on Cell ID. We take a closer look at these approaches in Section 8.2.5.

8.2.3.5 Physical Communications

For multiple access mechanisms, the users of cellular networks need special mechanisms to avoid interference and collisions. For example, if several users within a cell turn their telephone on at the same time, how do you assure that they do not interfere with each other? The three mechanisms used most commonly in cellular networks are:

- Frequency division multiple access (FDMA), used in 1G cellular networks
- Time division multiple access (TDMA), used in the very popular 2G systems (GSM)
- Code division multiple access (CDMA), used in some 2G but primarily in the 3G networks

These three schemes were discussed in Chapter 5. Section 8.2.6 gives cellular-specific details.

The users of the cellular networks need special mechanisms to avoid interference and collisions since the communication channel between senders/receivers is often impaired by noise and interference. To address these issues, a wide variety of error detection and correction techniques have been introduced over the years. We also reviewed these in Chapter 5. Cellular networks typically use forward-error-correction techniques and are expected to use Turbo Codes in the future. In addition, a combination of PSK and FSK are used in cellular networks. Future systems are increasingly relying on OFDMA at lower layers. In addition, pulse code modulation (PCM) is used frequently to support voice applications.

Table 8-1: Basic Information about Cellular Networks

Factor	Decisions in Cellular Networks
Data Rates and Distance Covered	Data rates range from 9.6 Kbps to over 1.2 Mbps depending on 1G to 3G. Distance covered in a cell ranges from 5 miles to 20 miles (newer systems have smaller cell sizes)
Target Applications	Mainly voice in 1G, but moving to fax and data applications in 2G, 3G and beyond
Frequency Allocations	Mostly between 900 MHz to 2 GHz
Location services	Mobility is users is high so location services are of crucial importance by using Cell ID GPS, or other services.
Physical communications, Signal encoding, Error Correction	FDMA in older systems, TDMA/CDMA now, CDMA in the future Forward error correction, a combination of PSK, FSK, and PCM. OFDMA in the future.

8.2.4 Cell Design and Frequency Utilization

Most cells are between 2 to 20 miles in radius depending on the population density and the strength of the signal. Some cells are smaller (1.5 km appears to be a practical small limit) while the others are larger (in fact a geosynchronous satellite can be thought of as a large cell that can cover around 13,000 kilo meters). Each cell is served by a base transceiver station (BTS), commonly known as a base station, consisting of transmitter, receiver, and a control unit. Base station (BS) antennas are placed in high places such as churches and high rise buildings. In several large cities, wireless operators pay around $500 per month for a base station (yet another way for the landlords to make more money in large cities!). Cells are set up such that antennas of all neighbors are equidistant from a base station. This is why hexagonal patterns are used to represent cells.

Frequency reuse is a major issue in designing a cellular network. Consider, for example, a cellular operator that obtains a license for frequency F to support a cellular network in a 10,000 square mile (100x100) area. The provider may decide to treat the entire area as one large cell. This implies the following:

- The entire frequency band F is dedicated to this region.
- All customers in this region will have to be supported by frequency F. If too many users log on, the frequency will be used and the users will be disconnected.
- A very powerful transmitter will be needed at the BTS to cover the area.
- Powerful batteries also will be needed in each handset so that they can communicate with the BTS.

Thus, it is better for the providers to divide up the area into smaller cells that can support more users with smaller, less powerful, handsets. Figure 8-4 shows a general approach used in reusing frequencies. Basically cells are grouped into a cluster of seven. Letters in each cell indicate the frequency being used. It can be seen that for each frequency, a buffer of two cells is used before reuse. Thus each cluster can reuse the same frequencies. To add more users, smaller cells (microcells) are used. However, cells that are too small lead to too many handoffs. Thus a tradeoff between cell size and number of handoffs is needed. In most cases, 10 to 50 frequencies are assigned to each cell.

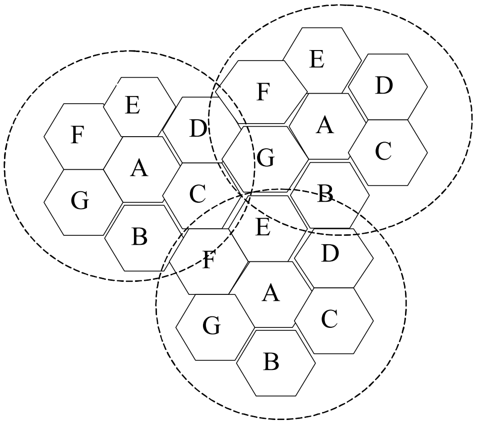


Figure 8-4: Allocating Frequencies in a Cellular Network

Once the cells have been designed, several adjustments still need to be made. Naturally, some cells are busier than others because of user population differences. Approaches to increase cell capacity are needed on a regular basis. Examples of these approaches are:

- Adding/reassigning channels by recognizing that some channels are not used
- Frequency borrowing – frequencies are taken from adjacent cells by congested cells
- Cell splitting – cells in areas of high usage can be split into smaller cells
- Cell sectoring – cells are divided into a number of wedge-shaped sectors, each with their own set of channels
- Microcells – antennas move to buildings, hills, and lamp posts

Design of cells by itself is a large area of work. See [Mark 2003] for additional details.

8.2.5 Location Services and Roaming Support

8.2.5.1 Why Location Services are Important in Cellular Networks

Location services, commonly known as location-based services (LBSs), are of great importance for two reasons: they are essential for directing mobile user calls to their target cells as the users move around, and they are also expected to generate revenues for cellular operators. LBS is a value-added service that utilizes the user's position information for customer benefit. In fact, LBS is expected to generate as much as $15 billion in revenues and is positioned to be the most popular service by 2005 [Jagoe 2002]. This technology has been regarded as a way for wireless operators to expand their service offerings, helping them to retain and attract customers while creating completely new sources of revenue. LBS is expected to provide services such as the following to meet the regulatory, business, and technological initiatives [Jagoe 2002]:

- FCC-mandated E911 service in the US, as well as the equivalent European Union requirements for E112 service, for emergency and public safety.
- Positional commerce services; i.e., is there a sales on clothes within 5 miles of where I am? Positional information, as an add-on to mobile commerce, is expected to generate tremendous revenues for wireless operators.

- Enhanced directory services that provide directions and maps based on location, i.e., is there a McDonald close by? This also includes transportation schedules based on location; i.e., which busses can I catch from here?
- Additional services such as child locator, medical alert, asset tracking, stolen car recovery, traffic management, and friend finder that rely on location information

However, extensive use of LBS can lead to loss of user's privacy, and mobile advertising based on the user's location is a sensitive issue. The potential loss of privacy versus the possible benefits of LBS will be an active area of discussion for a while.

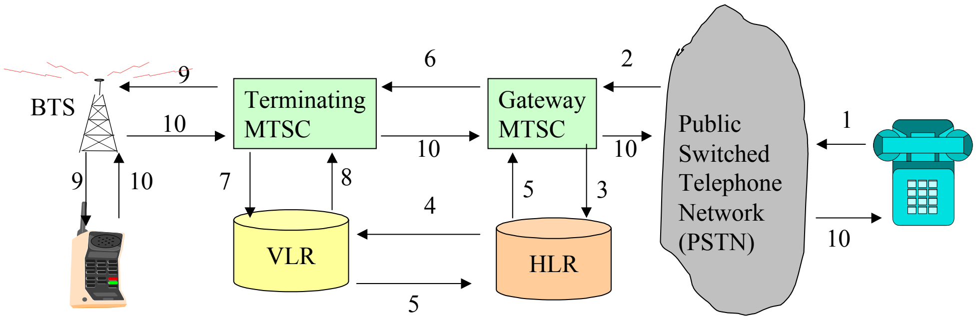
We discussed the various technologies to support LBS (e.g., cell-based, AGPS, AOA, UTDOA, EOTD) in Chapter 5. Let us take a closer look at the very popular cell-based LBS.

8.2.5.2 How Cell-based Location Services Work

The cellular systems use Cell ID to keep track of the cellular user by coordinating the home location register (HLR) and visiting location register (HLR) databases (see Figure 8-2). Here is a simplified view. Suppose you live in Princeton, New Jersey; your HLR will indicate that Princeton is your home town and the Princeton VLR will have an entry for you because you make most of your calls, one assumes, from Princeton. Every time you turn on your cellular phone in Princeton, the BTS communicates with the MTSC to verify that you are still in Princeton, so no location updates take place. Let us assume that you travel from Princeton to Philadelphia. Upon arrival in Philadelphia, you turn on your cellular phone. The cell phone will now communicate with a BTS in Philadelphia that will inform the MTSC about your new location. Basically, now the HLR and VLR will be updated by the MTSC to indicate that you are in Philadelphia so that the incoming calls can be routed to you.

How does it work? When a mobile unit (a cellular phone) crosses a cell boundary, it starts communicating with the new BTS, which automatically sends its location update request to the new cell's MTSC. The MTSC updates the HLR to indicate the new VLR (i.e., now your HLR indicates that your VLR is in Philadelphia). In addition, the Princeton VLR is updated to "cancel" your visiting status. Thus your HLR will indicate that you are in Philadelphia now, as indicated in your VLR.

But how are the calls routed in a cellular system? Figure 8-5 shows a conceptual view of how the cellular system routes the calls to the mobile users who roam from one cell to another. This figure is based on call routing in GSM. In step 1, a telephone user places a call through the public switched telephone network (PSTN) to a cellular phone (think of your friend calling your cellular phone number from her/his office). The call is routed to a gateway MTSC (step 2) which examines the dialed number and determines that it cannot route the call. It interrogates the customer's home location register (HLR) in step 3. The HLR in turn asks the visiting location register (VLR) where the user is currently visiting (step 4). The VLR returns a routing number in step 5 that is sent back to the gateway MTSC. Based on this information, the gateway sends the information to an appropriate MTSC in step 6. The terminating MTSC queries the VLR once again for verification and then sends a paging call to the cellular phone in steps 7, 8, and 9. The call is completed in step 10.



1. Call made to mobile unit (cellular phone)
2. Telephone network recognizes number and gives to gateway MTSC
3. MTSC cannot route further, interrogates user's HLR
4. Interrogates VLR currently serving user (roaming number request)
5. Routing number returned to HLR and then to gateway MTSC
6. Call routed to terminating MSC
7. MTSC asks VLR to correlate call to the subscriber
8. VLR complies
9. Mobile unit is paged
10. Mobile unit responds, MTSCs convey information back to telephone

Legend: MTSC= Mobile Telephone Service Center, BTS = Base Transceiver Station
HLR=Home Location Register, VLR=Visiting Location Register

Figure 8-5: Call Scenario from a Regular Phone to a Cellular Phone

8.2.5.3 Roaming Support

The term roaming is used frequently in cellular networks. Roaming is in reality a *business agreement* between network operators to transfer items such as call charges and subscription information as their subscribers roam into each other's areas. How does roaming really work? All GSM-enabled phones have a "smart card" inside the handset called the Subscriber Identity Module (**SIM**). The SIM card is personalized to the subscriber – it identifies the subscriber's account to the local network. For example, when I bought my GSM cellular phone, the salesman took about half an hour to initialize my SIM card. The net effect is that I get billed no matter where I am (sometimes technology is simply too good!).

SIM cards are not only used for roaming support but they are also being used for secure transactions. For example, a purchasing application on the server side can use the SIM card to identify and authenticate the user.

Roaming is well established in Europe and now is becoming available in North America and parts of Asia. For example, in North America, all the major GSM operators have roaming agreements with each other via the North America GSM Alliance, covering most of the major population centers. The basic idea is to create a global roaming infrastructure for GSM whereby you can roam around the globe and be promptly paged, and billed for it.

8.2.5.4 Additional Comments and Observations about LBS

Different location-based technologies offer different performance characteristics and can support various location-based services differently. Table 8-2, reproduced from Chapter 5, shows a comparison of the main location-based services in terms of two main parameters: accuracy and mobile device capabilities needed. As can be seen from this table, Cell ID-based systems are not very accurate but they require no handset capabilities. These services could become more accurate as the cell sizes decrease in the 3G and 3G+ systems. The AGPS systems are a good alternative but require special capabilities at the handset. As discussed in Chapter 5, UTDOA appears to be a promising alternative at present.

Table 8-2: Comparison of Location Services

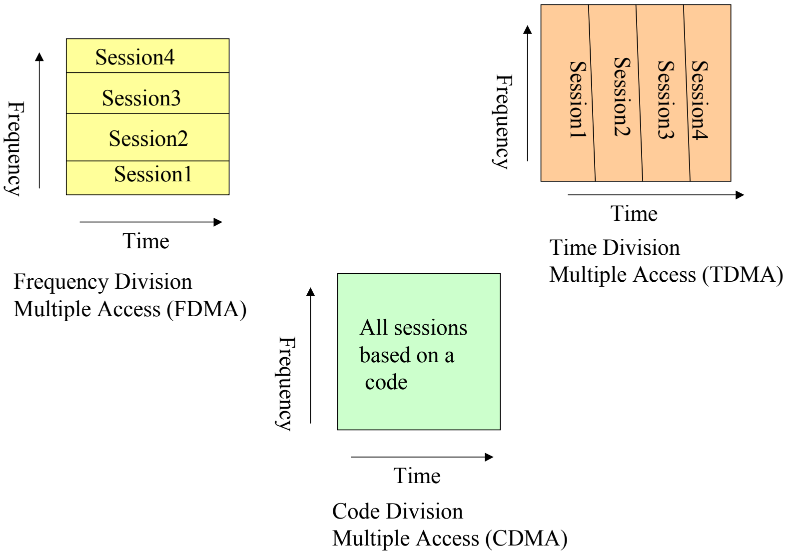
Location Service Approach	**Accuracy**	**Mobile Device Capabilities Needed**
Cell ID-Based	Depends on cell size (between 5 to 20 Km)	None – Network-Based
AOA (Angle of Arrival)	100 to 200 meters	None – Network-Based
AGPS (Assisted Global Positioning System)	10 to 50 meters	Yes – Mobile Device-Assisted
E OTD (Enhanced observed time difference)	100 to 150 meters	Yes – Mobile Device-Assisted
UTDOA (Uplink time difference of arrival)	50 to 100 meters	None – Network-Based

In addition to these LBS technologies, completely different approaches are being developed to solve other LBS problems. One of the major problems in LBS at present is that the users have to type address coordinates in terms of street address, city, state, country, zip code, etc. More than 80% saving of input keys can be obtained by using Natural Area Coding Systems that allow users to input only eight characters (Universal Address) to specify any location on the earth. In addition, the user types four characters (Natural Area Code) instead of country, province and city names to specify any area in the world. The Universal Addresses and Natural Area Codes are in alphanumeric characters, thus they can be input on all cell phones to eliminate the difficulty of inputting addresses and place names with special or foreign characters. Universal Addresses and Natural Area Codes can help people to specify any areas in the world for wireless location-based services, no matter where they are and whether they have names or not. The major problem with such systems is user acceptability. See Shen [2003] for a discussion of this topic.

For additional information on LBS, see the book by Jagoe [2002] and the information on the website, http://palowireless.com/lbs/.

8.2.6 Multiple Access Techniques and Transmission Errors

The three multiple access techniques (FDMA, TDMA, and CDMA) are illustrated in Figure 8-6. In an FDMA scheme, the different cellular users are assigned different frequencies and each user communicates in parallel on a different frequency. In a TDMA scheme, the users take turns, i.e., they are assigned different time slices. In CDMA, everyone talks at once by using a code. For example, a user u1 uses code c1, u2 uses c2, etc. In this case, the listener has to know the code of the sender, otherwise she gets a background noise signal. These techniques were discussed in Chapter 5. FDMA is used in older 1G systems but TDMA and CDMA are competing in the 2G and 3G systems, with CDMA being favored for 3G. We will discuss the tradeoffs between TDMA and CDMA in Section 8.5.5.



Frequency Division Multiple Access (FDMA)

Time Division Multiple Access (TDMA)

Code Division Multiple Access (CDMA)

Figure 8-6: Multiple Access Techniques

Besides multiple access considerations, the other problem cellular networks face is the unpredictable transmission characteristics of typical cellular channels. Unlike WLANs that operate in office buildings, cellular networks have to deal with the wireless transmissions in open air. This introduces extreme variability in received signal strength (fading) and arrival time.

The core problem is that multipath propagation occurs as a result of transmitted signals being reflected off objects (most commonly buildings) before they reach the receiver. Thus multiple copies of the transmitted signal arrive at the receiver at different times. Some of these signals have constructive effects (they strengthen each other) while others have destructive effects (they cancel each other).

The challenge in current cellular network designs is that the available frequency spectra are limited and the capacity of the system is increased by exploiting frequency reuse, at the expense of signal interference. This, and other signal quality challenges are addressed, to varying degrees of success, through the use of FEC (forward error correction), adaptive equalization, spread spectrum, and other techniques discussed in Chapter 5.

Time to Take a Break

✓ • Principles of Cellular Networks
• 1G, 2G, and 2.5G Cellular Networks
• 3G, 3G+, Cellular Engineering and Examples

8.3 First Generation (1G) Cellular

Mobile radio telephones were used for military communications in the early 20th century. Car-based telephones were first introduced in the mid-1940s. In fact, the first car-based telephone system was tested in Saint Louis in 1946. This system used a single large transmitter on top of a tall building. A single channel was used for sending and receiving. To talk, the user pushed a button that enabled transmission and disabled reception. Due to this, these became known as "push-to-talk" systems in the 1950s. Although these systems are quite old, taxis and police cars use this technology. To allow users to talk and listen at the same time, ***IMTS (Improved Mobile Telephone System)*** was introduced in the 1960s. It used two channels (one for sending, one for receiving – thus there was no need for push-to-talk). IMTS used 23 channels from 150 MHz to 450 MHz.

First-generation cellular networks were introduced in the 1980s. This started with the ***Advanced Mobile Phone Service (AMPS)*** that was invented at Bell Labs and first installed in 1982. AMPS has also been used in England (called TACS) and Japan (called MCS-L1). The key idea of 1G cellular networks is that the geographical area is divided into cells (typically 10-25km), each served by a "base station." Cells are small so that frequency reuse can be exploited in nearby (but not adjacent) cells. This allows many more users to be supported in a given area. For example, as compared to IMTS, AMPS can support 5 to 10 times more users in the same 100-mile area by dividing the area into 20 smaller cells that reuse the same frequency ranges. In addition, smaller cells also require less powerful and cheaper, smaller devices to transmit and receive information.

1G cellular networks are based primarily on analog communications. In North America, two 25 MHz bands are allocated to AMPS – one for transmission from base to mobile unit and one for transmission from mobile unit to base. Each phone has a 32-bit serial number and 10-digit phone number in its PROM (programmable read-only memory). When a phone is turned on, it scans for control signals from BSs:

- It sends this information to the BS with strongest control signal and the BS passes this information to MTSO as a packet.
- The subscriber initiates a call by keying in a phone number and pressing the send key.
- The MTSO verifies the number and authorizes the user.
- MTSO issues a message to the user's cell phone indicating send and receive traffic channels.
- MTSO sends a ringing signal to the called party.
- Party answers; MTSO establishes the circuit and initiates billing information.
- Either party hangs up; MTSO releases the circuit, frees the channels, and completes billing.

Security Issues with 1G. Analog cellular phones are insecure. Anyone with an all-band radio receiver can listen in to the conversation. Many scandals have been reported in this area. There are also thefts of airtime. Basically, a thief uses an all-band radio receiver that is connected to a computer. This computer can record the 32-bit serial numbers and phone numbers of subscribers when calling (recall that this information is sent as a packet). The thieves can collect a large database by driving around and can then go into business by reprogramming stolen phones and reselling them.

8.4 Paging Networks

8.4.1 What are Paging Networks?

Paging networks are one of the oldest wireless technologies. They support one-way and two-way alphanumeric messages between callers and pagers ("beepers"). The callers typically call a beeper company and leave a phone number and possibly a short message. Paging networks are being integrated with PDAs (persanal digital assistants) like Palm Pilots. An example of paging networks is the BellSouth Clamshell Pager with keyboard.

Paging networks require little bandwidth since each message requires only a single burst of perhaps 30-40 bytes. Thus a satellite with 1 Mbps can handle about 240,000 messages per minute. Older paging protocols operated at 1.2 Kbps (kilobits per second) per channel. Newer protocols such as FLEX (one-way) and ReFLEX (two-way) provide 6.4 Kbps per channel. Paging networks typically operate in the 930-932 MHZ frequency range and are not growing dramatically because paging is now being provided by other devices. Some forecasts at the time of this writing predict that US paging growth will plateau at 20% penetration.

8.4.2 Characteristics of Paging Networks

Paging networks have been around for a while and were among the first wireless networks used for sending numeric and alphanumeric messages to external devices carried by mobile workers. These are specialized wireless networks for broadcasting a message to a specific pager to call back a specific number. Figure 8-7 shows a conceptual view of paging networks. The paging network provider (paging operator), such as Skytel, runs a paging control center which receives paging requests from regular phones, cellular phones, or other pagers and routes them to their destination pagers. The paging BTSs (Base Transceiver Stations) are connected to the paging control center through leased lines or wireless links such as satellites or wireless local loops.

The paging networks come in two flavors: one-way paging networks and two-way paging networks. The two-way paging networks allow pre-defined messages to be sent back by the receiver of the message. The commercial paging operators can establish a network that meets subscribers' requirements and supports a wide range of paging devices. The paging devices can be equipped with sophisticated features such as priority paging, group paging, voice paging, voice prompts, and remote transmitter control.

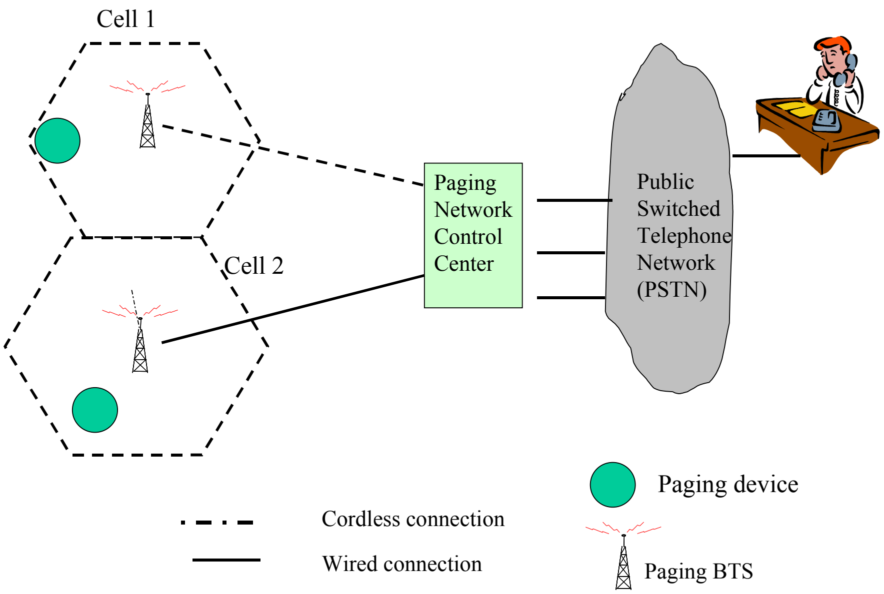


Figure 8-7: Conceptual View of a Paging Network

Here are a few characteristics of the paging networks:

- Common applications are personal numeric messaging for call-back, alphanumeric messaging (dispatching and service), and two-way messaging (call dispatching with confirmation).
- Capacity and speed includes 1200 bps for older and 6400 bps for newer systems. The paging networks are slower but have different design criteria for delivering the message within specific time periods.
- Frequency bands used include 800 MHz for older paging networks and 901-941 MHz, with gaps, for newer networks.
- Components of a paging network are a personal paging device, a paging computer/server at the paging operator's site, and a paging transmitter. These networks may also use satellites for national coverage.
- Coverage is 95% of the US, thanks to many local, regional and national paging network providers.
- Communications protocols supported include FLEX and ReFLEX developed by Motorola for two-way paging.
- Security is low and has not been considered a high priority.

The advantages of paging networks are:

- Very inexpensive
- Easy to operate for sender (from any telephone) and receiver
- Many options for users (numeric, alphanumeric, two-way, message storage)
- Wide coverage at local, regional , national, and international levels
- Good building penetration

The limitations of paging networks are:

- Slow data transfer rate (1200 bps)
- No acknowledgment (two-way paging costs extra)
- Some of the available paging networks are overloaded, causing delays.

8.5 Second Generation (2G) Cellular Networks

8.5.1 Overview

Second Generation (2G) cellular networks, introduced in the late 1980s, are based on digital transmission. Digital transmissions offer several benefits over analog (see the sidebar "Advantages of Digital Communications for Wireless"). Different approaches to 2G have been developed in the US and Europe. In the US, divergence happened because only one player (AMPS) existed in 1G. Because of this, several players emerged to compete in 2G. Although many players emerged, the following two have survived in the US:

- IS-54 and IS-135: backward-compatible with AMPS frequency allocation (dual mode – analog and digital)
- IS-95: uses spread spectrum

In Europe, exactly the reverse happened – there was a convergence because there were many (more than 5) incompatible 1G systems with no clear winner. This caused a major problem for the users (you could not use your telephones while traveling from England to France). European PTT (Post, Telephone and Telegraphic) sponsored development of the now very popular GSM that uses new frequency ranges and complete digital communication.

The primary differences between first and second generation cellular networks are:

- Digital traffic channels – first-generation systems are almost purely analog; second-generation systems are digital.
- Encryption – all second generation systems provide encryption to prevent eavesdropping.
- Error detection and correction – second-generation digital traffic allows for detection and correction, giving clear voice reception.
- Channel access – second-generation systems allow channels to be dynamically shared by a number of users.

Advantages of Digital Communications for Wireless

- Voice, data and fax can be integrated into a single system.
- Better compression can lead to better channel utilization.
- Error correction codes can be used for better quality.
- Sophisticated encryption can be used.

8.5.2 GSM (Global System for Mobile Communications) – The Popular 2G System

8.5.2.1 GSM Highlights

Although there are many competing technologies in the 2G cellular network landscape, GSM by far dominates the world today, with over 200 million users in over a hundred countries. GSM is very popular in Europe and is now gaining popularity in the US also. These networks operate at 9.6 Kbps and are based on international standards defined by the European

Telecommunications Standards Institute (ETSI). Due to the popularity of GSM, let us look at GSM somewhat closely.

GSM is completely designed from scratch (there is no backward compatibility with 1G systems such as AMPS). It can deliver data rate up to 9.6 Kbps by using 124 channels per cell; each channel can support 8 users through TDMA (maximum 992 users per cell, in practice about 500). Some GSM channels are used for control signals for mobile units to locate the nearest base stations.

In addition to voice, GSM phones provide data services for wireless users; i.e., you connect your GSM phone to your PC and it acts as a modem for email, fax, Internet browsing, etc. GSM also permits roaming between North American countries and European countries. To make it work, because of the frequency differences, you have to remove the user-specific SIM card from inside the American network's phone and place it into a European network's phone, or vice-versa. However, multi-band cards are available that operate in the US as well as on European frequencies (see the discussion below).

GSM's air interface is based on narrowband TDMA technology, where available frequency bands are divided into time slots, with each user having access to one time slot at regular intervals. Narrowband TDMA allows eight simultaneous communications on a single radio multiplexer and is designed to support 16 half-rate channels.

8.5.3 Using GSM and GSM Roaming Support

GSM networks presently operate in the following three frequency ranges:

- **GSM 900** (simply known as GSM) – operates in the 900 MHz frequency range and is the most common in Europe and the world.
- **GSM 1900** (also called PCS-1900, or DCS-1900) – the only frequency used in North America for GSM. Note that the term PCS is commonly used to refer to any digital cellular network operating in the 1900 MHz frequency range, not just GSM.
- **GSM 1800** (also called PCN or DCS-1800) – operates in the 1800 MHz frequency range, and is found in a rapidly increasing number of countries including France, Germany, Switzerland, the UK, and Russia.

Dual-band (900-1800 and 900-1900) phones and tri-band (900-1800-1900) are available to provide support everywhere.

What does it mean to the end users? Let us assume that you have a single-band GSM 1900 phone. This phone will only work in North America. But after landing in Europe, you can transfer your **SIM** (Subscriber Identity Module) card to a phone of the correct frequency. This is called SIM-roaming. It means that once you arrive in Europe, you must rent a GSM phone from a local network operator so that you'll have a phone that uses the correct frequency. Then you simply take the SIM out of your home phone and insert it into the rented phone (please do remember to take your SIM card back!). SIM-Roaming offers the advantage of letting you use your home phone number and being billed to your home account. Make sure that your local network operator has a roaming agreement with the destination country. Many North American companies have roaming agreements with countries abroad; some do not.

Once in Europe, you do not need to get new GSM phones as you roam around Europe. GSM 900 has been almost uniformly adopted as the cellular standard in Europe. A user with a single-band GSM 900 phone, commonly used in Europe, can successfully roam almost anywhere in that continent, as well as parts of Asia. Keep in mind the technical differences mentioned previously (i.e., the European version of GSM operates at the 900 MHz frequency while the North American version operates at 1900 MHz). But the SIMs are the same. Dual-band (900-1800 and 900-1900) and tri-band (900-1800-1900) phones can work everywhere. GSM phones are now available to allow interoperability between Europe and North America.

8.5.3.1 GSM Network Architecture

The architecture specification for GSM is very detailed (over 500 pages long). It defines several interfaces for multiple suppliers. The key players of this architecture are shown in Figure 8-8.

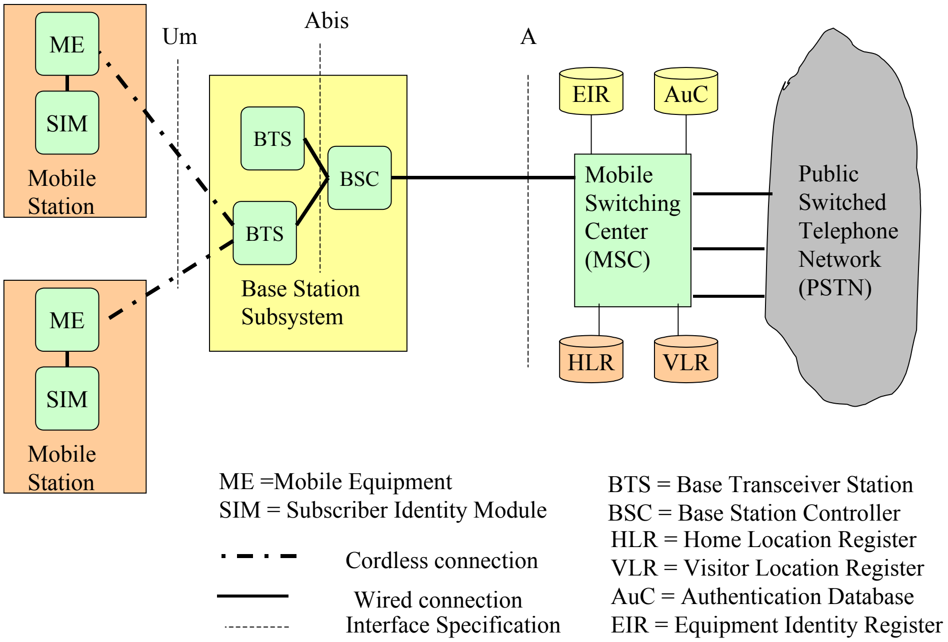


Figure 8-8: GSM Network Architecture

Mobile station (MS) represents the mobile user and communicates across the Um interface (air interface) with a base station transceiver in the same cell as the MS. The main part of MS is mobile equipment (ME) that represents physical terminals, such as a telephone or PDA. An ME includes a radio transceiver, a digital signal processor, and a subscriber identity module (SIM). GSM subscriber units are generic until SIM is inserted. SIMs are used to support roaming, as indicated previously.

Base Station Subsystem (BSS) consists of a base station controller (BSC) and one or more base transceiver stations (BTS). Each BTS defines a single cell and includes radio antenna, radio transceiver and a link to a base station controller (BSC). BSC reserves radio frequencies, manages handoff of mobile units from one cell to another within BSS, and controls paging.

Mobile Switching Center (MSC) is the nerve center of GSM. It provides links between cellular networks and public switched telecommunications networks. Specifically, an MSC controls handoffs between cells in different BSSs, authenticates users and validates accounts, and enables worldwide roaming of mobile users. To support these features, an MSC consists of the following databases:

- Home location register (HLR) database – stores information about each subscriber that belongs to it

- Visitor location register (VLR) database – maintains information about subscribers physically in the region currently
- Authentication center database (AuC) – used for authentication activities; holds encryption keys

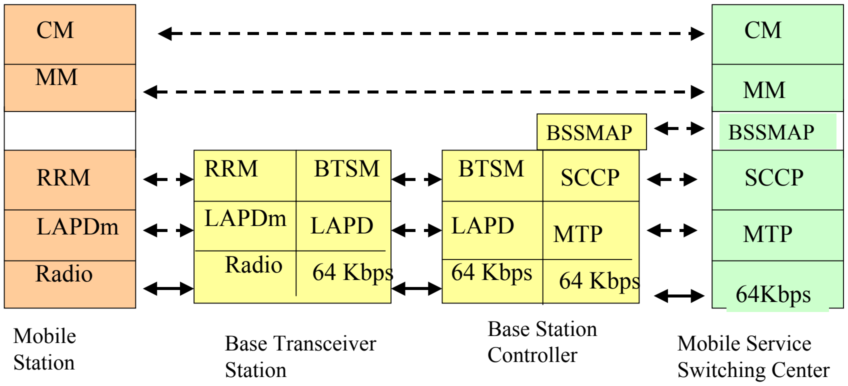
Equipment identity register database (EIR) – keeps track of the type of equipment that exists at the mobile station

GSM supports very extensive location services that use VLR and HLR to locate mobile users as they roam through the network. We discussed this in Section 8.2.5.

A number of control messages are exchanged between the key entities in the GSM architecture. These messages are used to support mobility and connection management. Figure 8-9 shows the GSM Protocol Architecture. The protocols, as can be seen, follow the typical 7-layer model, where the lower layers provide transport over radio links (between the mobile station and BTSs) and wired packet-switching network (between BTSs and MSCs). Protocols above the link layer of the GSM signaling protocol architecture provide specific functions such as the following:

- Connection management connects end users (mobile stations) to the MSC or to other end users. These protocols, at layer 6 of the protocol stack, are used when you dial a number, for example, from your phone to another mobile or wired phone.
- Mobility management provides location services and security controls. These protocols are supported at the layer 5 of the protocol stack.
- Mobile application part (MAP) is used between HLR and VLR to provide updates as the users move around. These layer 4 protocols are used between an MSC and a BSC.
- Radio resource management is used to control setup, termination and handoffs of radio channels. For example, all communications between your cellular phone and the base station are managed by using these layer 3 protocols.
- BTS management is used for management of the base transceiver system also at layer 3.

To learn more about GSM technology, visit the websites, www.gsmdata.com and www.gsmworld.com.



BSSMAP = BSS Mobile Application part
BTSM = BTS management
CM = Connection Management
LAPD = Link Access Protocol, D Channel

MM = Mobility Management
MTP = Message Transfer Part
RRM = Radio Resources Management
SCCP = Signal Connection Control Point

Figure 8-9: GSM Protocol Architecture

8.5.4 2G CDMA Cellular (IS-95)

GSM uses TDMA, but who uses CDMA in 2G? While some systems have appeared, IS-95 is the best-known example of 2G with CDMA. Recall that in the case of CDMA, each user is assigned a unique code that differentiates one user from others. This is in contrast to TDMA where each user is assigned a time slot. Why use CDMA for cellular? Although the debate between CDMA versus TDMA has been raging for a while (see Section 8.5.5), there are several advantages of CDMA for cellular networks. The main advantage of CDMA is that many more users (up to 10 times more) can be supported as compared to TDMA. Although this leads to some complications (see Section 8.5.5), the advantage of supporting more users far outweighs the disadvantage of added complexity.

The IS-95 cellular system has different structures for its forward (base station to mobile station) and backward links. The forward link consists of up to 64 logical CDMA channels, each occupying the same 1228 kHz bandwidth. The forward channel supports 4 different types of channels:

- Traffic channels (channels 8 to 31 and 33 to 63) – these 55 channels are used to carry the user traffic (originally at 9.6 Kbps, revised at 14.4 Kbps).
- Pilot (Channel 0) – used for signal strength comparison, among other things, to determine handoffs
- Synchronization (Channel 32) – a 1200 bps channel used to identify the cellular system (system time, protocol revision, etc.).
- Paging (channels 1 to 7) – messages for mobile stations

All these channels use the same frequency band – the chipping code (a 64-bit code) is used to distinguish between users. Thus 64 users can theoretically use the same band by using different codes. This is in contrast to TDMA where the band has to be divided into slots – one slot per user. The voice and data traffic is encoded, assigned a chipping code, modulated and sent to its destination. The data in the reverse travels on the IS-95 reverse links. The reverse links consist of up to 94 logical CDMA channels, each occupying the 1228 kHz bandwidth. The reverse link supports up to 32 access channels and up to 62 traffic channels. The reverse links support many mobile unit-specific features to initiate calls, and to update location during handoffs.

The overall architecture of 2G CDMA-based systems are similar to the TDMA-based GSM systems (see Figure 8-10). The main difference is that the radio communication between the Base Station Subsystem and Mobile System uses CDMA instead of TDMA. Of course, the MSC now has to worry about handling soft handoffs, but the overall structure stays the same.

8.5.5 Controversy: CDMA Versus TDMA

There are conflicting performance claims for CDMA and TDMA. The debate is raging because hardware vendors have chosen sides and consequently the standardizing bodies have been lobbied hard. The primary motivation for this level of debate is that vendors want their selection to become the industry standard. Since both TDMA and CDMA have become TIA (Telecom Industry Association) standards – IS-54 and IS-95, respectively – the debate goes on to determine which standard is better. Technically speaking, CDMA has the following advantages over TDMA.

- **Network capacity**: In CDMA, the same frequency can be reused in adjacent cells because the user signals differentiate from each other by a code. Thus frequency reuse can be very high and many more users (up to 10 times more) can be supported as compared to TDMA.

- **Privacy**: Privacy is inherent in CDMA since spread spectrum modulates data to signals randomly (you cannot understand the signal unless you know the randomizing code).
- **Reliability and graceful degradation**: CDMA-based networks only gradually degrade as more users access the system. This is in contrast to the sudden degradation of TDMA-based systems. For example, if the channel is divided between ten users, then the eleventh user can get a busy signal in a TDMA system. This is not the case with CDMA because there is no hard division of channel capacity – CDMA can handle users as long as it can differentiate between them. In case of CDMA, the noise and interference increases gradually as more users are added because it becomes harder to differentiate between various codes.
- **Frequency diversity**: CDMA uses spread spectrum, thus transmissions are spread over a larger frequency bandwidth. Consequently, frequency-dependent transmission impairments that occur in certain frequency ranges have less effect on the signal.
- **Environmental**: Since existing cells can be upgraded to handle more users, the need for new cell towers decreases.

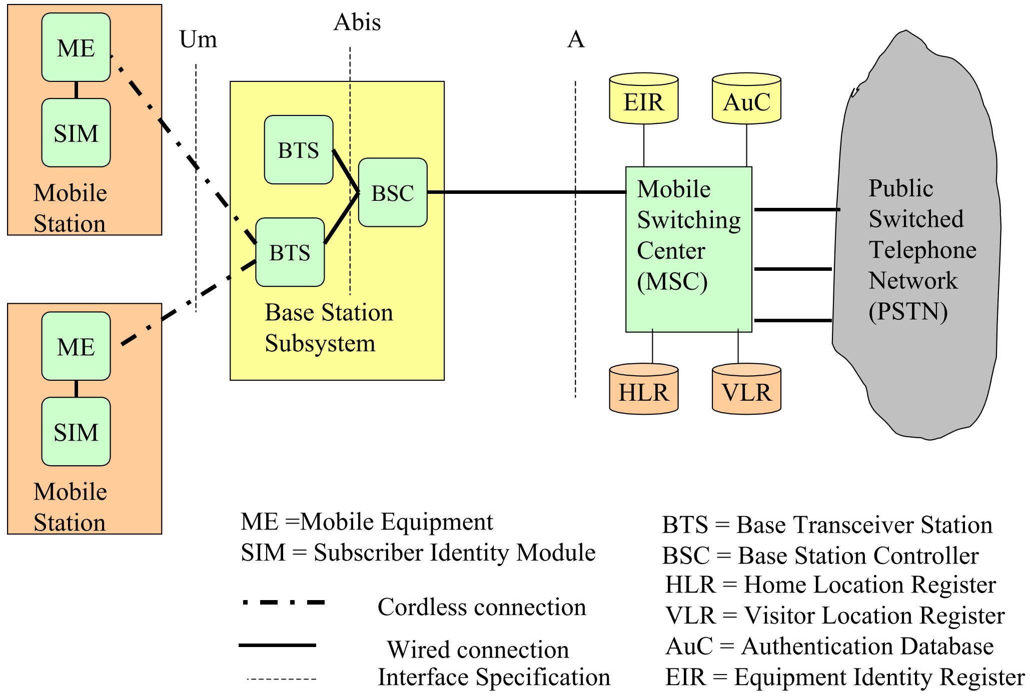


Figure 8-10: 2G CDMA (IS-95) Network Architecture

But, there are some drawbacks of CDMA cellular also:

- **Relatively immature**. As compared to TDMA, CDMA is a relatively new technology; but it is catching up fast.
- **Self-jamming**. CDMA works better if all mobile users are perfectly aligned on chip (code) boundaries. If this is not the case, then some interference can happen. This situation is better with TDMA and FDMA because time and frequency guard bands can be used to avoid the overlap.
- **Soft handoff**. An advantage of CDMA is that it uses soft handoff (i.e., two cells can own a mobile user for a while before the handoff is complete). However, this requires that the mobile user acquires the new cell before it relinquishes the old – a more complex process than hard handoff used in FDMA and TDMA schemes.

The main advantage of CDMA is that the frequency reuse can be very high and many more users can be supported in a cell as compared to TDMA. Although this leads to a soft handoff that is more complicated than the hard handoff used in TDMA, the advantage of supporting more users far outweighs the disadvantage of added complexity.

8.6 Data Over Cellular Networks

8.6.1 Overview

1G cellular systems, as indicated previously, are analog because mobile communications were initially developed for voice users (e.g., cellular phones). However, the use of cellular networks to support mobile computing applications is increasing rapidly due to the emphasis on the wireless Web. In particular, as the use of laptop computers, Palm Pilots, PDAs, and sophisticated mobile devices increases, the need to communicate from these mobile computers to access remote databases is also increasing. 2G+ systems use digital communications because digital communications systems can carry voice and data at high quality. If you are a user who wants to send an email over a cellular network, then you have the following choices:

- For an analog network (e.g., 1G), you can use a modem that converts digital data to analog signals.
- For a digital network (e.g., 2G or higher), you can use your digital phone for transmitting data.
- For a packet-switching system, if available, you can use a PAD (packet assembler/dis-assembler). An example of a packet-switching system is GPRS, which is built on top of 2G networks.

8.6.2 Data Over Analog Cellular and CDPD

You can send data over analog cellular networks by using cellular modems. Specialized systems have been developed for carrying data over analog cellular networks. An early example, still in use, is CDPD (Cellular Digital Packet Data) that has been developed by IBM. CDPD was designed specifically to carry digital data in TCP/IP formats (i.e., the Internet) over 1G cellular networks. The main strength of CDPD is that it supports TCP/IP networks at 19.2 Kbps and thus plugs into the Internet. A CDPD consortium of large telecommunications providers and an ATM Forum promote the commercialization of CDPD networks.

Basically, a CDPD-compliant modem segments, encrypts, and formats transmitting data into 138-byte frames. These frames are sent over the cellular networks by using a protocol that is similar to the Ethernet protocol. CDPD gives voice priority over data. The protocol is intelligent enough to look for clear cells on the cellular networks. This can be a limitation of CDPD because CDPD users may find it difficult to find empty cells in congested areas or at peak times.

Figure 8-11 shows a conceptual view of CDPD. It is built on top of AMPS, the popular 1G cellular network, so it uses the same spectrum and physical infrastructure as analog cellular. A CDPD modem sends IP packets over cellular phones; the packets are received by a CDPD

Base Interface Station. This station connects base stations to the IP routers that carry the traffic over the Internet.

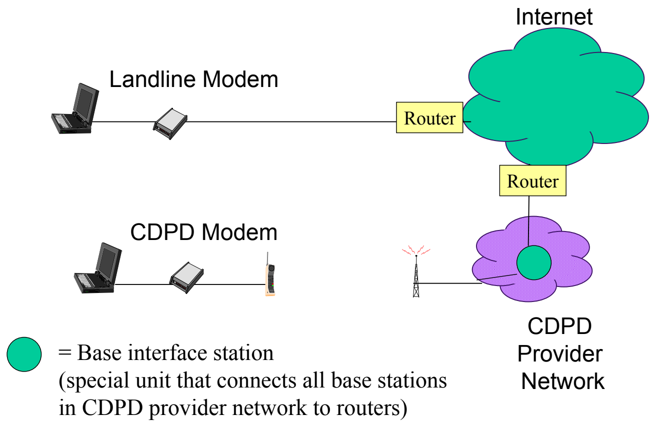


Figure 8-11: CDPD Network

8.6.3 Digital Cellular and GSM

A GSM phone can act as a wireless modem on a GSM network. You connect your PC to a GSM phone and connect to a remote network by using the GSM network. As explained in previous sections, the GSM traffic is picked up by the closest antenna and passed from cell to cell as the user crosses coverage areas, thus enabling data transfer between countries and continents.

Although GSM uses digital cellular technology, it was initially limited to voice-only services. However, GSM operators have expanded their services to include data services. In particular, some GSM operators are adding packet assembler/disassemblers (PADs) to access X.25 services and other packet-switching systems.

Data over GSM is transferred at the native GSM rate of 9.6Kbps. For higher data rates, GSM has been extended by the General Packet Radio System (GPRS) to support data rates of 112 kilobits per second, almost twice the rate of a standard computer modem (most computer modems operate at 56 Kbps). This should be enough to support high-quality streamed audio. GPRS, discussed later, is a packet-switching system that is built on top of GSM, thus it is the 2G version of CDPD (why?).

8.6.4 PCS (Personal Communication Services)

PCS (Personal Communication Services) was coined as a term for "people on the move." PCS is not a technology, it is a term used to represent user services that operate at lower power (suitable for light telephone devices), so the cell sizes have to be smaller. Thus 2G and 3G networks are useful for PCS.

At present, PCS refers primarily to a group of three digital cellular phone technologies in North America. These are GSM 1900, CDMA IS-95, and TDMA IS-136. Thus, by subscribing to PCS, you are getting access to one or more of these technologies. A popular example of PCS is Sprint PCS. If you connect your PCS cellular phone to your laptop, it acts as a wireless modem. Thus you can use your PCS phone to wirelessly access Internet resources, corporate LAN/database access, fax, short messaging service and email.

In general, analog cellular technology is not included as a PCS technology because PCS only refers to digital technologies which were designed specifically to provide improvements over analog. Analog cellular is inherently less optimal than digital for transmitting data. However, the analog cellular system has a very wide coverage with services available in almost any city or town, and on most major highways in the US. For this reason, analog cellular may remain the main wireless data option in rural areas for some time to come. Analog cellular should be considered as a backup solution to PCS technologies because analog cellular can be used for data computing, albeit less successfully,

The role of GSM in PCS should be noted. GSM is playing a key role in the PCS services in US. GSM 1900, also known as PCS-1900, is one of the three PCS technologies in use at present. The other two PCS technologies, CDMA IS-95 and TDMA IS-136, have pockets of users but GSM still dominates. Details about PCS can be found at the Web site (www.PCSdata.com).

Wireless Modems

Handheld digital devices need wireless modems with low battery requirements. Wireless modems are commercially available from several companies such as Motorola for cellular networks such as Cellular Digital Packet Data (CDPD). These modems, available as PC cards have been designed to work with standard throw-away nine volt or rechargeable batteries. When using the throw-away variety, the amount of power drawn from the host device is minimal—just enough to run some of the logic in the card. For security, each wireless modem has a unique identification number and sometimes an electronic serial number assigned to it and coded into the unit. Each device number must be enabled on a network basis before you can communicate.

As stated previously, a GSM phone can act as a wireless modem on a GSM network. In this case, the SIM card acts as the unique identifier.

8.7 The 2.5G Cellular Networks (GPRS)

2.5 G wireless cellular networks have been developed as a transition path to 3G. Examples of these networks are GPRS and EDGE. These systems build packet-switching systems on top of existing 2G systems to improve data rates significantly.

8.7.1 GPRS (General Packet Radio Service)

GSM networks offer circuit-switched data services at 9.6 Kbps. Most GSM carriers are developing a service called **General Packet Radio Service (GPRS),** a 2.5G technology. GPRS can theoretically provide IP-based packet data speeds up to a maximum of 160 Kbps. However, typical GPRS networks operate at lower data rates. One proposed configuration is 80 Kbps maximum (56 Kbps typical) for the downlink and 20 Kbps maximum (14.4 Kbps typical) for the uplink. GPRS supports both IP and X.25 networking.

GPRS can be added to GSM infrastructures quite readily. It takes advantage of existing 200 kHz radio channels and does not require new radio spectrum. GPRS basically overlays a packet-switching network on the existing circuit switched GSM network. This gives the user an option to use a packet-based data service. An architectural view of GPRS is presented in Figure 8-12. The main component of a GPRS network is the GSN (GPRS Support Node) that receives the packet data and transfers it to the Internet or other GPRS networks. To provide GPRS services on top of GSM, the network operators need to add a few GSNs and make a software upgrade to BSCs and few other network elements. This quick upgrade capability has fueled the popularity of GPRS.

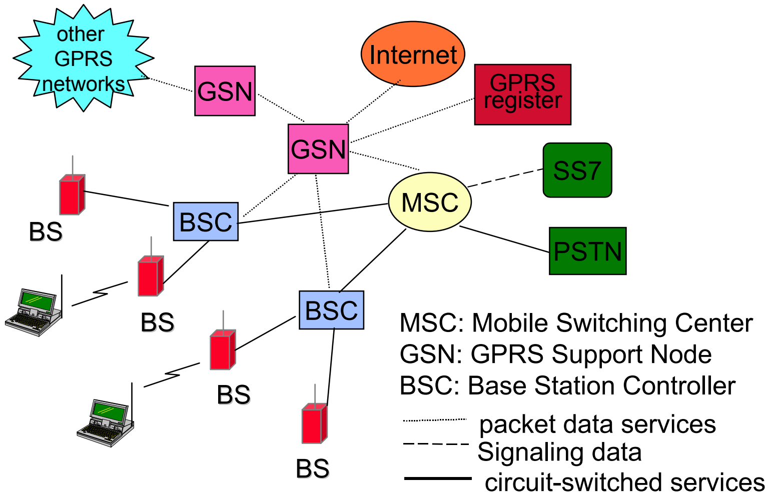


Figure 8-12: GPRS Network Architecture

GPRS capability has been added to cell phones, and is also available in data-only devices such as PC card modems. Pricing is either flat rate or based on the volume of information communicated. GPRS is appealing because it offers higher data rates and also allows, because of packet services, constant “virtual” connections without the need to constantly “dial” into the network. The ‘always-on’, higher capacity, GPRS networks are very suitable for Internet-based content and packet-based data services. You can do Web browsing, email, and file transfer over a GPRS enabled phone. To use GPRS, users specifically need a mobile phone or terminal that supports GPRS (existing GSM phones do NOT support GPRS necessarily) and a subscription to a mobile telephone network that supports GPRS.

For details on GPRS, see www.gsmdata.com and www.gsmworld.com.

8.7.2 EDGE

The phase after GPRS is called **Enhanced Data Rates for GSM Evolution (EDGE).** EDGE, generally considered a 3G technology, introduces new methods at the physical layer, including a new form of modulation (8 PSK) and different ways of encoding data to protect against errors. But the higher layer protocols stay the same. Thus EDGE can deliver maximum data rates up to 500 Kbps using the same GPRS infrastructure (practical throughputs may be only half the maximum rate).

EDGE has been designed to address some of the limitations of GPRS. For example, GPRS impacts a network’s existing cell capacity because voice and GPRS calls both use the same network resources. The extent of the impact depends upon the number of timeslots, if any, that are reserved for exclusive use of GPRS. In addition, GPRS actual data rates are much lower than advertised. Specifically, achieving the theoretical maximum GPRS data transmission speed of 172.2 Kbps would require a single user taking over all eight timeslots without any error protection. Finally, GPRS is based on a modulation technique known as Gaussian minimum-shift keying (GMSK). EDGE is based on the eight-phase-shift keying (8 PSK) modulation that allows a much higher bit rate across the air interface. Since 8 PSK is also used in 3G, network operators need to incorporate it at some stage to make the transition to third generation mobile phone systems.

Time to Take a Break

✓ • Principles of Cellular Networks

✓ • 1G, 2G, and 2.5G Cellular Networks

• 3G, 3G+, Cellular Engineering and Examples

8.8 Third Generation (3G) Cellular Networks

8.8.1 Highlights of 3G Networks

The third-generation (3G) vision is to create a unified global set of standards requirements that could lead to the commercial deployment of advanced multimedia wireless communications. The goal of 3G systems is to enable wireless service providers to offer services found on today's wireline networks.

3G is not one standard; it is a family of standards which can all work together. This is the main reason why there are too many terms and standards in the 3G space. The International Telecommunications Union (ITU) is coordinating this international harmonization of 3G standards under the overall umbrella of International Mobile Telecommunication 2000 (IMT-2000). See the sidebar "ITU's View of 3G" for the requirements that are driving 3G developments.

The best known example of 3G is the ***UMTS (Universal Mobile Telecommunications System)*** – an acronym used to describe a 3G system that originated in Europe and is being used elsewhere. In fact, several analysts claim that UMTS = 3G. The overall idea is that UMTS users will be able to use 3G technology all over the world under different banners. This roaming ability to use devices on different networks will be made possible by satellite and land based networks. UMTS provides a consistent service environment even when roaming via "Virtual Home Environment" (VHE). A person roaming from his network to other UMTS operators experiences a consistent set of services, independent of the location or access mode (satellite or terrestrial).

Whatever the name**,** 3G is designed to raise the data rate to 2 megabits per second (2 Mbps) – a much higher rate than 2G and 2.5G. Specifically, 3G systems offer between 144 Kbps to 384 Kbps for high-mobility and high coverage, and 2 Mbps for low-mobility and low coverage applications. In other words, 3G systems mandate data rates of 144 Kbps at driving speeds, 384 Kbps for outside stationary use or walking speeds, and 2 Mbps indoors. However, the indoor rate of 2 Mbps from 3G competes with high-speed 802.11 wireless

LANs that offer data rates of 11 to 54 Mbps. The main attraction of 3G is the 384 Kbps data rate for outdoor use as an IP-based packet-switching service over wide areas. This service can support wireless Internet access over very wide geographical areas.

3G systems are based on packet switching instead of the older circuit-switching systems used in 2G. What does this mean? In 2G cellular networks, most data communication, apart from the Short Message Service (SMS), requires a circuit-switched connection in which a user must connect to a server to check email, for example. The main limitation of this approach is that the users have to be online even when they are not sending data, so they pay higher costs and network capacity is wasted.

3G networks use a connectionless (packet-switched) communications mechanism. Data are split into packets to which an address uniquely identifying the destination is appended. This mode of transmission, in which communication is broken into packets, allows the same data path to be shared among many users in the network. By breaking data into smaller packets that travel in parallel on different channels, the data rate can be increased significantly. For example, splitting a message into 6 packets can theoretically increase data rate six times (e.g., from 9.6 Kbps to 56 Kbps, roughly). In addition, users can stay online throughout and yet not be charged for the time spent online. Rather, they only pay for the amount of data that they retrieve. This is in contrast to a circuit-switched network like the regular voice telephone network where the communication path is dedicated to the callers, thus blocking that path to other users for that period of time. This means that although a 3G handset is, in effect, permanently connected to the network, it only uses bandwidth when needed.

3G has evolved from 2G and is built on the success of GSM (GSM, GSM1800, GSM1900). Dual-mode terminals ease migration from 2G to 3G. Although many options for 3G exist (we will discuss them later), the radio technology in 3G will likely be Wideband CDMA (Collision detect multiple access). This is similar to local area network technologies such as Ethernet. In the US, CDMA2000 will be used (this is similar to Wideband CDMA but backward compatible with IS-95).

ITU's View of 3G

- Voice quality comparable to the public switched telephone network. This implies a higher speech quality than the current 2G networks.
- 144 Kbps data rate available to users in high-speed motor vehicles over large areas
- 384 Kbps available to pedestrians standing or moving slowly over small areas
- Support for 2.048 Mbps for office use
- Support for both packet-switched and circuit-switched data services
- Provide a real global system, comprising both terrestrial and satellite components
- More efficient use of the available spectrum in general
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies

8.8.2 MMS – the Main Driver for 3G?

While different applications are being envisioned for 3G, MMS (Multimedia Message Service) is getting the most attention. From an end-user point of view, MMS is the same as SMS (Short Message Service) but with pictures. We introduced SMS and MMS in Chapter 2. Let us examine the possible role of MMS in 3G cellular networks.

Several 3G cellular providers, such as Ericsson, are counting on MMS to drive the 3G developments because it is difficult to satisfy MMS requirements with 2G networks. Ericsson has an estimated 40% market share and more than 50% of the global subscriber base of MMS. Delivery of MMS services over 3G requires developments in handsets, infrastructure, content, and systems integration. Examples of the MMS applications include push messaging, automated data-generated graphics, picture messaging, cartoon delivery, and enhanced dating service including photos. Some operators such as the Telecom Italia Mobile are offering access to information on Italian football matches, TV program vignettes and Disney animated cards as part of its mobile multimedia services. Another MMS application uses the latest traffic-status information and knowledge of location to generate a map of the quickest route to a destination.

Many MMS applications for 3G are being built on top of existing popular services by adding images and audio to basic text services. As 3G makes higher bandwidth applications possible, more applications will be developed.

8.8.3 3G Alternative Interfaces and Implementations[2]

8.8.3.1 Interface Overview – The Alphabet Soup

Figure 8-13 shows the radio interfaces that have been approved as part of IMT 2000. As can be seen, the interfaces support CDMA and TDMA as well as FDMA, for backward compatibility with existing systems. The alternatives reflect the evolution from the 2G systems and represent European as well as American views. The best-known interface, based on ETSI (European Telecommunications Standards Institute), is W-CDMA (Wideband CDMA) that fully exploits CDMA technology to provide high data rates with efficient use of bandwidth. Another European interface, intended as an upgrade path from GSM, is TD-CDMA (also known as IMT-TC) that combines CDMA and TDMA. A North America-based interface is CDMA-2000, which is similar to but incompatible with W-CDMA. Other interfaces such as IMT-SC and IMT-FT are based on TDMA and FDMA technologies. We will discuss some of these interfaces later.

A natural question is: why so many interfaces? The simple answer to this question is that wireless operators want to minimize their cost to 3G by reducing the transition effort. As stated in previous chapters, the wireless operators have paid a great deal of money for 3G bandwidths – they dot have much left transition costs. The key players in evolution from 2G to 3G roughly fall into the wireless service providers that have currently invested either in GSM (a TDMA-based 2G system) or CDMA-based 2G systems. Members of these families are using different services to deliver data in the 2G, 2.5G, and 3G range (see Table 8-3).

---

[2] This section is unfortunately overloaded with acronyms that are simply unavoidable. .

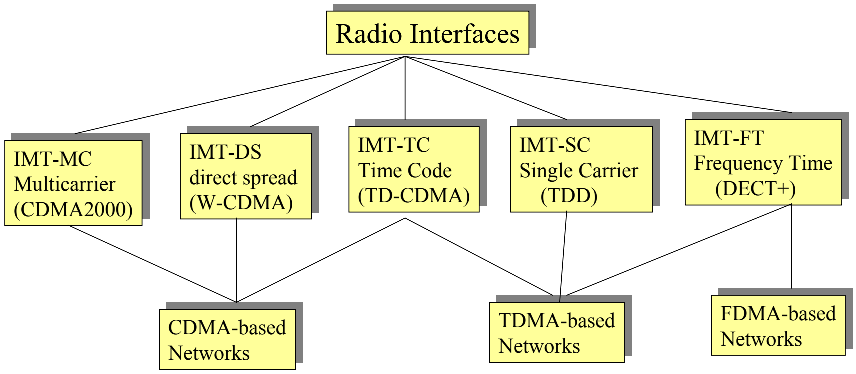


Figure 8-13: 3G Radio Interfaces

Before discussing the key elements, let us observe the following trends:

- The TDMA and CDMA technology families are slowly converging. An example is the interoperability between 3G versions of TDMA and CDMA.
- The connection between mobile computers and wireless devices is being simplified through personal-area network (PAN) technologies such as Bluetooth.
- Standards bodies are working hard to harmonize the radio technologies and also the networking infrastructure. The main goal is to allow users to seamlessly roam from private networks (e.g. Ethernet, wireless LANs) to public networks. Such roaming requires the implementation of standards such as ***Mobile IP***.

Table 8-3: Summary of Cellular Data Services (Source: www.pccdata.com)

Core Technology	**Service**	**Data Capability**	**Generation**
GSM (TDMA-origin) Family	Circuit-switched data based on the standard GSM 07.07 (based on TDMA)	9.6 Kbps or 14.4 Kbps	2G
	General Packet Radio Service (GPRS)	IP and X.25 communications over Kbps	2.5G
	Enhanced Data Rates for GSM Evolution (EDGE)	IP communications to 384 Kbps. Roaming with IS-136 networks possible.	2.75G
	TD-CDMA (also known as IMT-TC)	Combines CDMA and TDMA	3G
	Wideband CDMA (WCDMA)	Similar to EDGE but adds 2 Mbps indoor capability. Increased capacity for voice.	3G
CDMA-origin Family	Circuit-switched data based on the standard IS-707	9.6 Kbps or 14.4 Kbps	2G
	IS-95B	IP communications to 64 Kbps	2.5G
	CDMA2000 – 1XRTT	IP communications to 144 Kbps	2.5G
	Wideband CDMA (WCDMA)	Similar to EDGE but adds 2 Mbps indoor capability. Increased capacity for voice.	3G
	CDMA2000 – 3XRTT	IP communications to 384 Kbps outdoors and 2 Mbps indoors	3G

8.8.3.2 TDMA (GSM) Family

We have reviewed GPRS and EDGE previously. The 3G version of GSM, **Wideband CDMA (WCDMA)**, is based on CDMA technology. This version of CDMA deviates from American standards, although it uses the same spread-spectrum principles. For data, WCDMA adds the capability for 2 Mbps data rates indoors. The airlink, using either 5 MHz, 10 MHz, or 20 MHz radio channels, is completely different from GSM's current 200 kHz channels. However, the data networking for WCDMA is likely to be based on EDGE/GPRS infrastructure protocols.

We have not discussed **IS-136** technologies because they are beginning to merge with GSM (this saves us from many more acronyms). IS-136 carriers and vendors have decided to embrace EDGE for IS-136 networks and may eventually use WCDMA technology for 3G.

8.8.3.3 CDMA Family (IS-96A/B, CDMA2000)

CDMA has gained considerable momentum and has left TDMA far behind. CDMA data services are now available from a number of carriers. Currently, these carriers use circuit-switched technology operating at 14.4 Kbps. As with GSM, CDMA requires a handset that specifically supports data. You connect the phone to a laptop, and the phone operates just like a modem, enabling you to establish dial-up connections to the Internet. WAP-based microbrowser applications are also currently available.

Current CDMA service is based on the **IS-95A** standard. A refinement of this standard, **IS-95B**, allows up to eight channels to be combined for packet-data rates as high as 64 Kbps. Beyond IS-95B, CDMA evolves into 3G technology in a standard called **CDMA2000**. CDMA2000 comes in two phases. The first is **1XRTT** and the next phase is **3XRTT**. The 1X and 3X refer to the number of 1.25 MHz wide radio carrier channels used, and RTT refers to radio-transmission technology. CDMA2000 offers data rates up to 2 Mbps that meet the IMT-2000 requirements. The full-blown 3XRTT implementation of CDMA requires a 5 MHz spectrum commitment for both forward and reverse links. 1XRTT technology is a convenient stepping stone for CDMA carriers moving to 3G, and it can be thought of as a 2.5G technology. 1XRTT can be deployed in existing spectrum to double voice capacity, and requires only a modest investment in infrastructure. It provides IP-based packet-data rates of up to 144 Kbps.

As shown in Table 8-3, the 3G cellular networks are based on WCDMA for GSM and on CDMA2000 for CDMA. But CDMA2000 and WCDMA are different. The CDMA Operators Harmonization Group is developing the Global 3G CDMA standard (G3G) to harmonize these two versions of CDMA One issue in harmonizing CDMA data is that WCDMA is based on GPRS protocols while CDMA2000 is based on the Mobile IP standard. Any harmonized CDMA standard should ideally be based on the same set of tunneling and mobility standards. For this reason, the European Telecommunications Standards Institute (ETSI), responsible for GSM and GPRS, is investigating how GPRS/EDGE could integrate Mobile IP.

8.8.3.4 Compatibility of GSM/GPRS with 3G

The ITU envisaged that IMT-2000 would be a single global standard. However, that did not happen. After a great deal of "discussion," the representatives from different countries voted in 1999 to make IMT 2000 a "federal standard" that will support different families of standards. The main reason for this federation is that the world's regulators, vendors, and carriers could not agree on frequency ranges and other issues. For example, the FCC did not agree to license the same frequency spectrum as the Europeans.

Specific standards have been developed to assure compatibility. For example, UMTS specification is designed so that there is maximum compatibility between GSM, GPRS, and UMTS systems. Industrial products also provide cross-family support. For example, the Vodafone Mobile Connect 3G/GPRS laptop data card allows users to switch back to GPRS systems when a UMTS network is not available.

8.8.4 IEEE 802.11 Versus 3G Cellular

Although 3G cellular networks are getting a great deal of attention, the 802.11 WLANs are proving to be a tough competitor to 3G.

In the very best case, 3G networks are supposed to deliver around 2 Mbps in an office environment. This is in no way competition for 802.11 networks that can deliver from 11 Mbps to 54 Mbps. For data applications such as Web browsing, remote database access and software downloads, 802.11 is far superior to 3G. In addition to slower data rates, Web browsing on cellular phones requires use of special protocols such as Wireless Application Protocol (WAP) and markup languages such as Wireless Markup Language (WML). In short, viewing Web pages with 3G is inherently inferior to doing so with 802.11 LANs.

But 3G cellular networks are well suited for applications like instant messaging (IM), Short Messaging Service (SMS),or Multimedia Messaging Service (MMS). However, IM is not straightforward – you cannot send messages from IM to someone using MMS or SMS on a digital phone without a special gateway between the SMS/MMS servers and IM clients.

A very attractive alternative to 3G are the 802.11 hotspots that connect 802.11 LANs to wired networks at airports, Internet cafes, shopping malls and Starbucks coffee shops. While 802.11 hotspots have far less range than 3G, they are much cheaper to set up – a business class hotspot can be deployed for about $1500, while most 3G base stations start around $100,000. In addition, anyone can set up a hotspot but only a telephone carrier or corporation can afford 3G base station.

In short, 802.11 WLANs are easier to install and cost far less than setting up a 3G network. In addition, 3G's fastest data rate of 2 Mbps is slow compared to the slowest data rate of 802.11's 11 Mbps. As 802.11 WLANs move toward 54 Mbps, it is apparent that 3G cannot compete with the data rate of WLAN. Another difficulty is that the WLAN industry is growing at a stellar rate while 3G deployments have been slowed down considerably due to infrastructure costs. In some sense, the growth of WLANs is coming at 3G's expense. In reality, many of the 3G providers including T-Mobile, AT&T, and Verizon have made announcements about deploying WLAN services as their 3G plans are delayed. In particular, British Telecom is planning to deploy more than 4,000 WLAN hotspots based on 802.11 by the summer of 2005.

But the limitations of 802.11 should be also noted. 3G cellular phone network cells can transmit from 5 to 6 miles in diameter. Compare this to 802.11 access points which range only between 300 to 900 feet. Thus you will need millions of 802.11 based access points to cover a metropolitan area. Due to this, "hybrid wireless networks" that support hot spots and are connected through 3G or other networks make more sense.

The success of 802.11 versus 3G is also leading to interesting new developments. For example, Cisco has announced an 802.11 telephone that supports Voice Over IP (VOIP) over WLANs. This not good news for 3G (see the sidebar, "Voice Over 802.11 – Competition to 3G").

Voice Over 802.11 – Competition to 3G

Cellular phones are primarily used for voice communications, although data applications are growing. Conversely, 802.11 LANs are primarily being used for data, but now 802.11 is also beginning to support telephone services. This is not good news for 3G because bandwidth limitations have prevented many cellular services from coming to fruition. The main problem is that there is limited radio frequency spectrum available and there is limited bandwidth that can be delivered over cellular or satellite networks. In addition, there are also limited numbers of channels (or users) that a cellular tower can simultaneously connect. This number of connections is greatly reduced when the service is also supporting data services. Since the greatest source of revenue for cellular providers comes from voice services, the carrier's allocated spectrum for data is kept small, causing the data rates to be slow.

The advantage of using 802.11 for voice services is that no frequency allocation fees have to be paid. In addition, higher data rates can be provided by the 802.11 network for wireless Internet access (11 Mbps or higher – much better than the 2 Mbps of 3G). The cellular operators also add large new customers without having to install new towers. Several companies are beginning to provide "hybrid" cellular services where part of the phone service, for example in an office, is supported over 802.11 but the other is provided over a cellular network. An example of such a service is that provided by Vocera Communications (www.vocera.com). Cisco has also announced an 802.11 telephone that supports Voice Over IP (VOIP) over WLANs. Another example is Calypso's system that provides voice over 802.11 networks in office settings and also integrates with cellular providers (see Section 8.12.3 for an example).

8.8.5 3G Design Considerations

The common multiple access scheme of choice is CDMA, with a nominal bandwidth of 5 MHz and a fixed chip rate of 3.84 Mchips/sec. The goal of these technologies is to provide each user with increased data rates at a reasonable quality of service (QoS). Despite these lofty promises, the practical design and implementation of 3G cellular networks has been plagued by difficulties. 3G networks are massively complex networks that take both time and large investments to develop and deploy. The main reason is that 3G networks require too many interfaces and compatibilities, with too many existing systems that operate in different parts of the world under different regulatory bodies.

Although CDMA is most widely accepted in 3G, the main problem with CDMA is that the signals could interfere with each other (recall that all CDMA users share the same frequency band). To overcome this problem, CDMA codes are chosen so that they cancel each other out. For exact cancellation, signals must be perfectly timed; base stations need to make very precise measurements of their time and location. They do this by using signals from Global Positioning System (GPS) satellites, which can identify a location anywhere on Earth to within a few meters. Three CDMA implementations are part of 3G:

- CDMA2000-1XRTT: This spreads every signal over a 1.25 MHz channel, transmitting on the entire bandwidth at once. It uses a set of 64 codes, so up to 64 phones could theoretically use the channel at once.

- CDMA2000-3XRTT: This provides 2 Mbps by using the 3.75 MHz bandwidth – the result of three 1XRTT channels, 1.25 MHz each, joined together.
- Wideband CDMA (W-CDMA), most commonly known as Universal Mobile Telecommunications System (UMTS): This requires the new spectrum assigned by the ITU, and thus cannot be used in the United States. It is technically very similar to CDMA2000-3XRTT but uses a slightly wider bandwidth, hence the name. The wider bands are necessary so that the system can interoperate with GSM.

8.8.6 Industrial Issues – Evolution to 3G Cellular

Many companies are developing wireless solutions that protect the investment of the first- and second-generation service providers and offer an evolution to third-generation services. Some companies, such as Lucent, also support the development of a family of third-generation systems (the "Family of Systems" standards concept) offering wireless service providers flexibility in choosing wireless solutions that best meet their requirements.

The next generation of wireless entails creation of seamless multimedia services that attempt to transcend fixed/mobile, wired/wireless, voice/data, public/private network distinction. This is a challenging task that includes the following business challenges:

- Include integrated, end-to-end operations, administration, maintenance and provisioning support, billing, and customer care.
- Protect and leverage the current investments in 2G systems.
- Minimize the risk and infrastructure cost of migration to the next generation.
- Manage short-term risks with small incremental investments that add data capabilities.

3G is a major technical undertaking with many organizational and marketing overtones. Some people are quite happy with the 2.5G technologies such as GPRS. So questions about the need for the additional investment for 3G are being raised. Other high-speed wireless-data solutions compete with 3G (e.g., Metricom's Ricochet). In addition, wireless LANs in public places such as shopping malls and airports offer options to 3G.

Figure 8-14 shows the evolution of existing 2G to 2.5G, and on to third-generation cellular technology. With the proposed 3G wireless technologies, data rates of up to 2.05 Mbps are possible in stationary applications, 384 Kbps for slow-moving users, and 128 Kbps for mobile users in vehicles. Each of these technologies loosely provides operators with an upgrade path for existing cellular networks. Although all the 3G network standards have some commonalities, they are not compatible at the bottom (air interface) layer because the modulation formats are different.

8.8.7 3G Summary

Figure 8-14 presents a view of how 3G networks are evolving from 2G and 2.5G systems from CDMA as well as GSM families.

3G cellular technology is a major technical undertaking, with many organizational and marketing overtones. However, 3G needs to be understood in the context of other developments. Some people are quite happy with the 2.5G technologies such as GPRS and do not understand the need for the additional investment for 3G. In addition, there are other high-speed wireless-data solutions available that could compete with 3G. For instance, the Metricom's Ricochet network could become more widely available with higher data rates (Ricochet is available to a few cities in the US). Also, some companies are planning on deploying wireless LAN technology in public places such as shopping malls and airports.

These developments will not stifle the demand for 3G cellular-based data but will offer options, increase competition, and help drive down prices.

Obviously, a myriad of new applications will be possible with next-generation, wireless-data networks. But 3G networks are massively complex networks that will take both time and large investments to develop and deploy. For an ongoing discussion about 3G, see the websites http://www.3g-generation.com/ and www.pccdata.com.

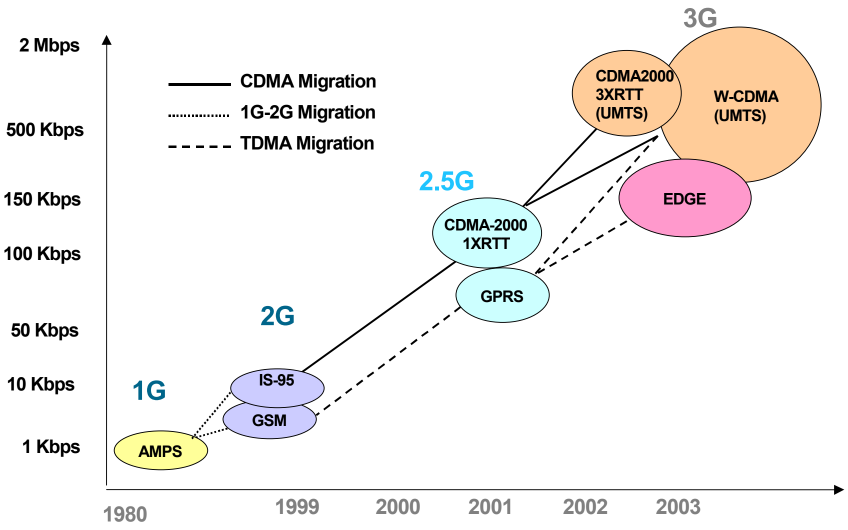


Figure 8-14: Evolution to 3G

8.9 Beyond 3G – 4G and 5G Systems

8.9.1 4G Cellular Networks

While 3G wireless networks are still on the design desks, researchers are working on 4G cellular networks with cellular data rates of 20 Mbps and beyond. The high data rate of 4G cellular phones could allow users to watch high-resolution movies and television programs on their cellular phones. A Fourth-Generation Mobile Forum (www.4gmobile.com) has been formed to foster developments in this area. The 4G networks are targeted for 2010 and beyond, although several technical and business questions, including frequency allocations, need to be addressed sooner.

The research towards very high (50 Mbps and above) cellular networks, now known as 4G, started in the 1990s. One of the best known projects was the Mobile Broadband System (MBS), a collaboration between several companies and universities overseen by the European Commission. Built in 1995, the MBS prototype had a data rate of about 34 Mbps and was tested indoors and at driving speed of 30 miles per hour. Other experiments since then have set a goal of 20 Mbps with commercialization around 2010.

Many new technologies and techniques (multiplexing, smart antennas, digital signal processing) are at the core of 4G networks. The physical layer of 4G will be based on Orthogonal Frequency Division Multiplexing (OFDM), and IPv6 will be used at the network layer level. Smart antennas with their ability to adjust based on object movements are an important part of 4G cellular. One of the most difficult questions is determining the frequency spectrum for 4G. The MBS prototype used the 60 GHz band, where there is a large amount of unused bandwidth, but the range is only 100 meters. With such a small range, a nationwide network would require millions of base stations, each one at the center of tiny “picocells.” Other experiments include 40 GHz, which would allow larger cells and reduce the cost of building networks.

Many companies are involved in this effort. AT&T has initiated a two-phase upgrade of its wireless network on the way to 4G networks, and Nortel is developing features for Internet protocol-based 4G networks. In addition, Alcatel, Ericsson, Nokia and Siemens have found a new Wireless World Research Forum (WWRF) for research on wireless communications beyond 3G. Perhaps the largest interest in 4G is being shown by the NTT DoCoMo, Japan’s largest cellular phone company. Although 4G is planned around 2010, DoCoMo plans to launch 4G cellular phone services by 2006. Encouraged by its success with i-mode, DoCoMo expects 4G systems to support the future mobile applications.

A natural question is: why interest in 4G when 3G is not settled yet? The enthusiasm for 4G is occurring because the 3G services have proven so disappointing with multitudes of standards and specifications. It is not clear if 4G will be all that different. For example, the crucial issue of frequency bands for 4G needs to be resolved. In addition, many technological, systems engineering, and economic factors need to be hashed to make 4G a business reality. It is non-trivial to develop a 4G architecture that utilizes the best features of W-CDMA, OFDM, smart antennas, and multi-band software-controlled radios.

8.9.2 5G Cellular Networks

Some futuristic work on 5G cellular should be mentioned here briefly. The idea is to investigate cellular networks that could deliver data rates above 50 Mbps. At the time of this writing, almost all futuristic work for the next 10 to 20 years is under the umbrella of 5G. The work is proceeding in different directions. Here is a quick recap of the main ideas.

Although data rates are the main appeal, the focus is shifting more towards intelligence and learning. For example, some work on "cognitive radio (CR)" is proceeding at Mitre (http://www.infoworld.com/article/03/02/28/09ctlong_1.html). A CR is a smart phone that detects the type of conversation and adjusts accordingly. For example, if a CR detects an interview, it could pop up a display suggesting cheaper and better ways of conducting an interview. The phone could learn over time and store the information that the user likes high-quality speech when doing interviews. In addition to learning about the user behavior, the software residing on the handset would determine the most appropriate frequency to be used. Thus the handset could choose, instead of the common cellular frequency of 800 to 900MHz band, automatically an ISM band. The handset could also automatically switch between the type of network (cellular, 802.11, or Bluetooth) based on the type of applications.

The general vision of 5G is that a PDA, laptop, and automobile would employ the mix of Bluetooth, IEEE 802.11, and cellular standards from 1G to 3G as needed by the user. Another aspect of 5G networks is that special value added services such as location-based services are automatically activated when needed. Of course, there is more emphasis on smart antennas, error correction through turbo codes, and improved signal encoding techniques.

One of the main emphasis of 5G cellular is collection of information that can be used to make decisions. For example, it could record the path from your home to work. It could also be measuring the radio propagation, signal strength, and the quality of the different bands as you use your cellular device during the day. It builds an internal database of what it can do when and where.

8.10 Alternatives to 3G – Public Data Networks and Flash OFDM

8.10.1 Why Alternatives to 3G?

A great deal of attention is currently being paid to the 2G, 2.5G, 3G, and 3G+ (4G, 5G) cellular networks. In particular, the 3G wireless technologies are in the limelight because they promise wide-area data rates of up to 2 Mbps in stationary applications, 384 Kbps for slow-moving users, and 128 Kbps for mobile users in vehicles. Despite their appeal, resistance to 3G has built up over the past few years for several reasons. The main concern is the expense involved versus business value. Many wireless network operators have invested massive sums of money in new frequency spectra and infrastructure development for 3G cellular networks. However, most consumer rollouts of these new services have been delayed for a variety of reasons ranging from handset shortages to shortage of investment capital.

There are additional concerns about data transmissions over 3G networks. A limitation of 3G cellular networks is how they interface with wired TCP/IP networks. TCP cannot easily distinguish between lost or dropped packets – resulting from wireless channels with significantly higher bit error rate (BER) than wired channels, and network congestion. TCP responds by slowing down the transmitted data rate. According to the International Engineering Consortium (http://www.iec.org), this problem is further exasperated by the typical slow-start implementation of TCP. This can lead to delays that are four to five times longer than the maximum allowable latency for interactive applications.

Another problem with 3G cellular systems is the large overhead associated with transmitting short messages. Large headers along with complex training sequences and additional guard bands are added to delay sensitive control data (typically only a few bits). This overhead increases latency, which is not good for multimedia applications.

The bottom line is that the longer it takes to actually offer 3G services to consumers, the more potential 3G users will look elsewhere for broadband wireless network access. Some alternatives being considered are:

- Public data networks that exist in different parts of the world to support wireless data access. Examples of these networks are Mobitex and Ricochet. Although older and slower, they are still used an alternative.
- Newer technologies such as radio router technology, also known as flash OFDM (Orthogonal Frequency Division Multiplexing). Flash OFDM is a packet-switched radio access network that seamlessly transports IP services over the air from an IP network to a mobile user device.
- Voice over 802.11. As this technology begins to appear, new competition is created for 3G. The advantages of using 802.11 for voice services are that no frequency allocation fees have to be paid, and higher data rates can be provided by the 802.11 network for wireless Internet access. Several companies are beginning to provide “hybrid” cellular services where part of the phone service, for example in an office, is supported over

802.11 but the other is provided over cellular network. An example of such a service is by Vocera Communications (www.vocera.com). See Section 8.12.3 for an example.

- High-speed access in high-traffic "hotspots" like airports, shopping centers, and Internet cafes. In these hotspots, access is wireless but roaming support is not provided. For example, instead of using your cellular phone for Internet access, you could do the same from a close-by Internet café that provides high bandwidth access to the Internet.

In this section, we briefly review some public data networks and Flash OFDM. The "hotspot" networks are supported through wireless LANs or wireless local loops – a topic discussed in previous chapters.

8.10.2 Mobitex

Mobitex, developed by Ericsson and Swedish Telecom, is a public data network in operation in Sweden, Norway, Finland, Canada, UK, and other European countries. In the US, Mobitex was introduced by BellSouth. Mobitex supports TCP/IP and X.25 and can support 400 users on one channel by using packet switching. Although Mobitex supports low data rates (nominally 8 Kbps), it uses a narrow band (2.5 kHz) as compared to 30 kHz (GSM) and 5 MHz (3G). This narrowband operation conserves bandwidth in an otherwise bandwidth-scarce wireless world.

Despite its low data rate, Mobitex is heavily supported by major wireless carriers such as Cingular. The Cingular Mobitex is a US nationwide system with 90 switches and more than 2,000 base stations that support TCP/IP, UDP/IP, Frame Relay, X.25, and ISDN. Mobitex is quite mature at present: the first generation was implemented in 1985; currently it is in its 16th software revision and 4th network hardware generation, with extensive redundancy and backup support. Details about Mobitex can be found at www.ericsson.com.

8.10.3 Ricochet

Ricochet, developed by Metricom (Los Gatos, California), was originally designed to automatically read electric and gas utility meters. This service was upgraded and made available in 1995. Ricochet has been providing high-speed wireless data services for the San Francisco Bay area, Washington DC, and the Seattle area, plus some airports and university campuses. Ricochet uses packet switching to deliver between 40 Kbps and 128 Kbps data rates.

Figure 8-15 shows an overview of the Ricochet architecture. Basically, the Ricochet network is a digital packet-switched radio network consisting of portable modems (carried by users and connected to their computing device) and fixed, omnidirectional "pole-top" radios. The pole-top devices form a "mesh" of MicroCells and are essentially base stations (BSs). The BSs are connected to wireless access points (WAPs) that are connected to IP routers through Ethernet. Please keep in mind that the Ricochet WAPs are hardware devices and should not be confused with the Wireless Application Protocol (WAP) architecture specified by the WAP Forum.

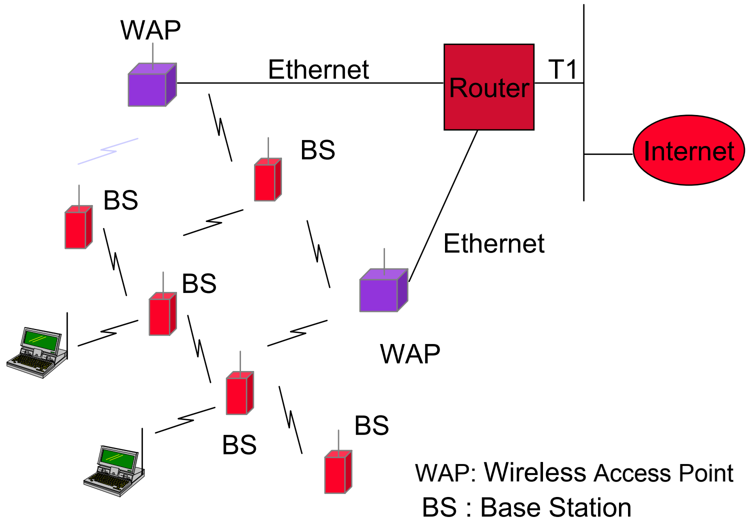


Figure 8-15: Ricochet Architecture

Ricochet uses portions of licensed and unlicensed spectrum for communications in the physical layer. User access is in the unlicensed Industrial, Scientific, and Medical band (ISM), at frequencies of 902-928 MHz. Frequency-hopping spread spectrum across 160 channels is used to reduce the effects of interference and fading on the signals.

Unfortunately, Metricom declared bankruptcy and shut down the service in August, 2001. At that time, Ricochet was available in about two dozen US cities through partner resellers, with flat rates between $70 to $80 per month. But this delivered between 40 Kbps and 128 Kbps data rates, with PDA-sized external modems selling for around $100 and the first PC cards retailing for $300. The end users were reasonably satisfied (I myself used the service and liked it). The main problem was that Metricom wanted to gain market share before 3G services took off. This required adding new service areas by expanding their network quickly, which in turn required large investments. In addition to the high cost of building the network, Metricom also lacked sufficient subscribers.

To illustrate Ricochet's difficulty, Metricom had only 51,000 subscribers in 2001 for the Ricochet service, even after spending tens of millions of dollars. At present, the Ricochet network is owned by Aerie Networks, which purchased Metricom's assets for $8.25 million. We will have to see how it works out. Much depends on Aerie's ability to pursue the original intended path for "Fourth Generation" Ricochet service, which included plans for utilizing the ISM band at 5 GHz. This could greatly improve the data rates offered by Ricochet and make it a viable competitor.

8.10.4 Flash OFDM (Orthogonal Frequency Division Multiplexing)

Flash OFDM, currently being developed by Flarion Technologies (http://www.flarion.com) is one of the most promising alternatives to 3G cellular. This IP-based architecture is designed to deliver around 1.5 Mbps at link layer for wide-area mobile data traffic. It comprises an air interface design that integrates layers one through three of the OSI model. The foundation of this technology is OFDM, an improvement over the classical FDM technology. In OFDM, a single channel is divided into multiple sub-channels, each having a different frequency. This allows multiple simultaneous transmissions, effectively increasing the bandwidth of the system. We will look at OFDM in Chapter 10. Flash OFDM's scheme builds on top of the OFDM lower-layer implementation. Layers three and above of the OSI model are entirely IP-based in Flash OFDM. The key advantage of this implementation is that common commercially available IP infrastructure equipment may be used to connect the network directly into the Internet, thus reducing the technology risk and total cost to the wireless operator.

Due to its approach, Flash OFDM technology provides the user with broadband data rates of 1.5 Mbps (with peak data rates of 3 Mbps) and the mobility of a traditional cellular network. Figure 8-16 shows the overall architecture of Flash OFDM. It can be seen that the architecture is quite simple. The base stations provided by Flash OFDM (called Radio Routers) connect to the edge routers in the managed IP network through the standard IP technology. The edge routers are then connected to the public Internet and also to the back-end systems. The physical data stream is secured using a 128-bit encryption scheme before transmission at the air interface. The Flash OFDM network also provides an interface to the authentication, authorization, and accounting (AAA) system that enables many key revenue streams and business models for wireless network operators.

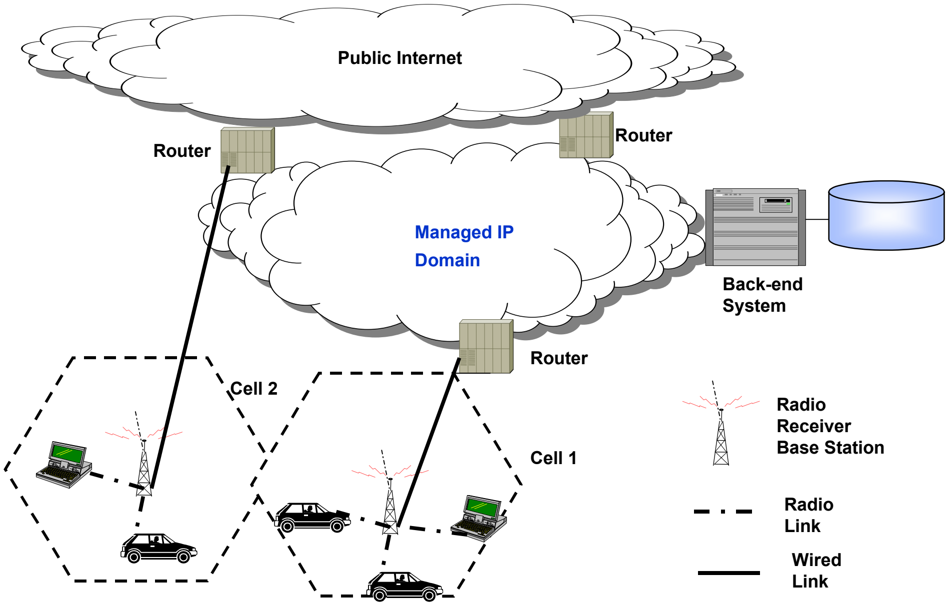


Figure 8-16: Flash OFDM Architecture

Details of the Flash OFDM design can be found at the Flarion Technologies web site (http://www.flarion.com). A good analysis can be also found in Boothe [2002]. The key ideas will be discussed in a later chapter (Chapter 10).

8.11 Cellular Network Engineering Issues

Next-generation cellular networks are increasingly providing data services as compared to the earlier voice-only cellular networks. This raises some practical design issues. Specifically, design of cellular networks requires considerations such as MTSO-controlled calls, TDMA design, CDMA design, fading, handoffs, and traffic engineering A brief overview is presented here. Additional details can be found in Mark [2003], Stallings [2002], and Gibson [1996].

8.11.1 General Network Design Considerations for Next Generation Cellular Networks

Many practical issues arise due to the focus of next generation cellular networks on data services. From a network design point of view, voice traffic is a relatively robust service that is tolerant of occasional transmission errors; however, data traffic differs from voice in several ways. First, voice traffic is not impacted by the transmission errors typical of the data traffic over most wireless links. Because errors are intrinsically more prevalent in wireless communications, data transmission places increased importance on powerful error detection and correction schemes. Second, compared to voice traffic, typical data traffic is subject to bursts, having a high variability in both the rate and length of transmitted packets. Finally, networks that carry data traffic must also successfully identify and process data of varying priorities. Data traffic may be prioritized to deliver a QoS based on maximum tolerable delay (for real-time data, for example) or pricing structures (higher-priced services have higher priorities). Traditional cellular networks do not adequately address these specific concerns of data-centric networks. The key to the success of next-generation cellular networks is to provide data users with the same experience and functionality they are already familiar with through typical wired networks. This implies the following:

- A packet-switched network with advanced coding and multiplexing techniques to achieve high efficiency is essential. The cellular network must also provide a quick and reliable interface to existing wired TCP/IP data networks.
- Network delay (latency) becomes critical when interfacing with existing wired TCP/IP networks, especially for interactive and real-time applications. Typically, a network latency greater than around 50 ms is too high for most interactive applications, even when the underlying network has the capability of very high data rates.
- Cellular system and network designers must find ways to minimize bandwidth consumption because bandwidth is expensive. In fact, the high cost associated with obtaining new frequency spectrum, in some cases millions of dollars, is the largest operating expense a wireless operator has to absorb.
- Robust end-to-end security is critical to next-generation cellular networks, especially if they are to support e-commerce applications that involve financial transactions. Security is of special importance in wireless communications because the air interface is inherently more susceptible to security attacks than traditional wired transmission mediums.
- Cost savings through the use of industry standards and existing equipment are essential for the market success of broadband cellular networks. The total cost of network design, implementation, and maintenance must be kept very low because the costs associated with acquiring suitable frequency spectra and building an infrastructure are enormous. Cost-efficient approaches also reduce the financial risk in offering new services.

8.11.2 Mobile Telecommunications Switching Office (MTSO) Operations

Mobile telecommunications switching office (MTSO), also known as MSC (Mobile Switching Center), is essentially an end office used to connect calls between mobile units. Several base stations are connected to an MTSO. In large systems, many MTSOs may be connected to a second-or third-level MTSO and so on. MTSOs are connected to BSs, PSTN and each other through fast packet switching (mostly based on ATM).

Two types of channels are available between mobile units and the BS: control channels that are used to exchange information having to do with setting up and maintaining calls, and traffic channels that carry voice or data connection between users. In an MTSO-controlled call between mobile users, the following steps occur:

- Mobile unit initialization – when a mobile unit is turned on, it scans and selects the control channel with the strongest signal. In effect, this means that the mobile unit has selected a base station.
- Mobile-originated call – when a mobile unit places a call to another mobile unit, then the MTSO finds and coordinates the channel on which the receiver can receive the information.
- Call accepted – the called unit is paged by the MTSO and the called unit responds with a call-accepted message.
- Ongoing call – the call proceeds and the two units exchange information through traffic channels.
- Handoff – if one of the mobile units crosses a cell boundary during an ongoing call, then the call is transferred ("handed-off") to the new channel assigned to the new cell.

In addition to these activities, the MTSO is responsible to handle call blocking (i.e., when a call is made to a unit already engaged in an ongoing call), call termination (i.e., releasing a channel when one of the parties hangs up), and call dropping (i.e., a call is terminated due to weak signal or interference).

8.11.3 Mobile Wireless TDMA Design Considerations

TDMA is at the foundation of GSM. So let us briefly review some of the TDMA design considerations. The overall objective of this analysis is to determine the time slots that need to be allocated to various users (i.e., how many users to allow in a channel through time slicing). The following design requirements typically drive this analysis:

- Number of logical channels (number of time slots in TDMA frame) is typically 8.
- Bandwidth is not to exceed 200 kHz (25 kHz per channel, assuming 8 logical channels).
- Maximum cell radius (R) is 35 km.
- Frequency is around 900 MHz.
- Maximum vehicle speed is 250 km/hr.

A number of steps, described in [Stallings 2002], are used to determine a TDMA time slot. Some of the steps consist of speech-coding selection for satisfactory speech quality, selection of error-correction codes, and determination of guard intervals to minimize interference. Consult Stallings [2002] for more details.

8.11.4 3G-CDMA Design Considerations

In CDMA, the users are differentiated through a code. Thus, decisions are made to handle handoffs efficiently and differentiate between overlapping signals. A soft handoff is used so that the mobile station is temporarily connected to more than one base station simultaneously. In essence, the mobile user acquires the new cell before it relinquishes the old. Soft handoffs do not switch the mobile user suddenly from one base station to another, as in the "hard handoff" used in FDMA and TDMA schemes. Consequently, soft handoffs are more complex processes than hard handoffs because during the handoff, more than one cell owns a user and the communication between participating cells must be coordinated by the MTSO.

When multiple versions of a signal arrive so that they could interfere with each other, then the system recovers dominant signals and treats remaining signals as noise. Significant improvements in performance can be achieved by recovering signals from multiple paths and combining them instead of rejecting many signals as noise. A specialized receiver, known as

RAKE receiver, is used to recover multiple signals instead of rejecting them. This method achieves better performance than simply recovering dominant signals and treating remaining signals as noise. Although the concept of RAKE receivers was introduced in 1958 [Price 1958], a great deal of work has been done since then (see the extensive reference list produced by [Tang 2003]).

8.11.5 Mobile Radio Propagation Effects and Handoff Performance

Mobile communications introduce unique challenges that are not found in wired or fixed wireless networks. Signal strength, fading, and handoff performance are among the few challenges.

Basically, the signal strength must be strong enough between base station and mobile unit to maintain signal quality at the receiver. However, this signal should not be so strong that it interferes with neighboring cells.

Fading of signals may disrupt the signal and cause errors. Fading refers to the variation in signal strength due to transmission media or path(s). In mobile environments, as the mobile units move around, they encounter different objects such as buildings that reflect, scatter and bend the signal in a variety of ways. This causes fading.

Handoff Performance Metrics. Handoff is the procedure used to change the assignment of a base station to a mobile unit as the mobile unit moves from one cell to the next. Handoffs can also be initiated by an MTSO because of traffic congestion, etc. In either case, the handoffs are based on a wide range of performance metrics such as the following:

- Cell blocking probability: probability of a new call being blocked
- Call dropping probability: probability that a call is terminated due to a handoff
- Call completion probability: probability that an admitted call is not dropped before it terminates
- Probability of unsuccessful handoff: probability that a handoff is executed while the reception conditions are inadequate
- Rate of handoff: number of handoffs per unit time
- Interruption duration: duration of time during a handoff in which a mobile unit is not connected to either base station
- Handoff delay: distance the mobile unit moves from the point at which the handoff should occur to the point at which it does occur

Communications engineers estimate and measure these metrics to provide an acceptable design that maximizes the number of users with minimum call blocking, unsuccessful handoffs, and other parameters (see [Mark 2003] for details).

8.11.6 Cellular Power Engineering

Design issues make it desirable to include dynamic power control in a cellular system. In particular, the received power must be sufficiently above the background noise for effective communication. But it is also desirable to minimize power in the transmitted signal from the mobile unit to reduce co-channel interference and alleviate health concerns. Conserving battery life is yet another reason for power control. If the mobile unit continuously transmits at a power higher than needed, the battery lifetime is reduced. Thus each mobile station should transmit using the minimum power needed for acceptable performance, to conserve its battery life.

Special power-control problems arise in spread-spectrum (SS) systems using CDMA. It is desirable to equalize the received power level from all mobile units at the base station (BS) because all CDMA users have the same frequency allocation. One critical problem with CDMA is the near-far problem. The main problem is that if all mobiles were to transmit at the same power level, the mobile closest to the base station will overpower all others (since the signal power drops exponentially with the distance). For a good discussion of power control for CDMA systems, see A. El-Osery, and C. Abdallah, "Power Control in CDMA Cellular Systems," http://www.techonline.com/community/ed_resource/feature_article/14863.

There are different types of power controls [Pincha 1997]:

- Open-loop power control. This type of power control depends solely on the mobile unit, with no feedback from the BS. This approach is used in some SS systems. The BS sends the mobile unit (MU) a pilot signal on a continuous basis. The MU uses this pilot to determine an appropriate power signal for transmitting its signals back to the BS. This technique is not as accurate as closed-loop because it assumes that the traffic to and from the MU can be at the same power level. But open-loop systems can react quicker to fluctuations in signal strength from BS to MU.
- Closed-loop power control. This adjusts signal strength in reverse (MU to BS) channel based on metrics of performance such as bit-error rate and signal-to-noise ratio. In this case, the BS and MU communicate with each other continuously to adjust power levels. The BS sends a pilot to the MU, and the MU adjusts power on the MU-to-BS channel as in the open loop system. But the BS now makes power-adjustment decisions based on metrics and communicates this information to the MU on the control channel.

8.11.7 Cellular Network Performance and Traffic Engineering – A Quick Overview

Ideally, available channels in a cell should equal the number of subscribers active at one time. So, for example, a cell with 10 logical channels can support 10 cellular users simultaneously. In practice, it is not feasible to have capacity to handle all possible load at all times. Thus, most systems are ***blocking systems*** where $L > N$ for N channels and L subscribers. Performance questions related to blocking systems are:

- What is the average delay?
- What capacity is needed to achieve a certain average delay?
- What is the probability that a call request is blocked?
- What capacity is needed to achieve a certain upper bound on probability of blocking?

The following discussion gives a simplified version of cellular network performance. Detailed discussion is beyond the scope of this chapter and can be found in network performance and queuing analysis books. An adequate treatment can be found in Stallings [2002].

Let us start with load presented to a system:

$$U = \lambda h$$

Where

λ = mean rate of calls attempted per unit time

h = mean holding time per successful call

U= average number of calls arriving during average holding period, for normalized λ (this is also called utilization)

In a blocking system, the manner in which blocked calls are handled depends widely on the system design criteria. The following are general options:

- Lost calls delayed (LCD): blocked calls are put in a queue awaiting a free channel
- Blocked calls rejected and dropped: the user has to call back
- Lost calls cleared (LCC): user waits before another attempt
- Lost calls held (LCH): user repeatedly attempts calling

Extensive and detailed mathematical models have been developed to handle traffic blocking based on the number of traffic sources, the buffer sizes of the devices, and whether number of users is assumed to be finite or infinite. We will develop a simple and intuitive approach here.

Let us start with two key parameters:

A(i) = arrival rate of calls to a cell i. This is the same as λ

S(i) = service time (holding time) per call in cell i. This is the same as h.

The following formula shows utilization U(i) of a cell I that supports N logical channels:

U(i) = server i utilization = A(i) * S(i) /N following well-known M/M/1 (Markovian arrival, Markovian service time, 1 server) formula [Kleinrock 1976]:

Queue length at server i = Q(i) = U(i)/1-U(i)

Where Q(i) shows the number of customers in the system, including the one being served. Thus Q(i)=1, if U(i)=0.5; Q(i) reaches infinity if U(i)=1. Table 8-4 shows the impact of utilization on system performance. The key point is that U must be kept below 0.5 to keep queuing low and thus to run the system at optimal performance. If U is too high, then the callers will have to be blocked, waiting for channels to free up. To reduce U, you could

A rule of thumb used in queuing calculations is that U(i) should be kept below 0.5 to avoid queuing. The theoretical foundation for this rule of thumb is the do the following to improve performance:

- Reduce service time S by using faster servers (i.e., faster channels with higher data rates)
- Reduce arrival rate A/N per channel by adding more servers (i.e., add more channels or "steal" free channels from neighboring less-busy cells)

For example, consider a cell with 20 logical channels that receives 1 phone call per minute (A = 1) and an average holding time per call of 10 minutes (s = 10); then the utilization U of the cell is 10x1/20 = 0.5. This is not too bad. However, if the calls doubled, then U = 1. This is not good because of the queue lengths (number of callers waiting to be serviced is infinite).

Table 8-4: Impact of Utilization on Queue Length and System Performance

Utilization U	Queue Length Q=U/1-U	Impact on System Performance
0.1	0.1	No queuing – system should perform optimally
0.5	1	On average one customer in queue, including one being served – some delays expected
0.7	2.3	On average two customers. Response time may double
0.8	4	Response time could be four times, causing serious performance problems
0.9	9	Response time could be nine times, causing disastrous performance problems
1.0	Infinite	Forget it

The basic assumptions of the M/M/1 queuing formula are:

- Arrivals at the server are independent of each other.
- Service times are independent of each other.

It is not necessary for the users to know that these two assumptions are based on stochastic processes and queuing theory. For example, these arrival and service time patterns are called Poisson and Exponential distributions, respectively, in stochastic processes. Poisson arrival rates and Exponential server times are referred to as Markovian behavior in queuing systems.

8.12 Short Case Studies and Examples

8.12.1 Do Cellular Phones Cause Brain Cancer?

Some media attention has focused on a possible link between cellular (cell) phone use and brain cancer, originally because of a lawsuit that alleged such a link. Based on this, network news programs ran their own tests of mobile phones, reporting to the public that some mobile phones exceed the maximum level of emitted radio-frequency (RF) energy allowed by the US Federal Communications Commission (FCC). Due to the large (more than 140 million subscribers estimated in US) and growing number of users and the seriousness of brain tumors, this is a topic of wide concern. The American Cancer Society has conducted a study and reported what they know about the carcinogenicity (cancer-causing potential) of using cellular phones. Here is a brief summary of the report.

Cell phones operate in RF (radio frequency) and do not emit ionizing radiation, the type that damages DNA and is known to have the ability to cause cancer. Cell phone makers are required to report the specific absorption rate (SAR) of their product to the FCC. The SAR is the amount of RF energy absorbed from the phone into the user's local tissues. The upper limit of SAR allowed is 1.6 watts per kilogram (W/kg) of body weight.

What can cause higher than needed dosage of RF? One of the factors that impacts the amount of RF exposure a person gets is the size of the cell. Smaller cells are associated with lower exposures, because the farther away a cell phone antenna is from its base station (a common situation in large cells), the higher the power level needed to maintain the connection, possibly resulting in a higher dosage of RF. However, the amount of power sent from a base station to a particular cellular phone can vary because of fading, scattering and other propagation factors. Naturally, more use of cellular phones implies more exposure. Finally, older cellular phones (analog models) involve higher exposure than newer, digital equipment.

Three recently published, large-case control studies and one large cohort study have compared cell phone use among brain cancer patients and people without brain cancer. In each of the 3 case-control studies, patients with brain cancer were compared to people free of brain cancer, in terms of their past use of cellular phones. All 3 case-control studies had similar results. First, the patients with brain cancer did not report more cellular phone use overall than the controls. Second, none of the studies showed a "dose-response relationship" – a tendency for the risk of brain cancer to increase with increasing cellular phone use, which would be expected if cellular phone use caused brain cancer. Third, the studies did not show a clear link between the side of the head on which the brain cancer occurred and the side on which the cellular phone was used (with the possible exception of the Swedish study). Results of the cohort study, conducted in Denmark, agree with the findings of the three case-control studies. Cellular phone use was not associated with an increased risk of developing brain tumors overall; nor was there an association with any brain tumor subtypes or with tumors in any location within the brain. As in the case-control studies, no link was found between brain tumor risk and RF dose, as assessed by length of cellular phone use, date since first subscription, age at first subscription, or type of cellular phone used. Studies in animals also showed similar results.

In summary, there is now considerable epidemiologic evidence that shows no consistent association between cellular phone use and brain cancer. A 2003 consumer information document issued jointly by the FDA and FCC reaches the same conclusions:

"The available scientific evidence does not show that any health problems are associated with using wireless phones. There is no proof, however, that wireless phones are absolutely safe. Wireless phones emit low levels of radiofrequency energy (RF) in the microwave range while being used. They also emit very low levels of RF when in the stand-by mode. Whereas high levels of RF can produce health effects (by heating tissue), exposure to low level RF that does not produce heating effects causes no known adverse health effects. Many studies of low level RF exposures have not found any biological effects. Some studies have suggested that some biological effects may occur, but such findings have not been confirmed by additional research. In some cases, other researchers have had difficulty in reproducing those studies, or in determining the reasons for inconsistent results." (FDA, 2003)

The bottom line is that cellular telephones are a relatively new technology, and we do not yet have full information on possible health effects. There is no evidence at present that they cause brain cancer, but other studies are looking at other potential health hazards. Stay tuned.

Main source:

> "American Cancer Society report on Cellular Phones," http://www.cancer.org/docroot/PED/content/PED_1_3X_Cellular_Phones.asp?sitearea=PED

Additional sources:

> Food and Drug Administration, "Cellular phone facts. Consumer information on wireless phones," accessed Sept. 2003 from www.fcc.gov/Bureaus/Wireless/News_Releases/1999/nrwl9044.html
>
> Federal Communications Commission, RF Safety Program, Office of Engineering and Technology – http://www.fcc.gov/oet/rfsafety/
>
> Food and Drug Administration, "Cell Phone Facts: Consumer Information on Wireless Phones," http://www.fda.gov/cellphones/
>
> National Institute of Environmental Health Sciences – http://www.niehs.nih.gov

8.12.2 CVS (Compressed Voice System) Reduces the Number of Leased Lines in Kazakhstan

Current and future cellular networks are trying to provide high data rates over existing facilities. Voice compression can also contribute to higher data rates. Here is a practical example.

Kazakhstan is one of the largest countries in the world, spanning over 1,000,000 square miles. Lacking a developed copper or fiber infrastructure, most of the communications are sent by satellites. Kcell, the Kazakh GSM operator, needed a cost-effective solution for transmitting cellular traffic over the very long distances between business centers. An E1[3] satellite link costs Kcell up to $30,000/month, and Kcell would need to lease many E1 links to accommodate all the traffic between its mobile switching centers (MSCs) and base station controllers (BSCs). It needed 31 E1 lines from Almaty alone, the largest Kazakh city.

RAD, a telecom consulting firm, installed RAD's CVS (compressed voice system) in each Kcell MSC and BSC, for efficient transmission of cellular traffic. Specialized multiplexers to support CVS, were installed on 2 Mbps satellite links between MSCs and BSCs. This enabled transmission of more than 210 concurrent voice calls over a single E1 channel, instead of the normal 30 calls. Using CVS, Kcell leases only six E1 lines for its Almaty MSC, instead of the 31 lines that were initially required. The multiplexors, with some add-ons, provide smooth migration to an IP network (e.g., to support GPRS).

Source: http://www.rad.com/Article/0,6583,16158,00.html

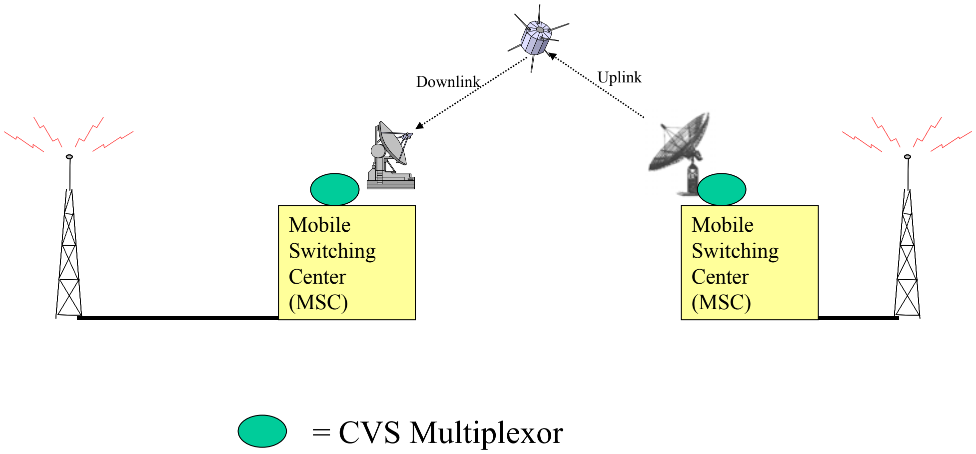


Figure 8-17: Conceptual View of the RAD Network

8.12.3 Wi-Fi as a Competition to 3G Cellular[4]

Cellular phones are primarily used for voice communications. As discussed in Chapter 6, 802.11 is also beginning to support telephone services, creating new competition for 3G. A discussion of one interesting example follows. Another example of such a service is by Vocera Communications (www.vocera.com), discussed in Chapter 6. Please also look at Cisco's 802.11 phone that supports voice over IP (www.cisco.com).

Calypso Wireless, along with other companies such as Vocera, is using voice over 802.11 to support mobile users. The main product of the company is ASNAP (Automatic Switching of Network Access Points) system. ASNAP allows a cellular phone to connect simultaneously to the cellular provider's network and a Wi-Fi network. This produces high data rates, in the 3G-plus range, without requiring more frequency allocation. With this technology in the handset and the network, a Wi-Fi/Cellular-enabled mobile phone subscriber is able to roam into any Wi-Fi coverage area and establish service with their wireless carrier's core network.

---

[3] An E1 line is a European equivalent of the US T1 line that delivers 1.54 Mbps.

[4] Suggested by Greg Kuperman

The subscriber's call-related features such as authentication, call waiting, mobile messaging, voicemail and message waiting indicator, are extended seamlessly from the cellular network to the Wi-Fi network via Calypso's Media Gateway Controller. The mobile carriers greatly benefit from this because they can deliver mobile telecommunication services over license-exempt Wi-Fi networks. They can provide wireless services to more subscribers without having to purchase additional radio frequency spectrum or install additional cellular towers.

Figure 8-18 shows a conceptual view of the network. Internet-ready devices – such as wireless phones, PDA's and notebooks – incorporating ASNAP technology, connect to either a cellular phone network or a wireless LAN, such as 802.11b (Bluetooth is also planned). A mobile phone interacts with the mobile carrier's mobile switching center (MSC) to route the call (or data) from the cellular base switching center (BSC) to the local WLAN or a standalone IP wireless transceiver. Calypso has also created a mobile video phone, the C1250i, that works seamlessly on both traditional cellular/digital frequencies and the Wi-Fi frequency and connects to the Internet at broadband speeds of 11 MB per second, many times faster than the 3G networks.

Source: http://www.calypsowireless.com/WP.pdf

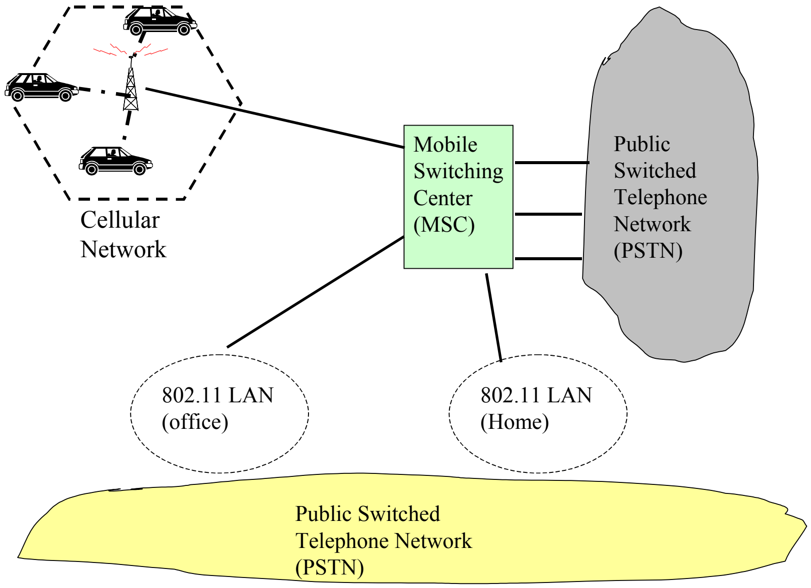


Figure 8-18: Conceptual View of Calypso Network

8.13 Summary of Cellular Networks

Wireless cellular networks establish connections between mobile users, corporate databases and applications. Cellular networks were initially developed for voice users and are predominantly analog. However, digital wireless networks are increasing rapidly. The 1G cellular systems are predominately analog while the 2G systems are digital. The most common 2G technology at present is the GSM systems that use TDMA. The 3G cellular networks are expected to deliver data rates around 2 Mbps. For computer use, you basically connect your laptop to a cellular modem or cellular phone that uses special cellular protocols to allow digital data transmission over the analog cellular network. CDPD (Cellular Digital

Packet Data)-based systems are an example of technologies that carry Ethernet-type packets for TCP/IP networks. GPRS is an attractive option (considered 2.5G) for cellular users who want to access data at 56 Kbps or higher.

The future of 3G wireless networks is being debated at present. 3G systems have to compete with other alternatives such as use of "hotspots" like airports, shopping malls, and Internet cafes, where users can access data at vey high data rates through wireless devices. Another alternative is simply extending the current 2.5G network to fill the need of existing cellular users. In addition, new technologies such as Flash-OFDM as the true high-speed mobile Internet enabling technology are a big threat to 3G. A great deal of research is currently being devoted to broadband mobile networking. Work is being done to optimize physical-layer technologies of existing wireless networks, as well as to develop and enhance the protocols and applications that facilitate user mobility between these different physical-layer technologies. It is most likely the case that the next-generation broadband mobile networks will need to support multiple physical-layer technologies for cellular systems.

8.14 Review Questions and Exercises

1) List the main steps involved in a cellular phone to cellular phone call.

2) Extend Table 8-1 to add two more factors.

3) What is the basic motivation for cell design? What are the advantages/disadvantages of small cell sizes?

4) Why are location-based services (LBSs) important for cellular networks? What are the main services and what are the tradeoffs?

5) From a consumer point of view, what are the advantages and disadvantages of LBS?

6) If you have to choose an LBS to support E911, which technique will you choose and why?

7) Capture the main characteristics of a 1G network**.**

8) What are paging networks and what are their major applications?

9) What are the two main competitors in the 2G family of cellular products? Compare and contrast the two**.**

10) What are the 2.5G cellular networks and why they are needed? Describe a popular 2.5G system.

11) What are 3G cellular systems and why they are needed? What are the main deterrents to their growth and why?

12) What are the 3G-plus systems and why they are needed? Are they real or just imagination? Explain your answer.

13) What are the principles of cellular network design?

14) Assuming each call is for 3 minutes, how many phone calls can a CDMA base station handle without dropping calls?

15) What are the main power-engineering issues in cellular networks?

8.15 References

Bates, R. *Wireless Broadband Handbook*. McGraw Hill, 2001.

Bekkers, R. and Smits, J. *Mobile Telecommunications*. Artech, 2000.

El-Osery, A. and Abdallah, C. "Power Control in CDMA Cellular Systems." http://www.techonline.com/community/ed_resource/feature_article/14863

Gibson, J., et al. *The Communications Handbook*. CRC Press, 1997.

Gralla, P. *How Wireless Works*. Que, 2001.

Guizzo, E. "Closing in on the Perfect Code." *IEEE Spectrum*, March 2004, pp. 36-42.

Jagoe, A. Mobile Location Services: The Definitive Guide. Prentice Hall, 2002.

Kleinrock, L. *Queuing Systems.* Vol. 2. John Wiley, 1976.

Mark, J., and Zhuang, W. *Wireless Communications and Networking*. Prentice Hall, 2003.

Milojicic, D., Douglis, F., and Wheeler, R. *Mobility: Processes, Computers, and Agents*. Addison Wesley, 1999.

Pichna, R. and Wang, O. "Power Control." In Gibson, J., et al., *The Communications Handbook*, CRC Press, 1997.

Price, R. and Green, P. "A communication technique for multipath channels." *Proc. IRE* 46 (Mar. 1958), pp. 555–570.

Rappaport, T. Wireless Communications: Principles and Practice. 2nd ed. Prentice Hall, 2001.

Shen, X. "Problems and Solutions; Wireless Location Based Services." *WirelessDevNet.com*, Jan. 22, 2003.

Stallings, W. *Wireless Communications and Networks*. Prentice Hall, 2002.

Stojmenovi, I., et al. H*andbook of Wireless Networks and Mobile Computing.* John Wiley, 2002.

Tannenbaum, A. *Computing Networks*. 3rd ed. Prentice Hall, 1996.

Tang, J. "References on RAKE Receiver." April 30, 2003, link: www.ece.umn.edu/users/tangjun/shared/RAKE.pdf

Walker, J., ed. *Advances in Mobile Information Systems*. Artech House Mobile Communications Library, December 1998.

Relevant Web Links

- Mobile Info web site (www.mobileinfo.com).
- www.pcsdata.com: PCS web site
- www.gsmdata.com: GSM web site
- (www.pcca.org) portable computers and communications association
- www.palowireless.com

http://www.key3media.com/interop/lasvegas2001/education/presentations/ieee/E6a_M_Ritter.pdf

http://nms.lcs.mit.edu/~haril/papers/CS294/paper/paper.html http://news.com.com/2100-1033-275389.html

http://www.redherring.com/mag/issue/issue101/1430019743.html

http://www-106.ibm.com/developerworks/library/wi-what2/?dwzone=wireless

http://www.shortcliffcommunications.com/magazine/volume.asp?vol=8&story=42