9

Wireless Telephone Service

Introduction

Wireless cellular mobile telephone service is a high-capacity system for providing direct-dial telephone service to automobiles, and other forms of portable telephones, by using two-way radio transmission.

Cellular mobile telephone service was first made available in the top markets in the United States in 1984, and in a very short time has achieved considerable growth and success. During its first four years in the United States, from 1984 to 1988, it experienced a compound annual growth of more than 100 percent. By 1990, its subscribers in the United States numbered 5.3 million; by 1996, its subscribers numbered over 44 million. Cellular mobile telephone service is also a great success in Europe and Scandinavia, where growth rates rival, and in some cases surpass, those in the United States.

Cellular telephone service was initially targeted at the automobile market, but small portable units have extended the market to nearly everyone on the move with a need to telecommunicate and now includes small personal units that can be carried in a pocket. One wonders whether a wrist radio telephone is only a matter of a few more years. The cellular principle has been suggested on a very low power basis to create community systems that could bypass the copper wires of the local loop—so-called wireless local loop (WLL).

The basic principles of wireless cellular telecommunication are described in this chapter along with a discussion of the various technological aspects of a wireless system that must be specified. These basic concepts serve to introduce the descriptions of the more popular specific implementations, such as the Advanced Mobile Phone Service (AMPS) and the Global System for Mobile (GSM) communication. AMPS is described in some detail in this book, since it was the first system to be implemented and also because its details serve to illuminate the differences between it and other, newer systems. AMPS of the 1980s is based on the analog technology; GSM and many other newer systems of the 1990s are based on digital technology. Standards are a big issue with cellular wireless telephone service, and many different countries have each adopted their own unique approach, with even different systems in use in the same country, as in the United States.

Wireless telecommunication is also known generically as personal communication service (PCS), although the term PCS is sometimes meant to refer exclusively to newer all-digital systems operating at 1,900 MHz. The term PCS has also meant the overall concept of being able to reach a person anywhere at anytime by any means of telecommunication. Because of all these different interpretations, to eliminate any confusion, the term PCS is avoided in this book.

The original AMPS cellular system and a newer digital version operate in a range of radio frequencies from 824 to 894 MHz. Since the demand for wireless service was so great, in the mid-1990s the FCC allocated additional frequencies in the 1,900-MHz band for wireless service and then auctioned off the channels to the highest bidder. The channels were assigned to create six blocks of channels for as many as six separate service providers. The prices paid in the auction by many were far too high to be commercially viable, although in theory, the government made billions of dollars. By the end of the 1990s, a number of the firms who had bid successfully had filed for bankruptcy, with the government collecting little. The lesson learned is that auctions are not the best way to allocate spectrum. Spectrum should probably be leased on a yearly basis with recurring fees.

A form of local or neighborhood two-way radio service, called a personal communication network (PCN), has been proposed. There are also cordless telephones that work over about 100 feet and enable people to walk about the home talking on the telephone. These cordless phones use two-way radio and connect to the standard telephone line. Modern cordless telephones utilize digital technology and, though fairly sophisticated, do not support the handoff feature that makes cellular mobile telephone service such a success.

This chapter describes the more popular wireless cellular mobile communication systems and ends with a description of the various new satellite telecommunication systems that are being developed and introduced. But first, a short history of the development of cellular service in the United States.

A short history

Prior to cellular mobile telephone service, mobile telephony was provided by conventional two-way radio, which allowed only a few dozen two-way radio channels in a given service area. A single, centrally located, high-power radio transmitter served a whole area about 50 miles in diameter.

The service in an area was provided either by a wireline common carrier (such as a Bell company), an independent telephone company, or a radio common carrier. The very small number of users who could be served in a given area meant that the service was quite costly, and the limited capacity of the service meant that many potential customers went unserved. Cellular mobile telephone service solved the problem of congestion, and its mass market acceptance made mobile service affordable to many customers.

Cellular mobile telephone service had lengthy delays in making its way to commercial introduction and availability. These delays were the result of the federal regulatory process. But once it was introduced, cellular service was and remains a phenomenal success.

The basic principles of mobile cellular telephone service were formulated at Bell Labs in the late 1940s. The technology to make the service economically feasible was not available, however, until the early and mid 1970s. AT&T had applied earlier to the Federal Communications Commission (FCC) for permission to offer an advanced mobile phone service (AMPS) based on the cellular principle, but the FCC wanted to determine how to introduce competition into the provision of cellular service. In early 1975, the FCC reallocated a portion of the UHF television band so that it could be used for cellular telephone service. The FCC opened 40 MHz of the 800-MHz radio band to any qualified common carrier, thus bringing competition to cellular service. In March 1977, the FCC granted authorization to the Illinois Bell Telephone Company to install and test a developmental version of AMPS in Chicago. The subsequent test was successful, and in 1983 the Chicago system offered the first commercial cellular service in the United States. The delays in offering cellular service were caused by the over ten years spent by the FCC in drafting regulation to stimulate competition. This regulation was finally approved in 1982.

Since the FCC had decided that it would be in the best interests of the public if competition were stimulated in cellular telephony, they issued two licenses in each area so that the public would have two service providers from which to choose. The wireline carriers were restricted to one license per area. As might be expected, there was an initial flood of applications to the FCC to obtain a license to provide cellular service. The FCC then encouraged competing applications to negotiate some form of consolidation. All this took more time and further delayed the introduction of cellular service, particularly for the nonwireline carriers.

Cellular service in each geographic area is provided by a wireline common carrier, which is a subsidiary of the local telephone company, and by a nonwireline common carrier. The radio spectrum space used for cellular service is divided in half to accommodate the two carriers serving a geographic area. The mobile equipment itself is available from a number of vendors. This equipment was initially costly, but these costs have dropped substantially as the service has become more widespread and used.

Basic principles

Prior to cellular telephony, mobile telephone service was obtained from a single high-power transmitter that served a single large geographic area. The service could serve only a small number of users and was very costly. With cellular mobile telephone service, a 50-MHz bandwidth in the 800-900 MHz radio band was used to create 832 two-way radio channels. This alone is a substantial increase over the few dozen channels previously available with conventional mobile telephony. However, the total number of customers served is increased further by reusing channels in the same geographic area. This feat is accomplished by the use of a number of low-power radio transmitters, each serving a small area, or cell, within the larger geographic service area.

The typical cell has a radius of about 6 to 12 miles. The low power of the transmitter means that the same channel can be used again in another part of the geographic area without causing interference. The entire geographic area is thus divided into cells, with each cell being served by its own transmitter. The cell configuration is chosen to minimize interference caused by the reuse of the channel—hence the use of the word "cellular." Usually, seven cells are taken to form a cluster, and the pattern of the cluster is repeated over and over again in the metropolitan area to be served. As shown in Figure 9.1, the cells can be depicted as hexagons; the actual shape of a cell varies with terrain and radio propagation. Cells serving a dense area with many users are usually allocated more channels. The channels are then reused in adjacent clusters. The spatial separation of cells using the same radio channels coupled with their low power reduces any cochannel interference to acceptable levels.

If congestion starts to appear, cells can be further subdivided, or split, into smaller cells using even lower powered transmitters. Thus, the system can grow gradually to serve more users as demand increases, although additional cell sites with antennas and network equipment are required. A larger number of users leads to lower prices for the mobile telephone instrument, and this leads to further increases in demand.

A key feature of cellular mobile telephone service is the mobility of the user. This mobility clearly extends across cells, and thus there is a need to track the user and to change radio channels for different cells.

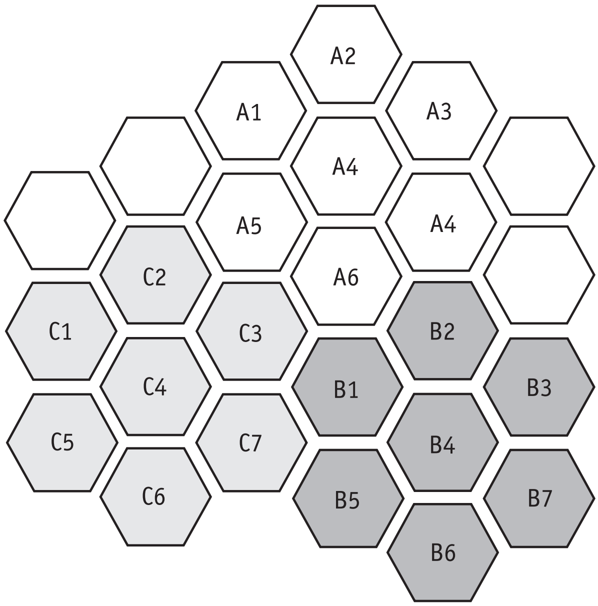

Figure 9.1 Cells are organized into clusters, with most cellular systems using seven cells per cluster. The clusters are then repeated over and over again to cover the whole geographic area served by the system. Although the cells are depicted as hexagons, their actual shape is quite irregular and depends on the terrain and radio propagation.

This dynamic tracking of the user along with changes in radio channel is called a handoff, and is a key feature of cellular service. The information necessary to cause a handoff is sent in the downlink speech channel, a technique called in-band signaling. Another essential feature is the use of a shared radio channel that is used to broadcast the numbers of the mobile units being called—a feature called paging.

To summarize, the basic features of wireless cellular telephone service are as follows:

- Low-power transmission;
- Frequency reuse through clusters of cells;
- Handoff from one frequency to another;

- In-band signaling; and
- Paging.

All the specific implementations of the various terrestrial mobile cellular systems around the world are based on these basic features and principles.

Multipaths

Cellular telephony uses high-frequency radio transmission, which is particularly susceptible to reflections that lead to multiple paths from the transmitter to the receiving antenna. Some of these multiple signals arrive out of phase with respect to each other and accordingly cancel. These cancellations cause fast fading of the received signal as the automobile is traveling down the road. Signal processing can be used to minimize the subjective annoyance of this fading by filling in missing portions of the speech signal.

One possible solution to the fading problem is the use of two receiving antennas at the mobile unit. The two antennas are separated by about half a foot. If the signal at one antenna is in a deep fade, then there is a strong probability that the signal at the other antenna is strong. An electronic switch compares the two signals and chooses the stronger. In this way, some of the fading problems caused by multiple-path (multipath) reflections can be corrected. This is known as switched space diversity and was used at one time by at least one manufacturer of mobile units for the Advanced Mobile Phone Service (AMPS) system in the United States.

Multipaths can be reduced by replacing omnidirectional antennas at the base stations with directional antennas that concentrate the radio signal in a narrow beam, thereby reducing reflections. The focusing of the antenna directional pattern to create pie-shaped sectors within a cell is called sectorization. Typically, there are three or six such sectors per cell.

The effects of fast fading can also be reduced by sending the radio signal in a number of frequency channels. This is accomplished by hopping across all the channels in a known repetitive pattern. In this way, if one channel is in a fade, the others most likely are not and most of the signal will get through. Frequency hopping is used in the Global System for Mobile (GSM) communication.

In newer digital cellular mobile systems, adaptive equalization of the received radio signal is used to combat multipaths. In effect, the reflected signals are subtracted from the received signal through the use of digital filters that dynamically change their characteristics in response to differing situations.

Implementation differences

All cellular mobile systems are based on the features and principles listed previously. The differences in various implementations are how individual radio channels are shared by users, how the speech signal is encoded, which radio bands are used, and how the radio carrier is modulated.

Advanced Mobile Phone Service (AMPS) was the first system to be implemented, and it was based on the technology of the 1980s. A baseband, analog speech signal is transmitted directly. Newer cellular systems encode the speech signal in a digital form. Digital encoding increases the bandwidth needed to sent the encoded signal, but bandwidth is severely constrained in cellular systems. Hence, some form of compression is usually used to encode the digital signal. Voice coders—called vocoders—have been investigated for decades, and the encoding used in cellular systems draws heavily on the results of this research. Most of the encoding schemes are a variant of a dynamic digital filter with varying coefficients whose values are obtained from linear predictive coding (LPC)—a technique invented at Bell Labs by B. S. Atal in the 1960s.

The frequency bands used for cellular were initially centered around 900 MHz. Newer systems operate as high as 1,900 MHz. The bands are divided into a number of radio channels with differing widths, depending on the implementation. The original AMPS system uses radio channels that are 30 kHz wide. Some newer digital systems have radio channels that are 200 kHz wide. The radio carrier for each channel is modulated through a variety of methods. Broadband frequency modulation is used for the radiofrequency modulation in the AMPS system. This technique was used to increase noise immunity for the low-power radio signal. Forms of phase-shift keying are used in some of the digital systems. Since all cellular systems use a number of separate radio channels, they all are based on a form of frequency-division multiple access (FDMA) at the radio-frequency level.

Multiple access

In the older AMPS system, a single voice signal occupies each entire 30-kHz radio channel. The newer systems attempt to increase their overall capacity by sharing a radio channel among a number of voice signals. This is accomplished through either time-division multiple access (TDMA) or code-division multiple access (CDMA), or (more usually) a combination of both.

The term "multiplexing" refers to the combining together of a number of separate signals to share a communication medium. This sharing through multiplexing is also referred to as multiple access and is usually accomplished through frequency-division and time-division multiplexing. In multiple access terminology, these are called frequency-division multiple access (FDMA) and time-division multiple access (TDMA). They are illustrated in Figure 9.2.

In frequency-division multiple access (FDMA), each signal corresponding to a telephone conversation is assigned its own exclusive band of frequencies for the duration of the call. In time-division multiple access (TDMA), the same band of frequencies is shared by all the calls, with a short burst of digital data from each conversation being sent alternately in a repetitive pattern. TDMA is usually performed in a number of separate bands—in effect, a combination of FDMA and TDMA.

A new method for multiple access that is being used in some newer digital wireless systems is code-division multiple access (CDMA). With CDMA, each digital signal is assigned a unique multiplicative code, which has the effect of spreading the spectrum to cover the entire assigned band. All the spectrum-spread signals are then sent on top of each other simultaneously and are separated at the receiver by an inverse application of the unique codes. Another form of spread-spectrum technology is frequency hopping, in which short bursts of data from each signal hop from one frequency to another in a known pattern.

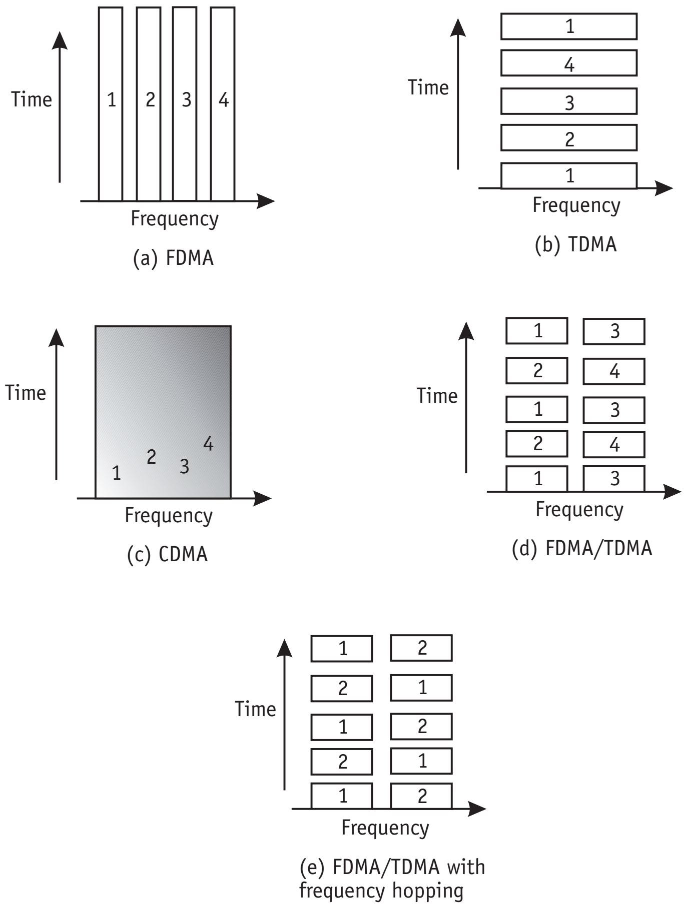

Figure 9.2 Various means are used to facilitate multiple access to a communication medium: (a) in frequency-division multiple access (FDMA), each signal corresponding to a telephone conversation is assigned its own exclusive band of frequencies for the duration of the call; (b) in time-division multiple access (TDMA), the same band of frequencies is shared by all the calls, with a short burst of digital data from each conversation being sent alternately in a repetitive pattern; (c) in code-division multiple access (CDMA), each digital signal is assigned a unique multiplicative code, which has the effect of spreading the spectrum to cover the entire assigned band—all the spectrum-spread signals are then sent one top of each other simultaneously and are separated at the receiver; (d) TDMA is usually performed in a number of separate bands, in effect, a combination of FDMA and TDMA; (e) with frequency hopping, short bursts of data hop from one frequency to another in a known pattern.

System operation

Cellular mobile telephone service is a system involving the equipment located at the mobile unit, the radio equipment located at the cell site, and a central switching office that controls the operation of the whole system and that interfaces to the public switched telephone network.

Each cell is served from its own master radio transmitter, receiver, and antenna. The antenna can be either omnidirectional or directional. An omnidirectional antenna would be situated in the center of the cell, and a directional antenna with a coverage of 120 deg could be situated at one of the vertices of the cell. A directional antenna is somewhat less susceptible to interference from other cells. Directional antennas are used at the center of a cell to create sectors, with three and six sectors being typical where such sectorization is implemented, as shown in Figure 9.3. The radio beams used with sectorization are more narrow, and hence are more powerfully concentrated and also are less subject to multipath reflection. The antenna and other equipment located at each cell site constitute a base station (see Figure 9.4). How signals are encoded,

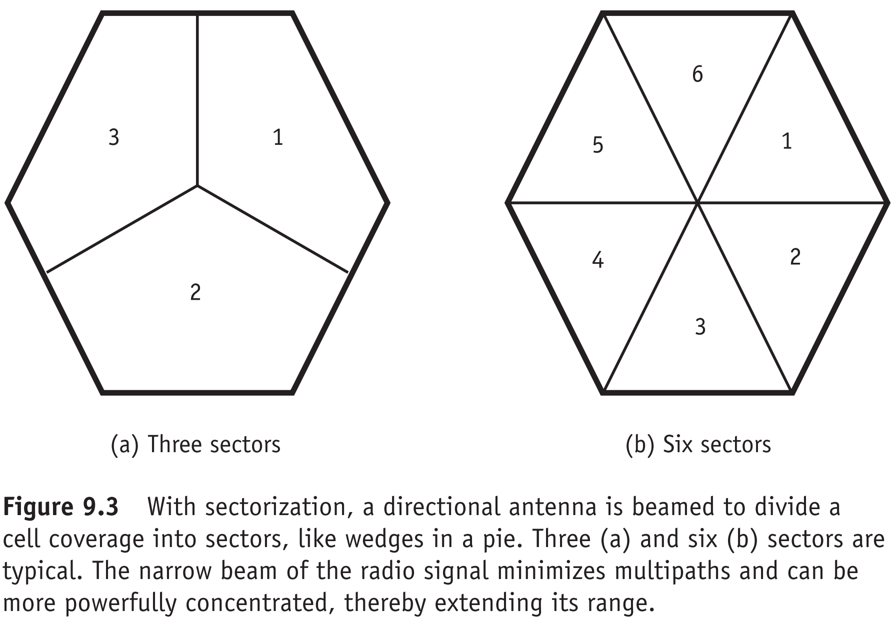

Figure 9.3 With sectorization, a directional antenna is beamed to divide a cell coverage into sectors, like wedges in a pie. Three (a) and six (b) sectors are typical. The narrow beam of the radio signal minimizes multipaths and can be more powerfully concentrated, thereby extending its range.

Figure 9.4(a) Photograph of cell site, or base station. (*Source*: Bell Atlantic Mobile Systems ©1986. All rights reserved.)

combined, and transmitted determines the differences between the various implementations of cellular mobile telephone service.

Advanced Mobile Phone System (AMPS)

The very first implementation of the cellular mobile concept was the Advanced Mobile Phone System, or AMPS. This is an analog system in which each user fully occupies each radio channel of 30 kHz. AMPS is old technology in an industry that is rushing ahead in terms of market saturation and of advances in technology. But AMPS fully utilizes all the features

Figure 9.4 (b) Photograph of Figure 9.4a's cellular antenna. (*Source*: Bell Atlantic Mobile Systems ©1986. All rights reserved.)

and principles of cellular mobile telephone service previously described and listed. AMPS therefore is a good place to start our study of the workings of specific implementations of cellular mobile telephone service.

Each base station in AMPS operates in the 800-900 MHz range. A radio frequency band from 824 to 849 MHz is used to receive signals from the mobile units (the uplink), and a band from 869 to 894 MHz is used to transmit signals to the mobile units (the downlink). The wireline carriers use the so-called B band, and the nonwireline carriers use the A band; each carrier has 416 two-way radio channels. The 416 two-way radio channels for each system are divided over the seven cells that form a cluster, giving an average of about 60 channels per cell.

The base station transmits with a power of up to 100W, and a non-portable mobile unit transmits at a maximum effective radiated power of about 7W. To help control interference, the transmitted power of the mobile unit can be remotely decreased in steps. This is accomplished by a special code that is transmitted to the mobile unit and causes the mobile unit to decrease, or attenuate, its transmitted power to any one of eight prespecified levels. Each level decreases by 4 dB from the preceding level. The code that accomplishes this decrease in transmitted power is called the mobile attenuation code.

Because noise immunity is very important, frequency modulation (FM) is used for the radio transmission between the mobile units and the base stations. FM with a peak deviation of 12 kHz of the carrier is employed with an rms frequency deviation of 2 kHz for a normal speaker. The radio channels are spaced every 30 kHz in the allocated bands. Since the bands have a total width of 50 MHz, the maximum number of two-way radio channels is 832. Half of these channels go to the A band and the other half to the B band.

The base stations are connected by landlines to a central place called the mobile telephone switching office (MTSO), as shown in Figure 9.5. The MTSO is connected by trunks to the public switched telephone network. An important feature with cellular service is the ability to make telephone calls to the mobile unit over the switched public network as if the mobile unit was a normal telephone with its own 10-digit telephone number. Hence, the MTSO is connected to the public switched network via these trunks.

The mobile unit can move from cell to cell, and when this occurs, it will need to change the frequencies of the radio channels used to transmit to and receive from the base stations. This is known as a handoff. The relative received signal strength of the mobile unit must be monitored, and when it leaves the range of one base station and enters the range of another base station, information to specify the new frequencies must be sent to it. This information is transmitted as a short burst of data over the voice channel that is being used. The mobile unit needs to know when an incoming call is occurring and also must be able to dial out to set up a call. A shared data channel (also called a paging channel, a setup channel, or a control channel) is used for these purposes. The MTSO supervises and controls the entire operation of the system, including the assignment of

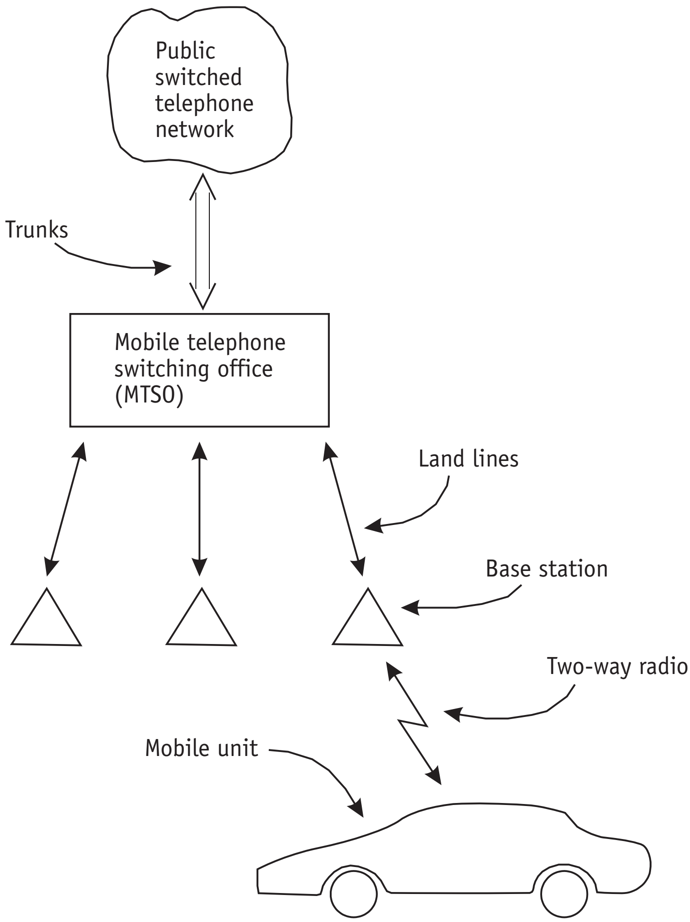

Figure 9.5 The mobile unit communicates by two-way radio with the base station. The base stations all communicate over landlines with the mobile telephone switching office (MTSO), which then maintains communication with the public switched telephone network (PSTN).

channels and the changing of frequencies during a handoff. The MTSO sends data over the landlines to the base stations for these control and supervisory functions.

The shared data channel transmits data at a 10-kbps rate. However, data encoding and message repeating reduce the actual information rate to 1.2 kbps, which is equivalent to a practical limit of 25 messages per second when fully loaded. Frequency shift keying is used, with a frequency deviation 8 kHz above and below the carrier frequency. The binary data is encoded using a biphase Manchester format, in which a 0/1 transition signifies a binary 1 and a 1/0 transition signifies a binary 0. The shared data channel is used to request service and to identify the mobile unit when its power is turned on, to assign the initial frequencies to be used for transmission and reception, and to terminate service.

A 34-bit binary number derived from the 10-digit telephone number assigned to the subscriber uniquely identifies each mobile unit and is entered and stored in the mobile unit. This number is sent by the mobile unit to the MTSO, where it is used for billing purposes. A 15-bit code entered into the mobile unit identifies the home system from which service is obtained. A 32-bit electronic serial number (ESN) is factory set into each mobile unit and can be accessed from the MTSO for security purposes.

The 50-MHz-wide radio spectrum available for cellular service is divided into two 25-MHz spaces that are assigned for use by the two separate mobile system operators in each area, a so-called A system and B system, as shown in Figure 9.6. The B system is operated by a subsidiary of the local wireline telephone company (a Bell company or an independent non-Bell company, such as GTE), and the A system is operated by a non-wireline carrier. The A system uses radio frequencies from 824 MHz to 835 MHz and from 845 to 846.5 MHz for transmissions from the mobile units and frequencies from 869 MHz to 880 MHz and from 890 to 891.5 MHz for transmissions to the mobile units. The B system uses 835 to 845 MHz and 846.5 to 849 MHz for mobile transmissions and 880 to 890 MHz and 891.5 to 894 MHz for base transmissions. Transmission from the base station to the mobile unit is called the forward direction, and transmission form the mobile unit to the base station is called the reverse direction. Each of the two systems has a total of 416 two-way radio channels available for its use in these frequency spaces, divided across the seven cells in a cluster.

Twenty-one channels in the A system, and 21 channels in the B system are used as shared data channels, or setup channels. The 21 setup channels are allocated across the cells, with usually one channel per cell. The mobile unit is programmed to scan all the setup channels and chooses

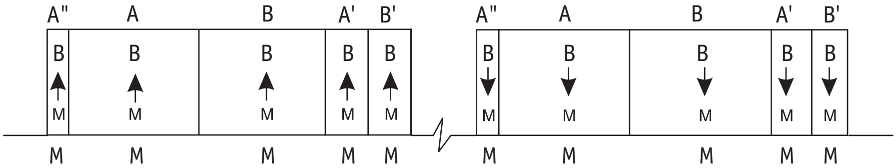

Figure 9.6 Two radio-frequency bands are used for cellular telephone service in the 900-MHz bands by the AMPS system. The band from 824 MHz to 849 MHz is used for transmission from the mobile unit to the base station (the uplink) and is shared by the A and B systems. The band from 869 MHz to 894 MHz is used for transmission from the base station to the mobile unit (the downlink) and is likewise shared by the A and B systems.

the setup channel with the strongest signal. This channel usually corresponds to the nearest base station. The mobile unit can be programmed to scan the setup channels for only one system or to scan both but with a preference for one system over the other.

A transfer from one radio channel to another is called a handoff. The MTSO makes a decision about whether a handoff is required by measuring the strength of the signal received from the mobile unit every few seconds. This periodic examination of the mobile's signal is called locating, which refers not to a precise geographic location but rather to signal strength. Thus, a mobile unit could be geographically closer to one base station, but because of terrain, its signal might actually be more strongly received at a more distant base station.

Supervision of a call is accomplished by out-of-band tones on the voice channel. A supervisory audio tone (SAT) of either 5,970; 6,000; or 6,030 Hz is regularly sent every ¼ second by the base station to the mobile unit, which then retransmits the tone back to the base station. If the tone is not received back at the base station for a long enough time, it is assumed that the mobile unit has ceased transmitting. The base station sends information (called the SAT color code, or SCC) to the mobile unit specifying the specific SAT to be used, and if the actual received SAT disagrees, voice communication is suspended. The round-trip delay of the SAT was at one time suggested as a gross measure of the physical distance of the mobile unit from the base station, but received signal strength is now used to determine handoffs.

A signaling tone (ST) of 10 kHz is sent from the mobile unit to the base station. The ST is used to acknowledge any orders from the MTSO, to perform flash requests comparable to the hook-flash of a conventional telephone, and to signal a release request when the user wishes to disconnect the call.

If the channel needs to be changed during a call, information is sent from the base station to the mobile unit over the voice channel as a very brief burst of digital data. The mobile unit decodes this information, changes its transmitting and receiving frequencies to the new channels, and establishes the voice circuit on the new cell. All this happens in a fraction of a second and is not noticed by the users. The AMPS cellular system is designed to handle calls arriving at a mean rate of one call per second in the densest cell.

The data channel is used by the mobile unit to request service. The identity of the mobile unit along with the telephone number of the called party are transmitted over this channel to the base station and then over landlines to the mobile telephone switching office (MTSO). The MTSO then establishes a conventional telephone circuit to the called party. When the mobile unit is turned on but is not being used for an actual call, it continuously monitors the strongest data channel for any transmitted paging messages containing its identification number. If the mobile unit recognizes its identification number in any of these paging messages, it responds to the page by sending an appropriate data message back to the base station over the data channel. It then receives information over the data channel telling it what specific voice channel to use to establish voice communication. Once the voice channel has been established, the base station sends a data signal over the voice channel to activate ringing at the mobile unit. The 10-kHz signaling tone is transmitted over the voice channel by the mobile unit to indicate that it is ringing. When this tone ceases, the base station knows that the mobile unit has answered, and the two parties are connected to begin their voice conversation.

Newer cellular systems

By 1990, cellular mobile telephony had been so successful that the demand had outstripped capacity. Hence, solutions were sought to increase the capacity of the existing allocation of radio spectrum space and also to use additional spectrum space. The AMPS system allocates a single user per 30-kHz radio channel. Digital encoding coupled with TDMA allows three users in the identical 30-kHz radio channel—the digital AMPS (DAMPS) approach, also known as IS-54. The European global system for mobile (GSM) communication is also digital TDMA-based, but uses TDMA within radio channels that are 200 kHz wide. An even newer approach is to spread the spectrum of the signals over a broad bandwidth and then send many signals at the same time using unique codes to separate them upon reception—the CDMA approach, also known as IS-95.

In these newer cellular systems, the stationary base station (BS) antenna site is known as a base transceiver station (BTS). A number of BTSs are controlled by a base station controller (BCS) and together form a base station subsystem (BSS), as shown in Figure 9.7. A number of BCSs then connect to the public-switched telephony network (PSTN) through a gateway mobile switching center (GMSC). The GMSC has access to a variety of databases containing such information as the equipment identity register (EIR), a home location register (HLR), and a visitors location register (VLR). The EIR contains the serial numbers of authorized mobile units and thus acts as protection against stolen mobile units. The paging channel is called a broadcast channel (BCH), and the actual two-way communication occurs over a traffic channel (TCH).

Global System For Mobile (GSM) Communication

The Global System for Mobile (GSM) communication was introduced in 1992 as a European standard and has achieved much success there. A variant of it is available in the United States. GSM initially stood for Gropue Spéciale Mobile.

GSM as first introduced in Europe operates in the 900 MHz band (called GSM900), and a newer system operates in the 1,800 MHz band

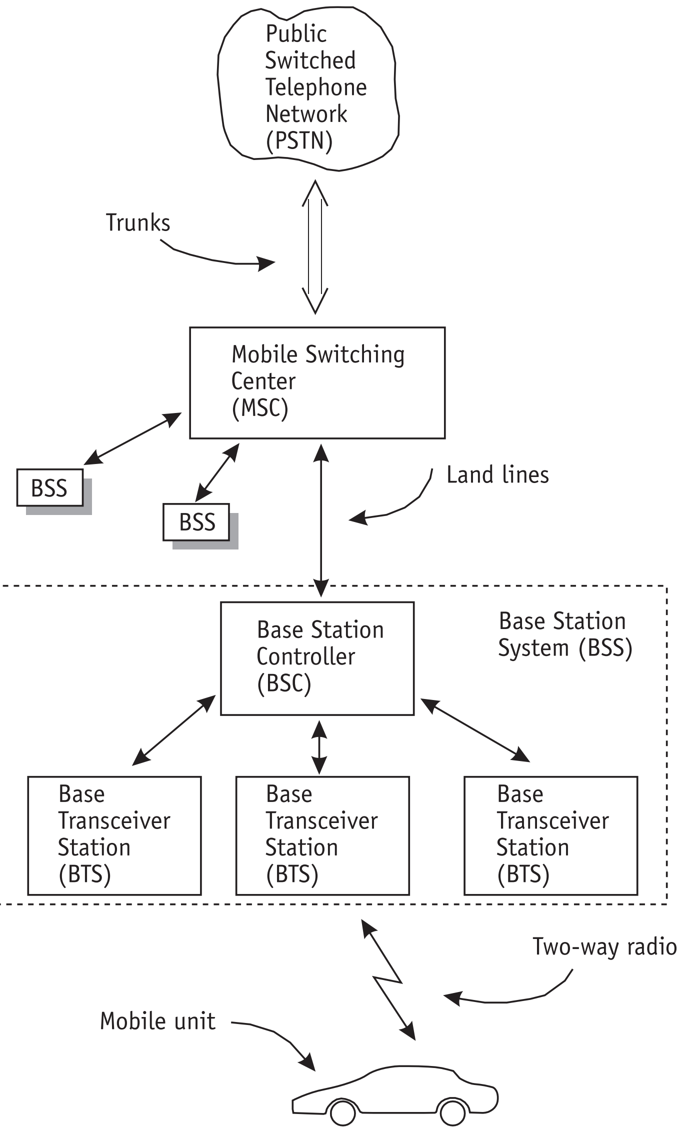

Figure 9.7 A mobile unit communicates by two-way radio with a base antenna at the base transceiver station (BTS). A number of BTSs are monitored and controlled by a BSC. The BSC and its BTSs form a base station subsytem (BSS). A number of BSSs are controlled and monitored by the mobile switching center (MSC), which also is the gateway to the public switched telephone network (PSTN). The MSC has access to various databases that contain information about the mobile users.

(called GSM1800). A GSM1900 system, intended for the United States, operates in the 1,900 MHz band. Other than operating in different radio bands, all the GSM systems are the same in terms of their principles of operation. An advantage of the GSM approach is that mobile phones can be manufactured that will work in all three bands and thus can be used in any country that has GSM.

In GSM900, the uplink radio connection is in a band from 890 to 915 MHz, and the downlink radio connection is in a band from 935 to 960 MHz. The uplink for GSM1800 operates from 1,710 to 1,785 MHz, and the downlink operates from 1,805 to 1,880 MHz. An uplink and a downlink taken together create a single two-way radio circuit, and such a pair is always chosen to be 45 MHz apart across the two links in GSM900 and 95 MHz apart in GSM1800. A radio channel within each band is 200 kHz wide. After allowing for a 200-kHz guardband, a total of 124 two-way radio circuits are formed in the uplink and downlink bands and are assigned across a cluster of seven cells in GSM900. GSM1800 uses 374 two-way radio circuits in its bands.

Eight users share each 200-kHz radio channel through the use of TDMA. This means that each user effectively has 200-kHz/8 = 25 kHz, which is comparable to the bandwidth assigned each user of AMPS. The GSM speech signals are encoded at 13 kbps using a form of predictive coding for compression, called regular pulse-excited, long-term prediction (RPE-LTP) and also known as residual-excited linear predication (RELP). The speech coder models the excitation source and the vocal tract, and encodes the information for every 20-msec segment of the speech signal into 260 bits. Thus there are 260 bits per 20 msec, or an overall data rate for the encoded speech signal of 13 kbps. The gross bit rate for the encoded speech signal plus channel coding for synchronization and control increases to 22.8 kbps.

Error correction is introduced along with interleaving of the signal so that any bursts of data that are destroyed can be reconstructed. These techniques are so powerful that two bursts lost out of eight bursts can be reconstructed perfectly. However, these error correction techniques add to the overall bit rate, which then becomes 33.85 kbps per speech circuit. The 200-kHz radio channel supports a data rate of 270.8 kbps for the eight circuits that are time-division multiplexed together. All the data for each circuit, including the encoded speech, synchronization, and error correction, is sent in a short burst of data lasting about 0.540 msec. Actually, time is allocated to ramp-up and than ramp-down gradually before transmitting the actual data. The time for this entire sequence of ramp-up, data, and ramp-down is 0.577 msec. Eight bursts, or time slots, of data taken together are called a frame. The radio carrier is modulated by a technique called Gaussian minimum shift keying (GMSK), which is a form of binary frequency shift keying (FSK).

Paging, signaling, and synchronization information are sent as bursts of data in a common control channel (CCCH), which is a logical channel created from the assignment of specific time slots in the flow of TDMA data in a radio channel. For example, the first time slot in the sequence of eight—a frame—might be assigned as the common control channel. This approach of creating a virtual channel within the stream of time slots is also used to create the broadcast channel (BCH) for paging of mobile units. When the mobile unit is first turned on, it begins an acquisition process to find the radio channel being used to send paging and control information. The process searches for the radio channel with the highest power and then examines that channel to determine whether it contains a peak in energy about 67 Hz above the center frequency of the radio channel. This peak corresponds to a sine wave that is transmitted in the control channel for frequency correction purposes—it is called a frequency-correction channel (FCCH). If the peak is not found, the mobile then searches other radio channels until it is found. The mobile is passive throughout this acquisition process, which typically takes only a few seconds.

Frequency hopping at the relatively slow frame rate is used—called slow frequency hopping (SFH). Each frame is sent in a repetitive pattern hopping from one frequency to another through all the available radio channels. Frequency hopping reduces the effects of fading. This is because fading is frequency dependent, and if fading is occurring at one frequency, it most likely will not be occurring at the other frequencies, and only a small amount of data will be lost.

The mobile unit is programmed to monitor the strength and quality of a sample of the received radio signals from adjacent cells. A report is constantly generated and transmitted back to the base station, which then determines when to switch the call to a new radio channel. The approach is called a mobile assisted handoff, or MAHO. A GSM handoff is decided on the use of radio signals received at the mobile unit as opposed to AMPS in which a handoff is decided on the strength and quality of the radio signal received at the base station.

A unique identity number identifies each mobile unit, and the mobile unit must have a card inserted into it containing this number before it can be activated. This card—called a subscriber identity module (SIM)—acts as an identity card for the mobile unit and affords some protection against loss of the mobile unit. The identity number is encrypted when transmitted over a radio channel. Signaling information and user information is encrypted to protect it from being intercepted and interpreted during radio transmission. As further security, each mobile user is assigned a temporary mobile subscriber identity (TMSI) for the time that the subscriber is using the mobile service.

With GSM, the system always knows the status of each mobile unit—for example, whether the mobile unit is on but idle or turned off. The mobile sends a message to the system when it moves to a new location so that the system always knows the location of each mobile unit—a process known as registration.

Digital AMPS (DAMPS)

Another solution to the capacity problem is the use of digital technology and TDMA to increase the capacity while staying within the present spectrum space. A digital approach can increase the capacity of each channel used, and the signal is more secure from someone listening in to the channel. With the old analog AMPS cellular system, anyone with a radio receiver tuned to the frequency of a cellular channel could listen to the conversation.

Digital AMPS uses a digital bandwidth compression technique called linear predictive coding (LPC). Three voice signals are time-division multiplexed together into a single radio channel. Each voice signal is encoded at 13 kbps using a form of LPC, and additional data is added for handshaking, noise immunity, and synchronization purposes. A length of 40 msec of each speech signal is analyzed and then sent in a burst. Three bursts corresponding to the three signals are sent sequentially every 40 msec within a 30-kHz cellular channel. The three signals time-division multiplexed together require a total of 48.6 kbps, which can be sent over a single 30-kHz radio channel. Each speech signal occupies its own data burst in the TDMA sequence. The final result is a tripling in capacity compared to conventional analog AMPS.

Digital AMPS operates in the same 30-kHz radio channels used by AMPS. In this way, an AMPS system can be gradually converted to DAMPS by assigning more and more radio channels to it. The radio signal is modulated using a form of differential phase-shift keying (DPSK). Modern cell phones can operate in either an AMPS or a DAMPS format. Such cell phones are called dual mode. They attempt to connect first using DAMPS and then if no capacity is available, switch to AMPS.

Code-Division Multiple Access (CDMA)

Another technology that can increase the capacity of cellular telephony is spread-spectrum transmission. With spread-spectrum transmission, each voice signal is sent over the full bandwidth of the total spectrum space. The trick is how to separate the jumble of received signals to concentrate on the desired single signal. One way is to digitize the voice signals and add a unique signature code to each by multiplying the signal bit stream by a unique signature bit stream. The receiver then searches for the unique signature code for the desired signal. This is somewhat similar to way we can listen to one conversation at a cocktail party even though our ears are being bombarded by dozens of speech signals. Since each multiplexed signal has its own unique code, the technique is called CDMA.

Another spread-spectrum technique is frequency hopping, in which each signal continuously switches channels in a known pattern. Again, the receiver searches for the appropriate pattern for the desired signal. Spread-spectrum transmission can be less prone to interference and thus allows more signals to share the same spectrum space. Slow frequency hopping is used in the GSM system.

Spread-spectrum technology in the form of CDMA was advocated and developed for cellular mobile telephone service by Qualcomm, Incorporated. Qualcomm claims an increase of from 10- to 20-fold in capacity over conventional analog AMPS. The spread-spectrum system was known initially as Qualcomm CDMA and then became formalized for North America as interim standard IS-95, adopted by the Cellular Telephone Industry Association (CTIA). It is now also known as CDMA-One. It operates in the same 900-MHz band as AMPS. Each radio channel has a width of 1,250 kHz for a total of 20 radio channels in each direction. The channels operate in uplink and downlink pairs separated by 80 MHz. CDMA is also being used by many of the new PCS systems in the United States operating in the 1,900-MHz band.

The speech signal is encoded and compressed through a technique called Qualcomm code-excited linear prediction (QCELP) at a bit rate that can vary adaptively from 1 kbps to 8 kbps. The speech data along with error-correction coding results in a gross bit rate that varies from 2.4 kbps to 19.2 kbps. In practice, the speech quality of the lower bit rates is usually not acceptable, and the higher rates must be used. The bit stream is multiplied by a pseudorandom code at a much faster bit rate. This has the effect of spreading the spectrum over a much greater bandwidth; the code is called a spreading code. The spread signal fully occupies the 1,250-kHz radio channel.

A number of signals are all sent on top of each other in the same 1,250-kHz radio channel. At the receiver, the appropriate pseudorandom spreading code is applied to extract the desired signal. All unwanted signals appear as random noise and are ignored.

Qualcomm claims considerable superiority of CDMA over all other methods for cellular mobile telephone service in terms of its capacity. But CDMA only works if all the received radio signals are about the same strength. If one signal is much larger than all the others, it will dominate and the others cannot be recovered. This means that mobile units have to adjust their transmitting power so that the signals received at the base station are all the same power regardless of distance. There are also quite complex timing issues with the received signals. Complexity is not necessarily a problem with today's technology, but there are far simpler wireless systems already available in the marketplace. Whether CDMA will achieve its great promise remains unclear at the time of the writing of this book.

Intersystem roaming

A cellular mobile unit will work anywhere there is cellular service, provided that an agreement exists to hand billing back to the unit's home system. A mobile unit could roam all over the country and make telephone calls. Billing is not a problem since the mobile unit contains its own identification number along with an identification of its home system. Reaching the mobile unit is another story, however.

One way to call a roaming mobile unit is for the caller to know the area where the roamer is located and to dial a roamer access number for that area. The caller then enters the 10-digit number for the mobile, and a page is made by that local system. The problem with this method is that the caller must know the roamer access number for the area where the roamer has roamed. A better way is GTE's Follow Me Roaming® service. Upon entering a foreign cellular area, the roamer sends a special code to the cellular system. The foreign cellular system then notifies the roamer's home system about where the roamer is located. Any calls to the roamer are then automatically forwarded to the foreign cellular system where a page is made to reach the roamer to complete the call.

The continuing search for increased capacity—a personal assessment

Cellular telephone service has almost been too successful, and some systems are running out of capacity. Cells can only be split a certain number of times before interference becomes a serious problem. The question has now become how to achieve more capacity.

The clearest and simplest solution is to add more spectrum space for cellular radio transmission. However, that space would need to be taken from spectrum space presently allocated to UHF television transmission, but the UHF broadcasters do not want to relinquish any space. Furthermore, some of the systems proposed for high-definition television (HDTV) would use the UHF spectrum. The TV broadcast industry and the cellular industry are engaged in a battle over this issue of spectrum space. My view is that with cable television passing nearly 90 percent of U.S. households, along with the strong penetration of VCRs, there is more than enough television diversity and that some more UHF space should be made available for two-way cellular service.

In the end, the great debate between CDMA and other methods over which system has the most capacity must accept that fact that Claude E. Shannon showed in 1948 that the maximum signal carrying capacity of a communication channel is finite and cannot be exceeded. Comparisons must be made on an equal basis to be assured that one is really comparing like items. As an example, the CDMA system takes into account the fact that telephone conversations are really one-way most of the time in the sense that one party is speaking while the other is listening. We saw how this can be used in transoceanic cable systems to more than double capacity using TASI equipment. Although CDMA uses this kind of an approach to increase its capacity, other cellular systems could too, but do not.

A simple way to increase the capacity of a cellular system is the use of single-sideband amplitude modulation (AM) transmission. However, noise and interference can be a problem with amplitude modulation. The advantage of frequency modulation (FM) is that it has a capture effect in that the strongest FM signal is locked onto by the receiver, and all weaker interfering signals are ignored. Although single-sideband amplitude modulation is very efficient in its use of spectrum, amplitude modulation is seriously degraded by the fading that is encountered in cellular wireless transmission. Advances in analog technology, perhaps coupled with digital processing, may someday in the future lead to innovations that could make amplitude modulation practical. The increase in capacity that could be possible with analog technology would be most impressive.

Consider the AMPS system with its 30-kHz wide radio channel allocated to only a single user—a tremendous waste of valuable spectrum space. Each baseband speech signal requires 4 kHz. If single-sideband suppressed-carrier modulation were used in a simple FDMA approach, the capacity could be increased sevenfold. If the one-way nature were used, the capacity could be doubled to a 14-fold increase. From my years at Bell Labs in the 1960s, I recall analog vocoders operating at a ten-to-one compression that sounded perfectly natural. If they were used, the overall capacity could be yet increased by a factor of ten—a net increase of 140-fold! Clearly, we have not yet seen the end of the progression of innovation in cellular technology.

It is quite conceivable, however, that ways will be invented to improve upon conventional FM and AM techniques to increase the capacity of a cellular system without creating serious interference problems. Whatever happens to increase capacity, the problem of standardization looms ahead. The present analog FM scheme is now established as the standard for millions of cellular users. The challenge for the cellular industry is to choose a new standard and then migrate toward it while still supplying service to all the users of the older technology. This is no easy task!

Satellite mobile communications

With terrestrial-based mobile communications, the base stations are fixed and the users are mobile. A number of fixed base stations are required because of the low-power and frequency nature of cellular wireless telephone service. One alternative approach is to place a single base station high in the sky above the region to be served. As we saw in a previous chapter, communication satellites accomplish this, but if placed in geostationary orbit are so high that the round-trip delay is a problem for two-way communication. A solution is to place the satellites in a much lower orbit. Low earth orbit (LEO) satellites have already been launched to offer mobile communication.

The first LEO system was developed by Motorola and is called Iridium. It uses 66 satellites in circular polar orbits about the earth in six orbital planes at a height of 420 miles (780 km). Each orbital plane contains 11 satellites so that there will always be a satellite above the area to be served. The satellites move across the sky while overhead, and a new satellite must come into place before the current one disappears over the horizon. Each satellite is in use for about six minutes. This means that handoffs must occur to maintain continuous communication. Each satellite in the Iridium system has a capacity of 3,840 full-duplex circuits with each circuit at 4.8 kbps. Compressed speech or computer data can be sent in a circuit. The Iridium system is scheduled to be operational in 1998, and the satellites have already been launched. At such a low orbit, the satellites encounter friction, will fall back to earth after about five years, and hence will need to be replaced quite frequently.

A better compromise with the need to avoid delay yet be at a height so that a reasonable number of satellites is required with fair lifetimes is to place the satellites in medium earth orbit (MEO). The TRW Odyssey system is a MEO system with satellites at a height of 5,575 miles (10,354 km). Twelve satellites are to be placed in three orbital polar planes. Each satellite will be overhead about two hours and will have a lifetime of 15 years. There will be a total of 2,300 full duplex circuits per satellite.

The Globalstar system being promoted by Loral, Qualcomm, and others will use 48 satellites in eight inclined circular orbital planes at a height of 754 miles (1,401 km). The satellites are expected to have lifetimes of five to seven years, will be overhead about 11 minutes, and can each serve 288 full-duplex circuits.

These LEO and MEO satellite systems are very costly and utilize technology that is yet untested. Since most of the surface of the earth is oceans, the satellites will be useless most of the time unless over large metropolitan areas. This means that their useful duty factor is very low. There are few people in rafts in oceans or in the rain forests of South America desiring telephone service and willing to pay a small fortune a minute. Yet a group of investors, including at least one billionaire, are supporting the Teledesic LEO system which plans to use 840 satellites in 21 polar planes at a development cost of $9 billion.

Satellites in geostationary earth orbit (GEO) can also be used for mobile communication if the user is willing to tolerate the round-trip delay. Mobile units for these GEO systems are the size of a laptop computer and cost a few thousand dollars. A call costs about $1.50 a minute. If there is any real market for personal satellite communication, the existing GEO systems already satisfy it.

It most certainly is far too early to tell which, if any, of these approaches will achieve commercial widespread viability. Perhaps one or more will discover very special "niche" markets that can afford the price and have few alternatives. But the obstacles to overcome are so many that I wonder whether the LEOs and MEOs will ever amount to anything other than a great deal of overpromotion and hot air!

One hot-air approach that could make sense is a hot-air balloon situated high above a metropolitan area. The balloon would carry a microwave transceiver system to offer mobile telephone service. The balloon would be at a low enough altitude to avoid any delay problems and also could be retrieved for servicing. Such hot-air balloon systems have been seriously suggested.

Cellular telephony—an assessment

Cellular telephony involves very sophisticated technology. The mobile unit is capable of being tuned automatically to any one of the two-way radio channels and can transmit and receive binary data and act on that data. The mobile telephone switching office must monitor thousands of calls, determine when handoffs are needed, send and receive data transmissions from the mobile units, and determine billing.

It is astonishing that mobile units have so shrunk in size that portable cellular phones that fit in a pocket are commonly available. The advances in cellular technology are most impressive, but are also the cause of ever-changing standards that appear to defeat compatibility. The advance of technology still has some challenges to overcome. One is how to locate physically a mobile unit so that the mobile can be handed to the appropriate public safety facility in the case of a call to 911. Appropriate localization methods are under investigation, but some users might be concerned about the potential loss of physical privacy.

There is one issue over cellular telephone service that could impede its use and ever-continuing growth. This issue is the health safety of the microwave radiation from the small antenna in the mobile unit. Mobiles transmit as much as 1W of microwave power, and this radiation is directly against the side of the user's head. Although using a cell phone for a few minutes a day is probably not a hazard, I wonder about the hazard of daily use of an hour or more, as seems so common for some heavy users. The effect will certainly be cumulative, and will appear far in the future in the form of a unilateral brain tumor. Cellular telephone service is only 15 years old, but such cumulative health effects could take a few decades of use to appear. We thus do not yet know the answer to the potential health hazards of heavy use of cellular phones. We do know, however, that automobile accidents linked to cell phone use while driving are on the increase.

The continued success and growth of wireless communication has created a great demand for increases in capacity. But because the radio spectrum is limited, ways must be discovered to use the existing spectrum more efficiently. This had led to the use of speech compression to reduce the bandwidth of each speech signal so that more voice circuits can share the same channel. As we saw earlier in this chapter, such compression is accomplished at bit rates as lows as 8,000 bps rather than the usual 64,000-bps rate of uncompressed digital speech. Bit rates lower than about 8,000 bps are not acceptable to most consumers since the compressed speech sound rough and unnatural. Digital wireless implies to consumers that the quality will be similar to a CD. Alas, it is not. Compression is usually a compromise with quality.

Compression algorithms are designed for speech but do not work well for computer data, which requires as much digital capacity as possible. When used to access the Internet or send computer data, cell phones need to bypass the speech compression algorithms and offer direct access to the data stream. But these data streams—usually about 13 kbps—though acceptable for compressed speech communication, are low by today's standard of 56 kbps for modems that work on regular phone lines.

Yet, more important than all the technological sophistication is the ease of use of cellular telephony. When one is driving along a busy freeway, bumper to bumper, at 65 miles per hour, it must be easy to place and receive a cellular call. The dialing buttons must be well placed for ease of use, so calls can be placed without taking one's eyes off the road ahead. The challenge for future cellular phones for the car is the user interface. This is one area where synthetic speech could augment the visual display of a telephone number. In cellular dialing, the user enters the number into the mobile unit, and only after the complete number has been entered does the unit send the number to the base station. The user can review the dialed number on a visual display before sending it out, but a synthesized-speech "read-out" of the number would perhaps be most useful during driving. So, too, would be speech recognition so that the user could speak the digits of the number to be called, as is done in some newer cellular phones for cars.

Cellular mobile telephone service continues to be very exciting with great growth potential. Some futurists predict a day when everyone will carry their own personal telephone, served by some form of cellular service. In fact, the existing wireline telephone network could be bypassed through cellular phones. This had led some long-distance companies to investigate the use of a form of fixed wireless as a substitute for the copper wire of the local loop controlled by the local telephone companies. Thus far, the wireless local loop (WLL) seems too costly to compete with copper wire for such fixed applications.

With portable phones, car phones, cellular phones, and cordless phones, we have the ability to be reached and to reach anyone by telephone anywhere at any time. Whether we will all want to continue to be that easily reached at all times, though, remains to be seen.

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