chapter 20

Cell Phone Technologies

With over a billion cell phones sold each year, the cell phone is the largest-volume consumer electronics device. It has changed the way that we communicate. 2005 was the first year in which cell phone subscribers numbered more than wired telephone subscribers. Today, for the majority of consumers, their mobile phone is their only phone. Furthermore, as the data speed of the newer digital cell phone transmissions increases, more cell phone accessories and applications are possible. These include cameras, Internet access, texting, e-mail, audio, gaming, navigation, and video. This chapter provides a technical overview of cell phone standards and operation. Other short-range wireless technologies are covered in Chap. 21.

Objectives

After completing this chapter, you will be able to:

- Describe the cell phone operational concept.
- Name the two most common second-generation digital cell phone systems, and describe the features of each.
- Define the cell phone terms *2G, 2.5G, 3G, 4G,* and *5G.*
- Describe the block diagram architecture of a modern digital cell phone.
- State the features, benefits, and applications of 4G cell phones.
- Explain the applications and benefits of location-based technologies in cell phones.
- Describe the architecture and operation of a cell phone base station.
- Define small cells and distributed antenna systems (DAS).

20-1 Cellular Telephone Systems

Cellular radio system

A *cellular radio system* provides standard telephone service by two-way radio at remote locations. Cellular radios or telephones were originally installed in cars or trucks, but today most are handheld models. Cellular telephones permit users to link up with the standard telephone system, which permits calls to any part of the world.

Advanced mobile phone system (AMPS)

The Bell Telephone Company division of AT&T developed the cellular radio system during the 1970s and fully implemented it during the early 1980s. Today, cellular radio telephone service is available worldwide. The original U.S. cell phone system, known as the *advanced mobile phone system,* or *AMPS,* was based on analog FM radio technologies. AMPS has gradually been phased out and replaced by second-generation (2G), third-generation (3G), and fourth-generation (4G) digital cell phone systems. This section provides an overview of this awesome worldwide network.

Cellular Concepts

Cells

The basic concept behind the cellular radio system is that rather than serving a given geographic area with a single transmitter and receiver, the system divides the service area into many smaller areas known as *cells,* as shown in Fig. 20-1. The typical cell covers only several square miles and contains its own receiver and low-power transmitter. The coverage of a cell depends upon the density (number) of users in a given area. See Fig. 20-2. For a heavily populated city, many small cells are used to ensure service. In less populated rural areas, fewer cells are used. Short cell antenna towers limit the cell coverage area. Higher towers give broader coverage. The cell site is designed to reliably serve only persons and vehicles in its small cell area.

Mobile telephone switching office (MTSO)

Each cell is connected by telephone lines or a microwave radio relay link to a master control center known as the *mobile telephone switching office (MTSO).* The MTSO controls all the cells and provides the interface between each cell and the main telephone office. As the person with the cell phone passes through a cell, it is served by the cell transceiver. The telephone call is routed through the MTSO and to the standard telephone system. As the person moves, the system automatically switches from one cell to the next. The receiver in each cell station continuously monitors the signal strength of the

Figure 20-1 The area served by a cellular telephone system is divided into small areas called *cells. Note:* Cells are shown as ideal hexagons, but in reality they have circular to other geometric shapes. These areas may overlap, and the cells may be of different sizes.

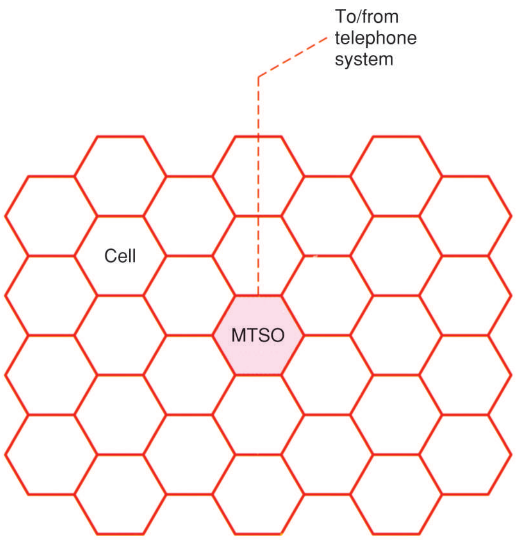
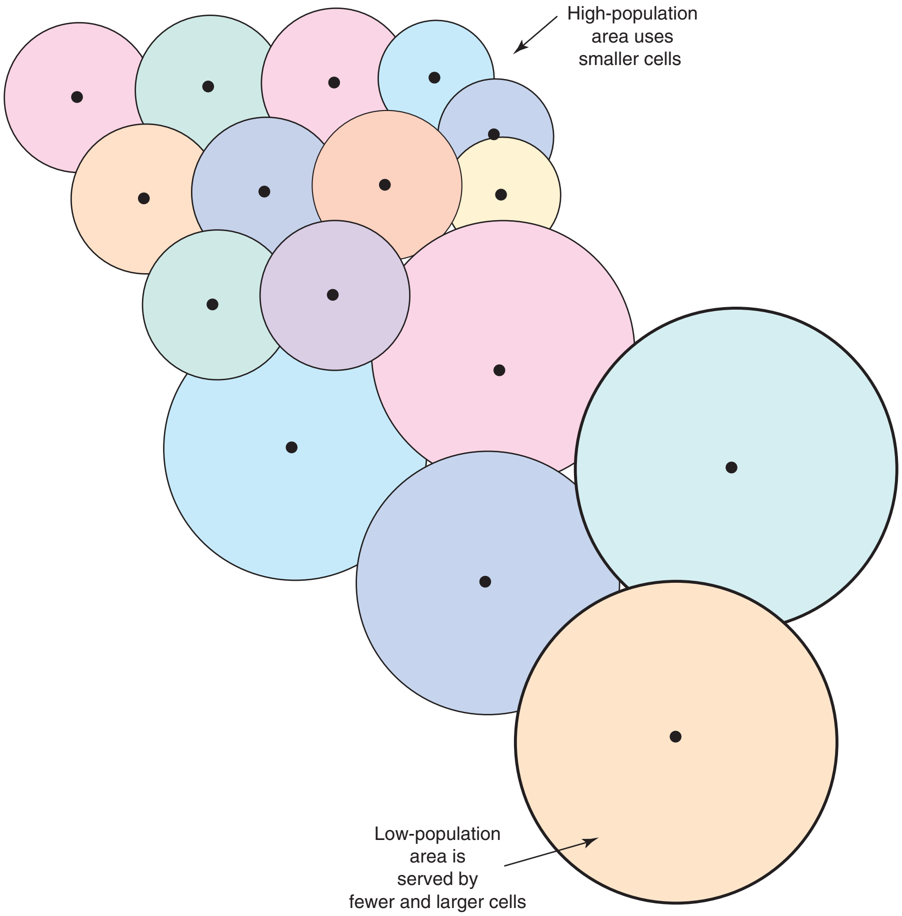


Figure 20-2 Area of cell coverage is determined by antenna height.



mobile unit. When the signal strength drops below a desired level, it automatically seeks a cell where the signal from the mobile unit is stronger. The computer at the MTSO causes the transmission from the person to be switched from the weaker cell to the stronger cell. This is called a *handoff*. All this takes place in a very short time and is completely unnoticeable to the user. The result is that optimum transmission and reception are obtained.

Handoff

Frequency Allocation

Cellular radio systems operate in the UHF and microwave bands as assigned by the Federal Communications Commission (FCC). The original frequency assignments were in the 800- to 900-MHz range previously occupied by the mostly unused UHF TV channels 68 through 83. Fig. 20-3 shows the most widely used bands. The frequencies between 824 and 849 MHz are reserved for the uplink transmissions from the cell phone to the base station. These are also called the reverse channels. The frequencies between 869 and 894 MHz are the downlink bands from base station to cell phone. Both of these 25-MHz segments of spectrum were originally divided into 832 channels 30 kHz wide. While these are still used, the different cell phone technologies use different amounts of bandwidth, such as 30 kHz, 200 kHz, and 1.25 MHz, so this spectrum gets used in different ways by different cell phone companies in different locations.

Another commonly used block of spectrum is shown in Fig. 20-4(*a*). Again, the use of this spectrum varies depending upon the cell phone carrier and the geographic area. A more recently allocated block of spectrum is shown in Fig. 20-4(*b*). These two blocks of 60 MHz are referred to as the personal communications systems (PCS) channels.

Figure 20-3 Standard U.S. UHF cell phone spectrum.

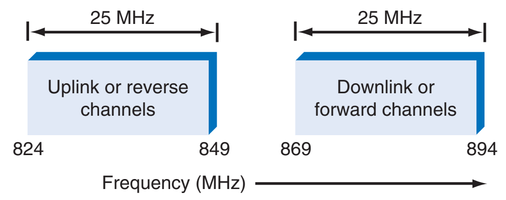
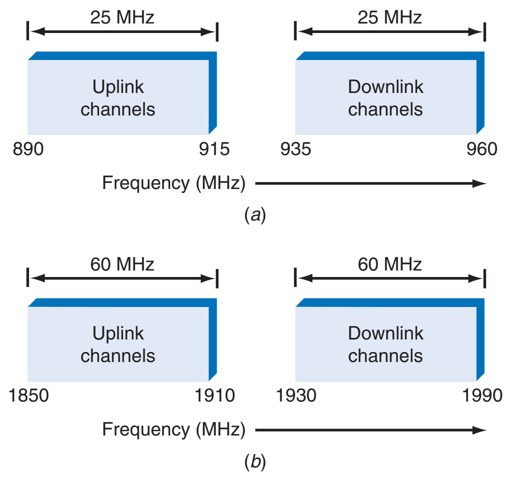


Figure 20-4 Additional U.S. cell phone spectrum. (*a*) 890 to 960 MHz and (*b*) 1850 to 1990 MHz are called the personal communication system PCS band.



While the range at these higher microwave frequencies is somewhat less than that achievable in the UHF bands, this block of frequencies provides greater system capacity, meaning more subscribers. Also the antennas are smaller at these frequencies.

One of the major issues in the cell phone business lies in obtaining more spectrum for more subscribers. More subscribers mean greater income. Yet, spectrum is scarce and very expensive. Now spectrum is available in the 700- to 800-MHz range. More recently, there is available space in the 1700- to 1750-MHz range. Some spectrum is also available in the 1900- to 2300-MHz and 2500- to 2700-MHz range for newer 4G systems. A new band near 3650 MHz is also available. Also keep in mind that different countries use different spectrum blocks. For example, in Europe the most commonly used bands are 900 and 1800 MHz.

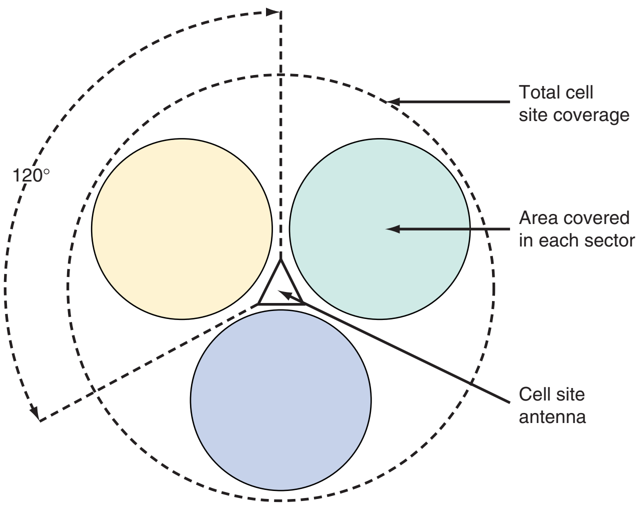
Multiple Access

Multiple access

Multiple access refers to how the subscribers are allocated to the assigned frequency spectrum. Access methods are the ways in which many users share a limited amount of spectrum. These are similar to multiplexing methods you learned about in previous chapters. The techniques include frequency reuse, frequency-division multiple access (FDMA), time-division multiple access (TDMA), code-division multiple access (CDMA), and spatial-division multiple access (SDMA).

Frequency Reuse. In frequency reuse, individual frequency bands are shared by multiple base stations and users. This is possible by ensuring that one subscriber or base station does not interfere with any others. This is achieved by controlling such factors as transmission power, base station spacing, and antenna height and radiation patterns. With low-power and lower-height antennas, the range of a signal is restricted to only a

Figure 20-5 Horizontal antenna radiation pattern of a common cell site showing 120° sectors that permit frequency reuse.



mile or so. Furthermore, most base stations use sectorized antennas with 120° radiation patterns that transmit and receive over only a portion of the area they cover. See Fig. 20-5. In any given city, the same frequencies are used over and over simply by keeping cell site base stations isolated from one another.

Frequency-Division Multiple Access. FDMA systems are like frequency-division multiplexing in that they allow many users to share a block of spectrum by simply dividing it up into many smaller channels. See Fig. 20-6. Each channel of a band is given an assigned number or is designated by the center frequency of the channel. One subscriber is assigned to each channel. Typical channel widths are 30 kHz, 200 kHz, 1.25 MHz, and 5 MHz. There are usually two similar bands, one for uplink and the other for downlink.

Time-Division Multiple Access. TDMA relies on digital signals and operates on a single channel. Multiple users use different time slots. Because the audio signal is sampled at a rapid rate, the data words can be interleaved into different time slots, as Fig. 20-7 shows. Of the two common TDMA systems in use, one allows three users per frequency channel and the other allows eight users per channel.

Figure 20-6 Frequency-division multiple-access (FDMA) spectrum.

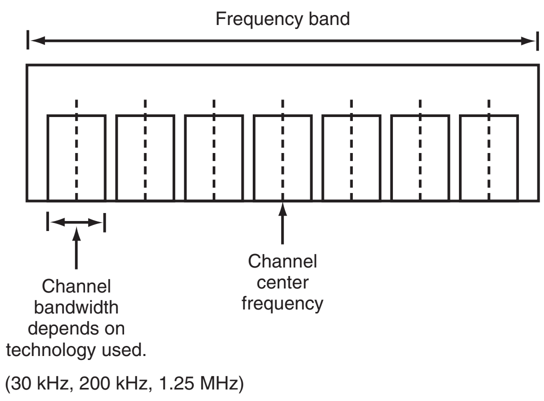
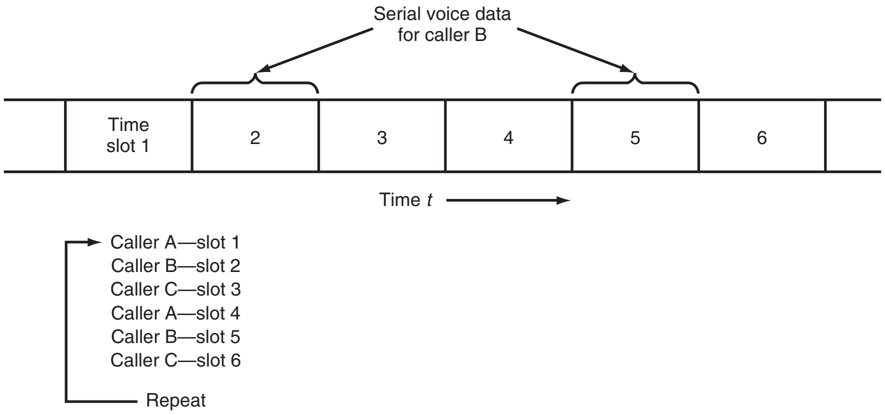
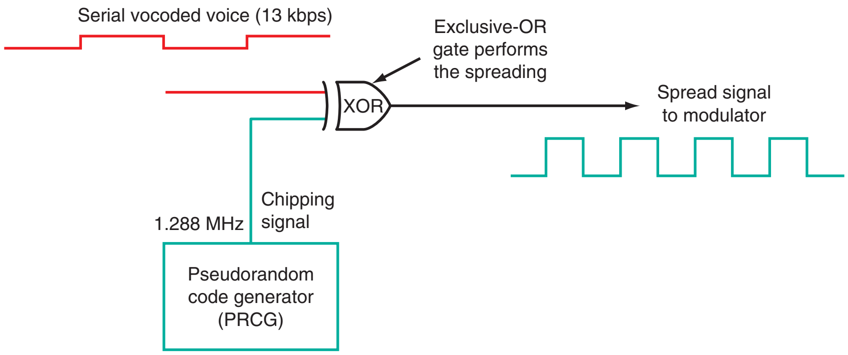


Figure 20-7 Time division multiple access (TDMA). Different callers use different time slots on the same channel.

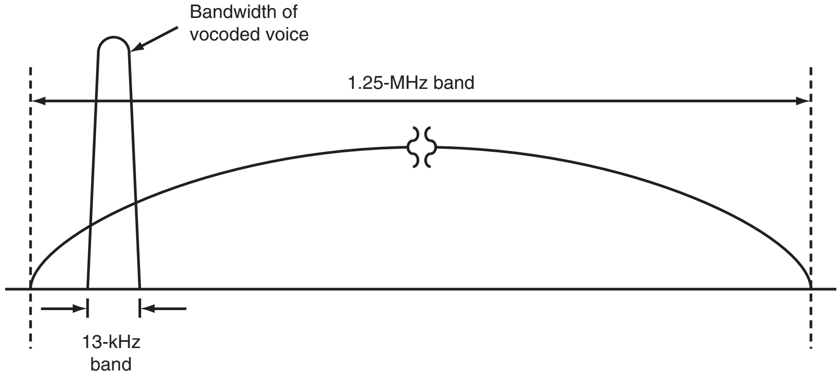


Code-Division Multiple Access. CDMA is just another name for spread spectrum. A high percentage of cell phone systems use *direct sequence spread spectrum (DSSS)*. Here the digital audio signals are encoded in a circuit called a vocoder to produce a 13-kbps serial digital compressed voice signal. It is then combined with a higher-frequency chipping signal. One system uses a 1.288-Mbps chipping signal to encode the audio, spreading the signal over a 1.25-MHz channel. See Fig. 20-8. With unique coding, up to 64 subscribers can share a 1.25-MHz channel. A similar technique is used with the

Figure 20-8 Code-division multiple access (CDMA). (*a*) Spreading the signal. (*b*) Resulting bandwidth.

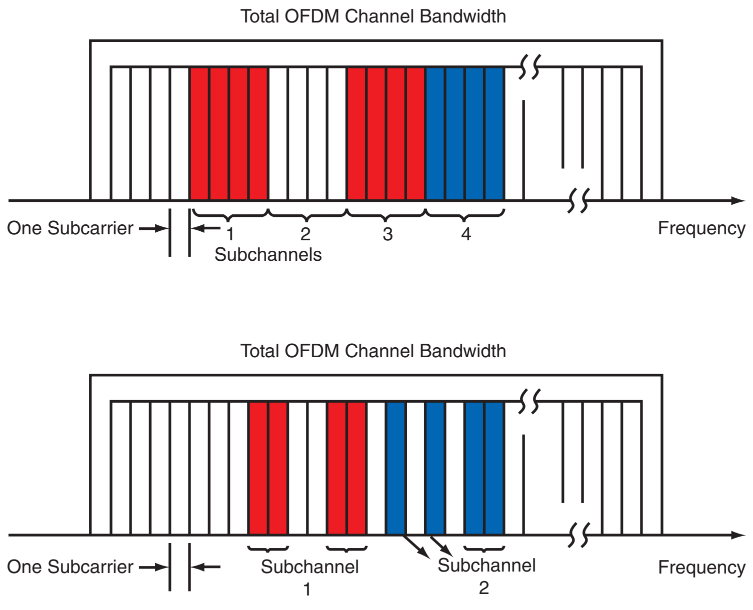


(*a*)



(*b*)

Figure 20-9 The Concept of OFDMA.



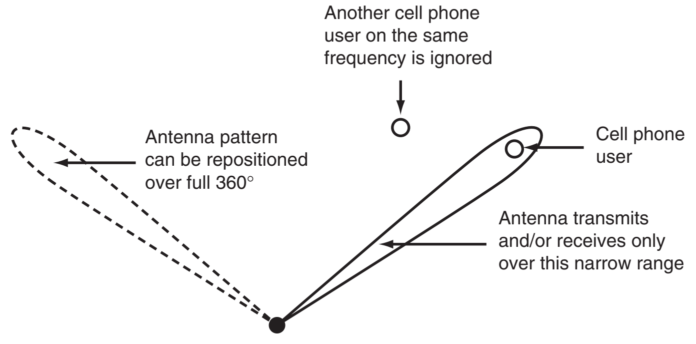
wideband CDMA system of third-generation cellphones. A 3.84-Mbps chipping rate is used in a 5-MHz channel to accommodate multiple users.

Orthogonal Frequency Division Multiplexing Access (OFDMA). OFDMA is the access method used with OFDM. OFDM uses hundreds, even thousands, of subcarriers in a wideband channel. This large number of subcarriers can be subdivided into smaller groups, and each group can be assigned to an individual user. In this way, many users can use the wideband channel assigned to the OFDM signal.

Fig. 20-9 illustrates the principle. Groups of subcarriers are formed to create a subchannel assigned to one user. In some systems, the subcarriers do not have to be contiguous, but instead might be spread around inside the total OFDM signal bandwidth.

Spatial-Division Multiple Access. This form of access is actually an extension of frequency reuse. It uses highly directional antennas to pinpoint users and reject others on the same frequency. In Fig. 20-10, very narrow antenna beams at the cell site base station are able to lock in on one subscriber but block another while both subscribers

Figure 20-10 The concept of spatial-division multiple access (SDMA) using highly directional antennas.



are using the same frequency. Modern antenna technology using adaptive phased arrays is making this possible. Such antennas allow cell phone carriers to expand the number of subscribers by more aggressive frequency reuse because finer discrimination can be achieved with the antennas. SDMA is also widely used in wireless local-area networks (WLANs) and other broadband wireless applications.

Duplexing

Duplexing
Half duplex
Full duplex

Duplexing refers to the ways in which two-way radio or telephone conversations are handled. Many two-way radio applications still use *half duplex* where one party talks at a time. The communicating individuals take turns speaking and listening. Telephone communications has always been *full duplex,* where both parties can simultaneously send and receive. All cell phone systems are full duplex.

frequency-division duplexing (FDD)

To achieve full duplex operation, however, special arrangements must be made. The most common arrangement is called *frequency-division duplexing (FDD)*. In FDD, separate frequency channels are assigned for the transmit and receive functions. The transmit and receive channels are spaced so that they do not interfere with one another inside the cell phone or base station circuits. The uplink and downlink channels in Figs. 20-3 and 20-4 are an example.

Time-division duplexing (TDD)

Another arrangement is *time-division duplexing (TDD)*. This is less common but is used in a few systems. The system assigns the transmit and receive data to different time slots, both on the same frequency. For example, the transmitted and received data is alternated in sequential time slots. While the transmitted and received signals do indeed occur at different times, the speed of the signals is fast enough that a human feels as though they are occurring at the same time. The primary benefit of TDD is that only one channel is needed. With FDD two separated channels are required. A TDD signal uses half the spectrum of FDD.

Still, FDD is far more widely used than TDD.

20-2 A Cellular Industry Overview

The cellular telephone industry is one of the largest industries in the world. Also known as the wireless or mobile business, it generates billions of dollars in revenue each year for the telephone companies, the cell phone manufacturers, and other allied businesses. And as you probably know, the cell phone has become the world's most popular consumer product. Over one billion new cells phones are sold each year. In developed countries, most consumers already have a cell phone of some type. China is the largest user of cell phones; the United States in second place in terms of total number of users. The cell phone is so pervasive that it has greatly affected how we live and work and how we do business. This section takes a brief look at how the cellular industry functions and some of the trends and critical issues associated with it.

The Cellular Carriers

Central to the functioning of the mobile wireless business are the cellular carriers, also known as the network operators. In the United States, there are four major carriers: AT&T, Verizon, Sprint, and T-Mobile. There are also a number of smaller carriers, but the four mentioned represent over 90 percent of the business. These are the organizations that build out the cellular network infrastructure and provide the mobile services. They are also the ones who offer the cell phones to the consumer. Even though the carriers do not design or build the cell phones themselves, they are very much a part of the design process.

The other major players are the cell phone companies themselves. The leaders are Samsung and Apple; other players include LG, HTC, Nokia/Microsoft, Google/Motorola, and newer players such as Huawei and Lenovo. These companies design and build the cell phones to the specifications provided by the carriers.

The reason the carriers have so much influence in the phones themselves relates to their frequency-spectrum holdings. Each carrier has access to its own specific range of frequency bands, and phones must be made to match their holdings. This means that for the most part a cell phone purchased from AT&T will not work on the Verizon network and so on. Another factor is that some carriers use different second- and third-generation technologies that are not compatible from carrier to carrier.

Other players in the industry include the software companies that provide the operating systems for the cell phones. The leaders are Google with its Android operating system, Apple with its iOS software, and Microsoft. There are also many companies offering additional software in the form of applications (apps) that give the cell phone far more capability than was ever imagined at first. You can actually look at the cell phone as a general-purpose high-power microcomputer with a radio built in. Most of the software apps do not use the radio communications capability. The semiconductor companies are also major players. They develop and provide the chips to implement the cell phones and the base station equipment.

The Technology Generations

The cellular industry is driven not only by customer demand for service but also by the available technology. In this regard, the cellular industry is one of the fastest changing in existence. New products and services are offered as rapidly as they are conceived and developed. Changes in the technological standards also force rapid changes. The technology itself is divided into and defined by generations.

The first-generation cell phones used analog technology with frequency modulation. This was rapidly abandoned as it was determined that carriers could not provide enough services to meet the demand. As a result, the first generation was quickly replaced with a newer, second-generation (2G) digital cell phone technology.

Multiple 2G standards were developed worldwide, yet only two major technologies and standards have survived to this day. These include GSM and the original CDMA. Although 2G technology is still in use today around the world, it is slowly fading away and many carriers have stated their desire to end second-generation services in the near future. This allows them to repurpose their precious spectrum holding for greater subscriber capacity and higher data rates.

A key factor was the development of data services, which happened during the second generation. Cell phones originally were designed primarily as voice telephones, but it was quickly discovered that it was possible to use them for data purposes. For 2G phones, data rates were slow, thereby limiting the functions to simple applications such as texting and e-mail. Once greater data capabilities were discovered, the demand for higher speeds and more exotic applications developed. This led to the creation of third-generation cell phones.

Third-generation (3G) cell phones continued to use standard digital voice techniques but also developed high-speed data capability. New modulation and access methods were created and standards were ratified. Third-generation phones rapidly became popular, and over a period of several years carriers adopted the new technology and built out their networks. New cell phones were developed to take advantage of the applications potential.

During this time, several competing 3G technologies were created. These incompatible technologies were adopted by different carriers, making cell phones and the networks incompatible. This ultimately led to the desire for a complete industry standard, which in turn led to the development of fourth-generation phones and systems.

The fourth generation (4G) has brought about the creation of a single standard or family of standards that all carriers could adopt. This 4G technology is known as Long Term Evolution (LTE), and it is slowly being adopted in one form or another by all U.S. and worldwide carriers. While most of the major carriers have already converted to the

4G LTE technology, the process is still rolling out across the United States and the progress is widely varied worldwide.

The 4G systems and phones have led to much higher data rates and amazing new cell phone capabilities, particularly that of being able to receive and generate video. Technology advances have given us not only the high-speed data capability necessary for video but also large, color touch screens, making the cell phone a more popular consumer product than ever.

While most carriers are still implementing 4G LTE systems in the States and in other countries, work is already under way to define the next, fifth generation. The main purpose of 5G is to make the cellular and data services available over a wider range and to provide even higher data speeds.

Trends and Critical Issues

The basic trend in the cellular industry is continued growth and technological development. In the developing countries, market saturation has already been achieved, meaning that most individuals already have cell phones and services. This has the effect of reducing the growth rate, but it still provides an opportunity for consumers to upgrade to improved phones and services. In addition, substantial growth is still available in other parts of the world, especially undeveloped countries where telephone service is not typically available. In many parts of the world, cellular telephone service is the only telephone service available.

Another major trend is the decline in the number of wired telephone customers. Many consumers have already abandoned their basic wired telephones in favor of using only cell phones. Today over 50 percent of consumers now use cellular telephones as their primary communications service and that trend appears to continue.

Another trend is that carriers are continuing to build out their networks and improve data rates in an effort to reach more consumers and capture more business. Keeping in step with that, the cell phone manufacturers continue to provide even more sophisticated and capable cell phones that consumers desire.

As for critical issues, the primary one is frequency spectrum availability. Only certain parts of the frequency spectrum (roughly 600 MHz to 4 GHz) are useful for cellular service, and this frequency spectrum is already heavily occupied. The ability of a carrier to continue to offer expanded service capacity as well as higher speeds is determined strictly by the amount of spectrum available. High capacity and high speed require wider bandwidth. However, there is only a certain amount of spectrum available, and most of it is already owned and occupied. Today carriers who want to expand their operations must buy spectrum from others or purchase it through the regulatory agency, the Federal Communications Commission (FCC), in their regular auctions. Spectrum costs billions of dollars, and only the largest of carriers can afford it.

To solve this problem, the FCC has been attempting to free up spectrum from other spectrum holders, such as the government, the military, and the TV broadcasters. The TV broadcasters gave up spectrum during the changeover to digital TV in 2009. The 700- to 800-MHz band is now available and is already being used by some of the cellular carriers. Forthcoming is another segment of spectrum in the 600- to 700-MHz range, which will be auctioned off to the highest bidders. Eventually, higher frequencies are going to have to be used to achieve improved service and data rates. The 5G standards are already looking to the millimeter wave bands (28 to 70 GHz) as a potential solution to the need for increased spectrum holdings.

Another issue is how long older technology should continue to be supported. With today's high-speed LTE 4G capability, most voice calls are still handled by the carriers' 2G and 3G switched-circuit networks. Soon these will be phased out in favor of internet protocol (IP) voice services such as voice over LTE (VoLTE). This has yet to be fully implemented by the carriers. And few cell phones support it. Yet it is the voice method of the future. In the meantime, all cell phones, despite the fact they may be 4G LTE capable, must continue to carry 2G and/or 3G capability to provide voice service.

20-3 2G and 3G Digital Cell Phone Systems

Digital cell phone system

The original cellular technology AMPS used FM analog communications. However, today all new cell phones and systems use digital methods. These all-digital systems were developed primarily to expand the capacity of the cell phone systems already in place. The rapid growth of the number of wireless subscribers forced the carriers to seek new and more efficient methods of increasing the number of users a system could handle. The main problem was that the carriers were restricted by the Federal Communications Commission to specific segments of the frequency spectrum. No additional space was available for expansion. Digital techniques provide several ways to multiplex many users into the same spectrum space.

The use of digital techniques brought several additional benefits. Digital communication systems are inherently more robust than analog systems in that they are more reliable in a noisy environment. Furthermore, digital circuits can be made smaller and more power-efficient, and therefore handsets can be more compact and can operate for longer times on a single battery charge. In addition, digital cell phones greatly facilitate the transmission of data as well as voice, so that data services such as e-mail and Internet access are possible with a cell phone. Digital methods also offer high-speed data capability making video, gaming and social media applications possible.

The first digital cell phones are referred to as *second-generation (2G) phones*. Today, third-generation (3G) and fourth-generation (4G) cell phones and systems are in use. But 2G phones are still in use in the United States and around the world. The 2G phones will eventually be phased out. This section covers the 2G systems still in use and describes the various 3G systems that have mostly replaced 2G technology. 4G phone are discussed in a separate section.

2G Cell Phone Systems

2G cell phone system

Three basic *second-generation (2G) digital cell phone systems* were developed and deployed. Two use time-division multiplexing, and the third uses spread spectrum (SS) or CDMA. The TDM systems are the Global System for Mobile Communications (GSM) and the IS-136 standard for time-division multiple access. The SS system is code-division multiple access. The IS-136 system was phased out early and replaced with GSM. Both GSM and CDMA are still widely deployed throughout the world.

Vocoder

Vocoders. To use digital data transmission techniques first requires that the voice be digitized. The circuit that does this is a *vocoder,* a special type of analog-to-digital (A/D) converter and digital-to-analog (D/A) converter. With voice frequencies as high as 4 kHz, the minimum Nyquist sampling rate is two times the highest frequency, or 8 kHz. This means that the A/D converter in a vocoder should sample the voice signal every 125 μs and generate a proportional binary word. Assuming that it is an 8-bit value, during the 125-μs period, the 8 bits is transmitted serially. This translates to a serial data rate of $125/8 = 15.625\ \mu\text{s/bit}$, or $1/15.625 \times 10^{-6} = 64$ kbps. This is how the T1 telephone system described in Chap. 12 works.

This serial data signal, representing the voice, is now used to modulate the carrier and the composite signal transmitted over the assigned channel. Recall that the bandwidth required to transmit a digital signal depends primarily upon the data rate. The higher the data rate, the wider the bandwidth required. As a rule of thumb, the bandwidth is roughly equal to the data rate. For example, a 64-kbps signal would require about 64 kHz of bandwidth. That represents 1 bit/Hz. Different modulation methods result in different degrees of data rate per bandwidth. Some are more spectrally efficient than others. A 1-bit/Hz rating is essentially wasteful of precious spectrum space. If the 30-kHz AMPS channels are to be used to transmit 64-kbps voice, a more efficient modulation scheme is needed, or some other technique is required.

GOOD TO KNOW

To estimate the bandwidth necessary to transmit a specified data rate, use the rule of thumb of a one-to-one correspondence between data rate and bandwidth, for example, 1-Mbps data rate and 1-MHz bandwidth.

The main function of a vocoder is data compression. Data compression techniques are used to process the digitized voice signal in such a way as to reduce the number of bits needed to represent the voice reliably. This in turn allows the speed of data transmission to be reduced to a level compatible with that of the available channel bandwidth. In modern cell phones a variety of vocoding data compression schemes are used. An A/D converter is followed by a digital signal processing (DSP) chip that does the compression in accordance with some algorithm. The vocoder then generates a serial digital voice signal at a rate of 7.4 to 13 kbps. This permits three to eight voice signals to occupy the same channel by using TDM. At the receiver, the demodulated digital data is sent to the vocoder, where a DSP chip takes the serial bits and converts them back to binary words representing the voice. A D/A converter then recreates the voice. All 2G and 3G phones contain a vocoder.

GSM (Global System for Mobile Communications)

GSM. The most widely used 2G digital system is GSM. *GSM* originally stood for "Group Special Mobile" but has become known as the "Global System for Mobile Communications." It was developed in Europe under the auspices of the European Telecommunications Standardization Institute (ETSI) to replace the many incompatible analog systems used in different European countries. The GSM was designed to permit widespread roaming from country to country throughout Europe. GSM is implemented primarily in the 900-MHz band in Europe, but is also used in the 1800-MHz (1.8-GHz) range in Europe, where it is referred to as the *digital cellular system (DCS),* or *DCS-1800.* GSM is also widely implemented in the United States in both the 800- and 1900-MHz personal communication system band.

Digital cellular system (DCS), or DCS-1800

Regular pulse excitation-linear prediction coding (RPE-LPC) or residual excited linear predictive (RELP) coding

Gaussian minimum shift keying (GMSK)

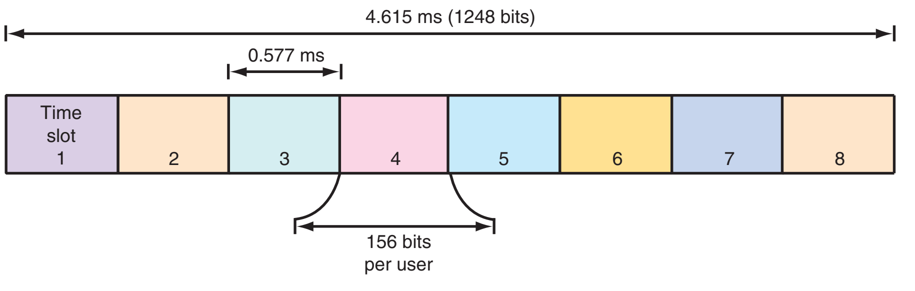
GSM uses TDMA. The vocoder uses a compression scheme called *regular pulse excitation-linear prediction coding (RPE-LPC)* or *residual excited linear predictive (RELP) coding* that produces a 13-kbps voice bit stream. It allows eight telephone calls to be transmitted concurrently in a single 200-kHz-wide channel. The modulation method, known as *Gaussian minimum shift keying (GMSK)*, is similar to frequency-shift keying (FSK) but has improved spectral properties that allow higher speeds to be transmitted in a narrower channel. A Gaussian response filter shapes the serial digital bit stream before modulation to narrow the signal bandwidth. The basic GSM data rate is 270 kbps in the 200-kHz channel, giving 270 kbps/200 kHz = 1.35 bits/Hz. Considerable error detection and correction coding is used to improve the reliability in the presence of noise, multipath fading, interference, and Doppler shifts. The basic GSM TDMA frame is shown in Fig. 20-11. Each frame is 4.615 ms long, and each voice slot is 0.577 ms long. GSM also uses a frequency-hopping scheme to minimize interchannel interference. The hop rate is 217 hops per second, or about 1200 bits per hop. FDD is used for full duplex operation.

Two key additions to GSM are general packet radio service (GPRS) and enhanced data rate for GSM evolution (EDGE). These are packet-based data services designed to permit Internet access, e-mail, and other forms of digital data transmission. These technologies are described later under the section 2.5G Cell Phone Systems.

IS-95 CDMA

IS-95 CDMA. This TIA cell phone standard is called code-division multiple access (CDMA). Also known as *cdmaOne,* it uses spread spectrum. This system was invented by Qualcomm, a company that makes the chip sets used in CDMA cell phones. The company

Figure 20-11 A GSM TDMA frame for eight time slots.



also holds most of the patents in this field. CDMA uses direct sequence spread spectrum (DSSS) with a 1.2288-MHz chipping rate that spreads the signal over a 1.25-MHz channel. As many as 64 users can use this band simultaneously with little or no interference or degradation of service, although in practice typically only 10 to 40 subscribers occupy a channel at one time. This CDMA system uses FDD for duplexing.

As in other cell phone systems, CDMA takes the voice signal and digitizes it in a vocoder. The output is a 13-kbps serial voice signal that is further processed before it is used to modulate the carrier. The digitized voice is fed to an exclusive-OR (XOR) gate where it is mixed with a 64-bit pseudorandom code occurring at the chip rate of 1.2288 Mbps. This signal is then used to modulate the carrier with QPSK. The carrier may be in the regular 800- to 900-MHz band or in the PCS-1900 band. The resulting signal occupies a huge bandwidth spread over a wide spectrum. It may also coexist with up to 64 other CDMA signals that use the same carrier but have different pseudorandom codes. These special codes are known as *Walsh codes* and are chosen so that they are easily recognized and recovered at the receiver by using the correlation technique described earlier.

Walsh codes

A key part of a CDMA system is APC. All cell phones have APC, but for CDMA it is especially important. For the receivers to recover a CDMA signal, all incoming signal levels must be at the same power level. This ensures that the receiver does not confuse a higher-power signal with a lower-power signal during the decorrelation detection process. The base stations increase the power level of weak distant signals and decrease the power level of signals near the cell site.

Digital Cell Phone Architecture

Fig. 20-12 is a block diagram of a 2G cell phone. The RF section contains the transmitter and receiver circuits including mixers, local oscillators or frequency synthesizers for channel selection, the receiver low-noise amplifier (LNA), and the transmitter power amplifier (PA). The baseband section contains the vocoder with its A/D and D/A converters plus a DSP chip that handles many processing functions typically performed by analog circuits in older systems. For example, today most baseband and intermediate-frequency filtering is done digitally, as are modulation, demodulation, and mixing.

GOOD TO KNOW

Cellular phones equipped with a digital signal processor (DSP) chip can compress speech to fit many digital calls in the same amount of radio spectrum previously required for analog calls.

An embedded controller handles all the digital control and signaling, handoffs, and connection and identification operations that take place transparent to the subscriber. It also takes care of running the display and keyboard and all user functions such as number storage, autodialing, and caller ID. Because of the complexity of the baseband and control functions, this embedded controller is usually a very fast (more than 100-MHz) 32-bit microprocessor with considerable RAM, ROM, and flash memory. A separate DSP chip handles the signal processing duties.

In addition to adopting digital techniques in 2G and later phones, designers have worked hard to eliminate costly components such as filters and to create circuitry that conserves power and thereby provides longer battery life. This has led to some interesting architectures, especially in the receiver section. Today, the dominant architectures are the direct-conversion and very low-IF designs.

Direct Conversion. The direct-conversion or zero-IF design sets the LO frequency to the incoming signal frequency so that the translation is made directly to the baseband signal. See Fig. 20-13. Because direct conversion works only with double-sideband (DSB) suppressed AM signals, changes have been made to accommodate FSK, BPSK, QPSK, and other forms of digital modulation. Specifically, the incoming signal is applied to two mixers simultaneously. One mixer receives the LO signal directly (sine), and the other receives a signal shifted 90° (cosine). This results in down conversion to baseband as well as the generation of in-phase *(I)* and quadrature *(Q)* signals that preserve the frequency and phase information in the signal necessary for demodulation.

Direct conversion is popular because it eliminates the need for an expensive and physically large selective SAW IF filter. It also eliminates the imaging problem so

Figure 20-12 Block diagram for a 2G digital cell phone.

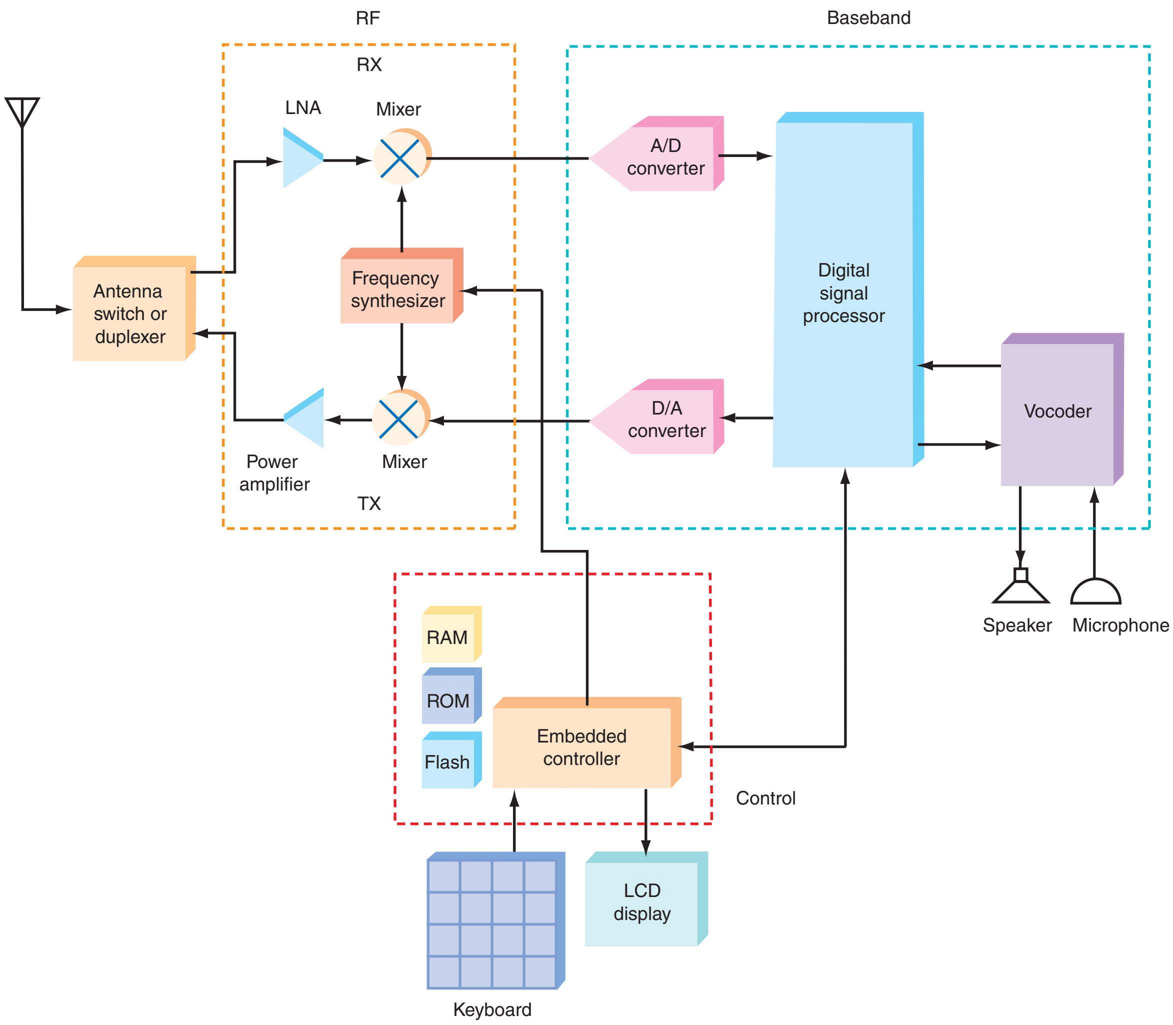
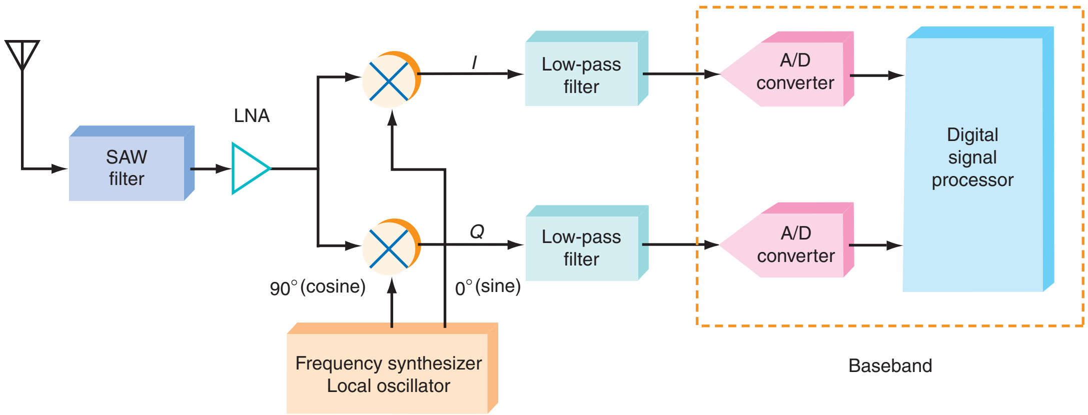


Figure 20-13 A direct-conversion receiver.



common in superheterodyne designs, especially in the crowded multiband cellular spectrum. With direct conversion, baseband filtering can be accomplished by using simple low-pass *RC* filters and/or DSP filters. The *I* and *Q* signals are digitized, and a DSP chip performs additional filtering, demodulation, and voice decoding. Modern IC designs have essentially eliminated the LO leakage and dc offset problems ordinarily associated with direct-conversion designs.

Low IF. Another popular alternative is low-IF architecture. When an IF is used near the baseband frequencies, filtering is simple and very effective. Using an IF near 100 kHz permits simple RC filters to be used, eliminating the larger and more expensive SAW filters. The low IF design is no longer widely used.

2.5G Cell Phone Systems

2.5G cell phone system

The designation *2.5G* refers to a generation of cell phones between the original second-generation (2G) digital phones and the newer third-generation (3G) phones. The 2.5G phones bring data transmission capability to 2G phones in addition to normal voice service. A 2.5G phone permits subscribers to exchange e-mails and text messages and access the Internet by cell phone. Because of the small screen size and a small or very restricted keyboard, data transmission capability is limited but available to those who need it.

Currently, three technologies are used in 2.5G systems: GPRS, EDGE, and CDMA2000. Although GPRS and EDGE systems have been implemented, they are generally considered to be temporary solutions to the need for data transmission capability in cell phones. True high-speed packet data capability is available with 3G phones. The CDMA2000 technology is an extension and improvement of the IS-95A/B standard.

GPRS (general packet radio service)

GPRS. One popular 2.5G technology is the *general packet radio service (GPRS).* This system is designed to work with GSM phones. It uses one or more of the eight TDMA time slots in a GSM phone system to transmit data rather than digitized voice. Depending on how many of the eight time slots are used, the data rate can vary from about 20 kbps up to a maximum of 160 kbps. A typical rate is about 40 kbps, which is more than enough for e-mail and short message service (SMS) but poor for Internet access.

Each GSM frame has eight time slots for data. Refer to Fig. 20-11. The overall bit rate is 270 kbps. In voice operation, each slot contains the compressed or vocoded voice signal. In GPRS, other types of data can be transmitted. The data rate that can be achieved is a function of the type of coding used (FEC) and the number of time slots allotted to the data. The GPRS standard, which was created by the European Telecommunications Standards Institute (ETSI), is now maintained by the 3rd Generation Partnership Project (3GPP). It defines four levels of data coding referred to a CS-1 through CS-4. The most robust coding scheme CS-1 produces fewer errors, but the maximum data speed per slot is 8 kbps. The least robust coding method is CS-4, but it produces a data rate to 20 kbps. To achieve maximum data rate, you could use all eight slots for a rate of 8×20 kbps $= 160$ kbps. However, this is never done. Instead, GPRS defines 12 classes that give different levels of data speed. The selection of the desired class is made by the cell phone carrier who sets just how much of the network capacity is devoted to voice and to data.

Class 12 gives downlink and uplink data rates of 80 kbps maximum. The carrier usually adjusts the class to match its own mix of voice and data users and often charges the data user on a per-kbps basis. Keep in mind, too, that the GPRS method involves an automatic rate adjustment algorithm that adjusts the class and data rate to the robustness of the wireless channel. Over shorter distances with less noise and interference, the system can achieve the maximum data rate. Over longer distances with added noise, the system adjusts itself to a lower data rate to ensure accurate transmission of the data.

Virtually all modern GSM phones come with GPRS, but the user must sign up for services (instant messaging, e-mail, etc.) related to this capability.

EDGE (enhanced data rate for GSM evolution)

EDGE. A faster 2.5G technology is *enhanced data rate for GSM evolution (EDGE).* It is based upon the GPRS system but uses 8-PSK modulation instead of GMSK to achieve even higher data rates up to 384 kbps.

EDGE is sometimes referred to as enhanced GPRS (EGPRS). It is usually implemented as a software upgrade to the base stations but also requires a linear power amplifier. Both hardware and software changes are needed in a GPRS handset. EDGE uses the GPRS class concept whereby the data rate is a function of the encoding and the number of time slots used. By using $3\pi/8$-8PSK modulation, 3 bits is coded per symbol change, thereby tripling the gross data rate. The theoretical maximum data rate is 473.6 kbps with all eight slots used. A more typical implementation is the use of four slots for a data rate of 236.8 kbps. Again, a data rate algorithm automatically backs off on the rate as channel conditions degrade due to noise or increased distance. Typical everyday rates are usually over 100 kbps but less than 200 kbps.

One of the key changes required when EDGE is implemented is the need for linear power amplifiers both at the base station and in the handset. GMSK as used in GSM and GPRS is a type of FM with a constant envelope (amplitude) carrier that changes in frequency with the modulation. FM permits more efficient class C, D, E, and F amplifiers to be used. These amplifiers clip or distort the amplitude of a signal but with FM that does not interfere with the modulation. When $3\pi/8$-8PSK is used, the envelope does change as the signal switches from one phase to another. Therefore, to retain the information content, the amplitude of the signal must be preserved through amplification. A class AB linear power amplifier must be used. Some base stations already use such amplifiers and so may simply adjust them to maximum linear operation rather than maximum efficiency.

In the handsets, efficient class C or E/F power amplifiers in the transmitter must be replaced with a class AB linear amplifier. This is a significant change in a handset as the lower efficiency produces greater heat and shortens the battery life.

3G Cell Phone Systems

3G cell phone system

International Mobile Telecommunication 2000 (IMT-2000)

Third-generation (3G) cell phones are true packet data phones. They feature enhanced digital voice and high-speed data transmission capability. Third-generation phones were originally described by the term *International Mobile Telecommunication 2000,* or *IMT-2000.* The 2000 refers to 2000 MHz, the approximate center of the frequency range defined for 3G (1800 to 2200 MHz). The goal of the International Telecommunications Union (ITU) was to define a worldwide standard for future cell phones to which all other systems could evolve, thereby providing full global roaming. An IMT-2000 phone can achieve a data rate up to 2.048 Mbps in a fixed position, 384 kbps in a slow-moving pedestrian environment, and 144 kbps in a fast mobile environment. With such high-speed capability, a 3G phone can do lots more than just transmit high-quality digital voice.

Some potential 3G applications include fast e-mail and Internet access. With larger color screens and full keyboards, cell phones can act more as small computer terminals. High speed also permits the transmission of video. Subscribers can watch a movie on their 3G phones, although the small screen limits viewing. In most models, a built-in an image sensor and lens lets cell phones become picture phones and digital cameras.

UMTS 3G

Universal Mobile Telecommunications Service (UMTS)

The ITU did not specify a particular technology to implement 3G. However, it did recommend one worldwide version known as wideband CDMA (WCDMA). This system is also known as the *Universal Mobile Telecommunications Service (UMTS).* While the standard is still based in the ITU, it is developed, maintained, and promoted by the Third Generation Partnership Project (3GPP).

WCDMA. WCDMA is a direct sequence spread spectrum technology. In the most popular configuration, it is designed to use a 3.84-MHz chipping rate in 5-MHz-wide bands. Duplexing is FDD requiring the matching of 5-MHz channels. The modulation is QPSK. It can achieve a packet data rate up to 2 Mbps.

A key problem in implementing 3G is the need for huge portions of spectrum. New spectrum is scarce and expensive. In Europe, paired bands in the 1900- to 2200-MHz range are available. In the United States, the 806- to 890-MHz range can be used for 3G in some areas. Some spectrum in the 1710- to 1885-MHz range is also available to some carriers. Also, some segments of the 2500- to 2690-MHz band are available. The exact 3G spectrum varies widely depending on which part of the world you are in, making it extremely difficult to design a cell phone that is fully operable worldwide.

TD-SCDMA. The UMTS 3G standard also defines a TDD version known as TD-SCDMA for time-division synchronous code-division multiple access. It is designed to use a 1.6-MHz-wide channel with a chipping rate of 1.28 MHz. Different time slots in the time-multiplexed data stream are assigned to uplink and downlink activity. The number of uplink and downlink channels may be dynamically assigned so that a carrier can adjust the system to the traffic load at any given time. The primary benefits of TD-SCDMA are that less spectrum is needed. Only a single 1.6-MHz channel is needed. Furthermore, since duplexing is TDD, there is no need for paired spectrum as in WCDMA or GSM or any other FDD system. The downside is that the system is more complex because of the extreme need for accurate timing and synchronization required for proper operation. So far, the only nation to adopt TD-SCDMA as a standard is China.

HSPA. High-speed packet access (HSPA) is an enhancement to WCDMA systems to make them faster. There is a *high-speed downlink packet access (HSDPA)* and a high-speed uplink access (HSUPA) version. They can be used separately or together. Together, they are referred to as HSPA. When the 3G WCDMA standard was first adopted, it was assumed that it would be put into use far faster than it has. During the past years, wireless technology has changed, making the original specifications somewhat behind the times. The maximum 2-Mbps data rate was assumed to be fast enough for any service. But today, the demand for faster data speeds is growing, especially because of the growing demand for mobile video service. Because of the need for faster systems, a new system compatible with WCDMA has been developed. Known as high-speed packet access (HSPA), it provides a packet data rate from the base station to the handset many times that of the 2-Mbps maximum rate of WCDMA.

High-speed downlink packet access (HSDPA)

HSDPA uses an adaptive coding and modulation scheme with QPSK and 16-QAM. Data is transmitted in 2-ms frames. There are 12 categories of HSDPA that define different coding and modulation schemes. The minimum is category 11,900 kbps using QPSK. Category 6 gives 3.6 Mbps using 16-QAM. The maximum data rate is 14.4 Mbps using 16-QAM in category 10. The actual rate achieved is a function of the link quality. High noise and long range give a lower rate. The rate adapts to the channel conditions automatically.

While most data needs will be served by a high-speed downlink capability, in some applications a fast uplink may be needed. This is accommodated by a companion standard known as *high-speed uplink packet access (HSUPA)*. A fast handset to base station rate is more difficult to implement so uplink rates are naturally slower. HSUPA provides a maximum data rate of 5.76 Mbps. Again, the rate adapts to the channel conditions.

High-speed uplink packet access (HSUPA)

An enhanced version called HSPA+ is now also available from some carriers. It permits the use of 64QAM allowing many systems to deliver downlink rates of 21, 28 or 42 Mbps. Although not common there are more advanced versions that use multiple carriers and MIMO to deliver even higher speeds. For example two or four 5 MHz channels can be combined to double or quadruple data speeds to 84 or 168 Mbps. Adding 2×2 or 4×4 MIMO can deliver peak rates in the 336 to 672 Mbps. Today most HSPA systems are still in operation but have been replaced in usage by the newer faster LTE 4G systems.

CDMA2000

This standard was developed by Qualcomm. It is an extension of the widely used IS-95 CDMA standard also known as cdmaOne. The earliest versions of this radio system were correctly designated as a 2.5G technology, but subsequent improved versions have clearly made it a 3G technology because of the high data rates it can achieve.

The basic CDMA2000 data transmission method is generally called 1×RTT (radio transmission technology). It uses the same 1.25-MHz-wide channels but also changes the modulation and coding formats to actually double the voice capacity over that in IS-95. The data capability is packet-based and permits a data rate of up to 144 kbps, which is comparable to EDGE. A version designated 3×RTT uses three 1.25-MHz channels for a total bandwidth of 3.75 MHz. By using a higher chip rate, a maximum date rate roughly three times the 1×RTT speed (432 kbps) is possible.

The more recent version is called 1×EV-DO or Evolution-Data Optimized. It has a higher data rate approaching 3.1 Mbps downlink and an uplink rate up to 1.8 Mbps.

Another version known as 1×EV-DV for Evolution-Data/Voice has a maximum packet rate of 3.07 Mbps. Uplink speed is the same as that of 1×EV-DO. Many carriers still implement CDMA2000, but it is used by the older phones for voice and low-speed data like texting and e-mail. It has been superseded by the newer LTE 4G systems.

20-4 Long Term Evolution and 4G Cellular Systems

Long Term Evolution (LTE) is the wireless cellular technology that is being adopted around the world as the primary cell phone communications service. Multiple 2G and 3G cellular radio methods are heading toward phase-out as carriers build their new LTE networks. It will be years before this expansion is complete, and the older radio technologies like GSM and CDMA will coexist with LTE for a while. In the meantime, the next phase of the LTE standards as put forth by the Third Generation Partnership Project (3GPP) is ready to be deployed. Called LTE-Advanced, it is a significant upgrade to the LTE standard that will provide more speed and greater reliability. Even though LTE-A is still being developed, it is already in service in some areas. This section is a review of LTE basics, a look at the features and benefits of LTE-A, and a glimpse of what 5G systems may be like.

The Road to LTE

LTE is a standard developed by the Third Generation Partnership Project (3GPP). This is the international organization that developed the widely used 3G standards UMTS WCDMA/HSPA. LTE has been in development for years, and different phases of it have been released sequentially over the years. The final LTE standard designated Release 8 was completed in 2010. Release 9 was an update to that. Release 10 defines LTE-Advanced and is available now.

Over the years, multiple cell phone technologies have been developed. The first generation was analog (FM) technology, which is no longer available. The second generation (2G) brought digital technology with its benefits to the industry. Multiple incompatible 2G standards were developed. Only two, GSM and IS-95A CDMA, have survived.

The third-generation (3G) standards were created next. Again multiple standards were developed. Notably the major ones were WCDMA by the 3GPP and CDMA2000 by Qualcomm. Both have survived and are still in use today. The 3G standards were continually updated into what is known as 3.5G. WCDMA was upgraded to HSPA and CDMA2000 was expanded with 1×RTT EV-DO Releases A and B. Both are still widely deployed. In fact, in many places around the world, carriers are still adding 3G or upgrading their 3G systems. In the United States, AT&T and T-Mobile use GSM/WCDMA/HSPA, whereas Verizon and Sprint use CDMA2000/EV-DO. Sprint implemented a

Section 20-4 is largely derived from the original article "An Introduction to LTE-Advanced: The Real 4G" by Louis E. Frenzel, published by *Electronic Design* magazine (Penton Media Inc.) in January and February, 2013, www.electronicdesign.com.

network based on WiMAX, a technology similar to LTE, but is phasing it out. All of these carriers are now offering LTE.

LTE came into being as an upgrade to the 3G standards. Its major benefits were recognized by the cellular industry and were embraced by virtually all mobile carriers as the next generation. All cellular operators are now on the path to implementing LTE. While 3GPP still defines LTE as a 3.9G technology, all of the current LTE networks are marketed at 4G. The real 4G as designated by 3GPP is LTE-Advanced.

Currently LTE is alive and functioning in many U.S. cellular companies and in others worldwide. The networks are not fully built out, and most of the older 2G and 3G systems are still functioning in parallel. Because LTE coverage is not universal, most cell phones still incorporate 2G and 3G systems for voice in areas where LTE is not yet fully deployed. LTE-A deployment is a future rollout.

Why LTE? LTE brings amazing new capabilities to the cellular business. First, it expands the capacity of the carrier, meaning that more subscribers can be added for a given spectrum assignment. Second, it provides the high data rates that are needed by the growing new applications, mainly video downloads to smartphones and other Internet access. And third, it makes cellular connectivity more reliable. All of these needs are important to maintaining growth and profitability in the wireless business.

LTE Technicalities

LTE is likely the most complex wireless system ever developed. It incorporates features that could not have been economically implemented even a decade ago. Today, with large-scale ICs, LTE can easily be accommodated not only in a base station but in a battery-powered handset. The complexity is a function of the advanced wireless methods used as well as the many options and features that can be implemented. This section examines mainly the physical layer of LTE, including modulation, access, duplexing, and the use of MIMO.

Frequency. LTE operates in some of the existing cellular bands but also newer bands. Specific bands have been designated for LTE. These are shown in Table 20-1. Different carriers use different bands depending upon the country of operation and the nature of their spectrum holdings. Most LTE phones use two of these bands, and they are not the same from carrier to carrier. For instance, the iPhone 5 for Verizon uses different bands than the iPhone 5 from AT&T. Most of the bands are set up for frequency-division duplexing (FDD), which uses two separate bands for uplink and downlink. Note in Table 20-1 that bands 33 through 44 are used for time-division duplexing (TDD), and therefore the same frequencies are used for both uplink and downlink.

Bandwidth. LTE is a broadband wireless technology that uses wide channels to achieve the high data rates and accommodate lots of users. The standard is set up to permit bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz. The carrier selects the bandwidth depending on spectrum holdings as well as the type of service to be offered. The 5- and 10-MHz widths are the most common. Some bandwidths cannot be used in different bands.

Modulation. LTE uses the popular orthogonal frequency-division multiplex (OFDM) modulation scheme. It provides the essential spectral efficiency to achieve the high data rates but also permits multiple users to share a common channel. The OFDM technique divides a given channel into many narrower subcarriers. The spacing is such that the subcarriers are orthogonal—that is, they will not interfere with one another despite the lack of guard bands between them. This comes about by having the subcarrier spacing equal to the reciprocal of symbol time. All subcarriers have a complete number of sine wave cycles that upon demodulation will sum to zero.

In LTE the channel spacing is 15 kHz. The symbol period therefore is 1/15 kHz = 66.7 μs. The high-speed serial data to be transmitted is divided up into multiple slower streams, and each is used to modulate one of the subcarriers. For example, in a 5-MHz

Table 20-1 LTE Bands

LTE Band Number	Uplink (MHz)	Downlink (MHz)
1	1920–1980	2110–2170
2	1850–1910	1930–1990
3	1710–1785	1805–1880
4	1710–1755	2110–2155
5	824–849	869–894
6	830–840	875–885
7	2500–2570	2620–2690
8	880–915	925–960
9	1749.9–1784.9	1844.9–1879.9
10	1710–1770	2110–2170
11	1427.9–1452.9	1475.9–1500.9
12	698–716	728–746
13	777–787	746–756
14	788–798	758–768
15	1900–1920	2600–2620
16	2010–2025	2585–2600
17	704–716	734–746
18	815–830	860–875
19	830–845	875–890
20	832–862	791–821
21	1447.9–1462.9	1495.9–1510.9
22	3410–3500	3510–3600
23	2000–2020	2180–2200
24	1625.9–1660.9	1525–1559

(Continued)

25	1850–1915	1930–1995
26	859–894	814–849
27	852–869	807–824
28	758–803	703–748
33	1900–1920	1900–1920
34	2010–2025	2010–2025
35	1850–1910	1850–1910
36	1930–1990	1930–1990
37	1910–1930	1910–1930
38	2570–2620	2570–2620
39	1880–1920	1880–1920
40	2300–2400	2300–2400
41	2496–2690	2496–2690
42	3400–3600	3400–3600
43	3600–3800	3600–3800
44	703–803	703–803

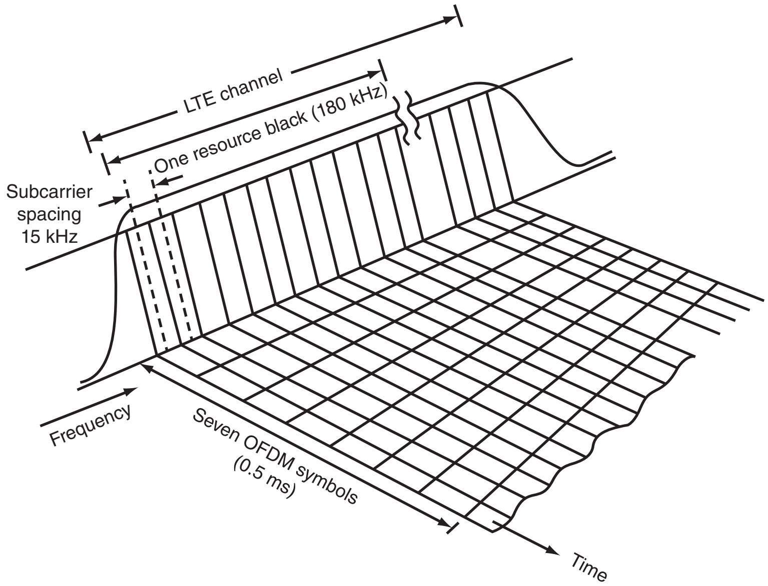
Note: These cellular bands are allocated specifically for LTE. Different carriers in different countries use different bands that are unique to their cell phones. The spacing between FDD channels in bands 1 through 28 varies considerably depending upon carrier spectrum holdings. Bands 33 through 44 have the same uplink and downlink frequencies as these are TDD bands.

channel, up to 333 subcarriers could be used but the actual number is less like 300. A 20-MHz channel might use 1024 subcarriers. The modulation on each can be QPSK, 16QAM, or 64QAM, depending on the speed needs.

Fig. 20-14 shows how OFDM uses both frequency and time to spread the data, providing not only high speeds but also greater signal reliability. For each subcarrier, the data is sent in sequential symbols where each symbol represents multiple bits (e.g., QPSK, 2 bits; 16QAM, 4 bits; and 64QAM, 6 bits.) The basic data rate through a 15-kHz subcarrier channel is 15 kb/s. With higher-level modulation, higher data rates are possible.

Data to be transmitted is allocated to one or more resource blocks. A resource block (RB) is a segment of the OFDM spectrum that is 12 subcarriers wide for a total of 180 kHz. There are seven time segments per subcarrier for a duration of 0.5 ms. Data is then transmitted in packets or frames, and a standard frame contains twenty 0.5-ms time slots. A resource block is the minimum basic building block of a transmission, and most transmissions require many RBs.

Figure 20-14 Data is transmitted by dividing it into slower parallel paths that modulate multiple subcarriers in the assigned channel. The data is transmitted in segments of one symbol per segment over each subcarrier.



Keep in mind the fact that the only practical way to implement OFDM is to do it in software. The basic process is handled with the fast Fourier transform (FFT). The transmitter uses the inverse FFT, while the receiver uses the FFT. The algorithms are implemented in a digital signal processor (DSP), an FPGA, or an ASIC designed for the process. The usual techniques of scrambling and adding forward error correcting codes are implemented as well.

The choice of OFDM for LTE is primarily due to its lesser sensitivity to multipath effects. At the higher microwave frequencies, transmitted signals can take multiple paths to the receiver. The direct path is the best and preferred, but signals may be reflected by multiple objects, creating new signals that reach the receiver somewhat later in time. Depending upon the number of reflected signals, and their strengths, ranges, and other factors, the signals at the receiver may add in a destructive way, creating fading or signal dropout.

The multipath effects occur when the signals reach the receiver all within the time for one symbol period. Remember, a symbol is a modulation state that is either an amplitude, a phase, or amplitude-phase combination that representing two or more bits. If the multipath effects are such that the signals arrive at the receiver spread over several symbol periods, the outcome is called intersymbol interference (ISI). The result is bit errors. This can be overcome with error detecting and correcting codes, but these codes add to the complexity of the system. An equalizer at the receiver that collects all the received signals and delays them such that they all add can also correct for this problem but only further complicates the process.

Spreading the signals in the form of multiple subcarriers over a wide bandwidth lessens these effects. This is especially true if the symbol rate of each subcarrier is longer, as it is in OFDM. If the multipath effects occur in less than one symbol period, then no equalizer is needed. Another effect is frequency variation of the subcarriers at the receiver caused by time or frequency shifts, such as that produced by the Doppler effect in a moving vehicle. This shift in frequency results in the loss of orthogonality and subsequently in bit errors. This problem is mitigated in LTE by adding a cyclical prefix (CP) to each transmitted bit sequence.

The CP is a portion of an OFDM symbol created during the DSP process that is copied and added back to the front of the symbol. This bit of redundancy allows the receiver to recover the symbol if the time dispersion is shorter than the cyclical prefix. This allows OFDM to be implemented without the complex equalization that can also correct for this problem.

While the downlink of LTE uses OFDM, the uplink uses a different modulation scheme, known as single carrier-frequency division multiplexing (SC-FDMA). OFDM signals have a high peak-to-average-power ratio (PAPR), requiring a linear power amplifier with overall low efficiency. This is a poor quality for a handset that is battery operated. SC-FDMA has a lower PAPR and is better suited to portable implementation. The SC-FDMA process is complex, and a detailed discussion of it is not included here.

MIMO. A key feature of LTE is the incorporation multiple input multiple output (MIMO), a method of using two or more antennas and related receive and transmit circuitry to achieve higher speeds within a given channel. One common arrangement is 2×2 MIMO, where the first number indicates the number of transmit antennas and the second number is the number of receive antennas. Standard LTE can accommodate up to a 4×4 arrangement.

The MIMO technique divides the serial data to be transmitted into separate data streams that are then transmitted simultaneously over the same channel. Because all signal path are different, with special processing they can be recognized and separated at the receiver. The result is an increase in the overall data rate by a factor related to the number of antennas. This technique also mitigates the multipath problem and adds to the signal reliability because of the diversity of reception.

A special version of MIMO known as multi-user MIMO is being implemented in some cellular systems as well as in some Wi-Fi systems. It allows multiple users to share a common channel. MU-MIMO relies upon many antennas implementing spatial division multiple access (SDMA) as well as unique channel coding to keep the signals separate. Channel bandwidth is divided amongst the users as needed.

The difficultly in implementing MIMO arises because of the small size of the handset and its limited space for antennas. Already most smartphones contain five antennas, including those for all the different cellular bands plus Wi-Fi, Bluetooth, GPS, and perhaps NFC. It is not likely that most phones will contain more than two LTE MIMO antennas, and their inclusion depends on being able to space them far enough apart so that spatial diversity is preserved with sufficient isolation between them. Of course, it is easier to use more base station antennas. A typical LTE arrangement appears to be 4×2 to provide optimal coverage with the space available.

Data Rate. The data rate actually used or achieved with LTE is dependent upon several features, as you have seen. It depends on channel bandwidth, modulation type, MIMO configuration, and of course the quality of the wireless path. In the worst-case situation, data rate could be only a few Mbps, but under good conditions data rate can rise to over 300 Mbps. On average, most practical LTE downlink rates are in the 5- to 15-Mbps range. This is faster than some fixed Internet access services using cable or DSL.

Access. Access refers to using the same channel to accommodate more than one user. This is effectively a multiplexing method. Standard methods include frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA). OFDMA makes use of some of the available subcarriers and time slots within those subcarriers for each user. The number of subcarriers and time slots used depends on multiple factors. In any case, it is usually possible to accommodate up to hundreds of users per channel bandwidth.

TD-LTE

Most LTE will be of the FDD variety, at least in the United States, Europe, and parts of Asia. Paired-spectrum groups are required for the separate uplink and downlink transmissions. TD-LTE requires only a single spectrum segment. TD-LTE is being widely implemented in China and India because of the more limited spectrum availability. This conserves spectrum and provides for more users per MHz. The LTE standards include a definition for TD-LTE. It is expected that some U.S. carriers, including Sprint, will use TD-LTE.

LTE Advanced

LTE-A builds on the LTE OFDM/MIMO architecture to further increase data rate. It is defined in 3GPP Releases 10 and 11. There are five major features: carrier aggregation, increased MIMO, coordinated multipoint transmission, Hetnet (small cells) support, and relays. Small cells are covered in the next section.

Carrier aggregation refers to the use of two or more 20-MHz channels combined into one to increase data speed. Up to five 20-MHz channels can be combined. These channels can be contiguous or noncontiguous as defined by the carrier's spectrum assignments. With maximum MIMO assignments, 64QAM, and 100 MHz bandwidth, a peak downlink data rate of 1 Gbps can be achieved.

LTE defines MIMO configurations up to 4×4. With LTE-A that is extended to 8×8 with support for two transmit antennas in the handset. Most LTE handsets use two receive antennas and one transmit antenna. These MIMO additions will provide future data-speed increases if adopted.

HetNet support refers to support for small cells in a larger overall heterogeneous network. The HetNet is an amalgamation of standard macro cell base stations plus micro-cells, metrocells, picocells, femto cells, and even Wi-Fi hot spots. This network provides increased coverage in a given area to improve connection reliability and increased data rates. Small cells are covered in the next section.

Coordinated multipoint transmission is also known as co-operative MIMO. It is a set of techniques using different forms of MIMO and beamforming to improve the performance at cell edges. It makes use of coordinated scheduling and transmitters and antennas that are not collocated to provide greater spatial diversity that can improve link reliability and data rate.

Relays is the use of repeater stations to help coverage in selected areas, especially indoors where most calls are initiated. LTE-A defines another base station type called a relay station. It is not a complete base station but a type of small cell that will fit in the HetNet infrastructure and provide a way to boost data rates and improve the dependability of a wireless link.

Some deployment of LTE-A occurred in late 2013 with increasing adoption in 2014 and beyond. LTE-A is forward and backward compatible with basic LTE, meaning that an LTE handset will work on an LTE-A network and an LTE-A handset will work on a standard LTE network.

LTE-A Challenges

LTE solves many problems in providing high-speed wireless service. There is no better method, at least for now. However, it does pose multiple serious design and deployment issues. The greatest problem to overcome is the necessity of having to use multiple bands that often are widely spaced from one another. As a result, this requires multiple antennas, multiple power amplifiers, multiple filters, switching circuits, and sometimes complex impedance matching solutions in the base stations as well as the phones themselves. Each cellular operator specifies cellphones for their spectrum.

In addition, the power amplifiers (PAs) must be very linear if error vector magnitude (EVM) is to be within specifications for the various multilevel modulation methods used. Linear amplifiers are inefficient, and because of this they are the biggest consumer of power in the phone except for the touch screen. The need to cover multiple bands necessitates the use of multiple PAs. Battery life in an LTE phone is typically shorter as a result. The need to include MIMO also means additional antennas and PAs.

Solutions to these problems lie in more-efficient power amplifiers and fewer of them. Also, wider-bandwidth antennas solve the multiband problem. Tunable antennas are also being designed by several companies to cover multiple bands with a single structure.

Another challenge is testing. Testing LTE systems with MIMO is a particularly complex process. Luckily a number of test equipment companies have created systems for this purpose. One of the greatest challenges is testing the higher-level MIMO configurations. LTE-A permits up to 8×8 MIMO.

Voice over LTE

LTE is a packet-based IP data network. Initially LTE did not include a voice service. However, LTE voice is now being implemented. Today, if you are using an LTE smartphone, you may still be using the existing 2G or 3G network for what is called circuit-switched voice service. Eventually voice over LTE (VoLTE) will be fully implemented in the base stations and in the handsets. VoLTE is just VoIP over LTE, and it will operate simply as a data application on the IP network.

Although a VoLTE protocol has been defined, implementing it requires major engineering decisions and network changes. Most of these concern maintaining voice connections for older non-LTE phones for some extended period. Particularly tricky are the changes that will allow LTE phone users to get voice service if they move out of an area with no LTE. When VoLTE is available, a subscriber could initiate a call using the LTE system but drive out of the LTE coverage area. Systems must be able to hand that call off to a traditional voice network. The mechanism for this is network software called circuit-switched fallback (CSFB). It is now available on most networks. Another issue is getting VoLTE into the handsets. VoLTE requires a separate chip in the phone, and few have such a capability today.

Implementing VoIP requires a vocoder, a circuit that is essentially an A-to-D converter to digitize the voice signal and a D-to-A converter to convert the digital voice back into analog voice for the user. A vocoder also incorporates voice compression, a technique that effectively minimizes the number of bits used to represent voice. This allows voice to be transmitted faster but at lower data rates so it does not occupy much bandwidth.

LTE uses what is called the Adaptive Multi-Rate (AMR) vocoder. This is also used in GSM systems and other 3GPP standards. It has a variable bit rate capability from 1.8 kbps to 12.2 kbps. Digitized voice is then assembled into AMR packets and then into IP packets, which are then scheduled into transmission sequence. A call is allocated some of the OFDMA subcarriers and some of the time slots within the bit streams of each subcarrier.

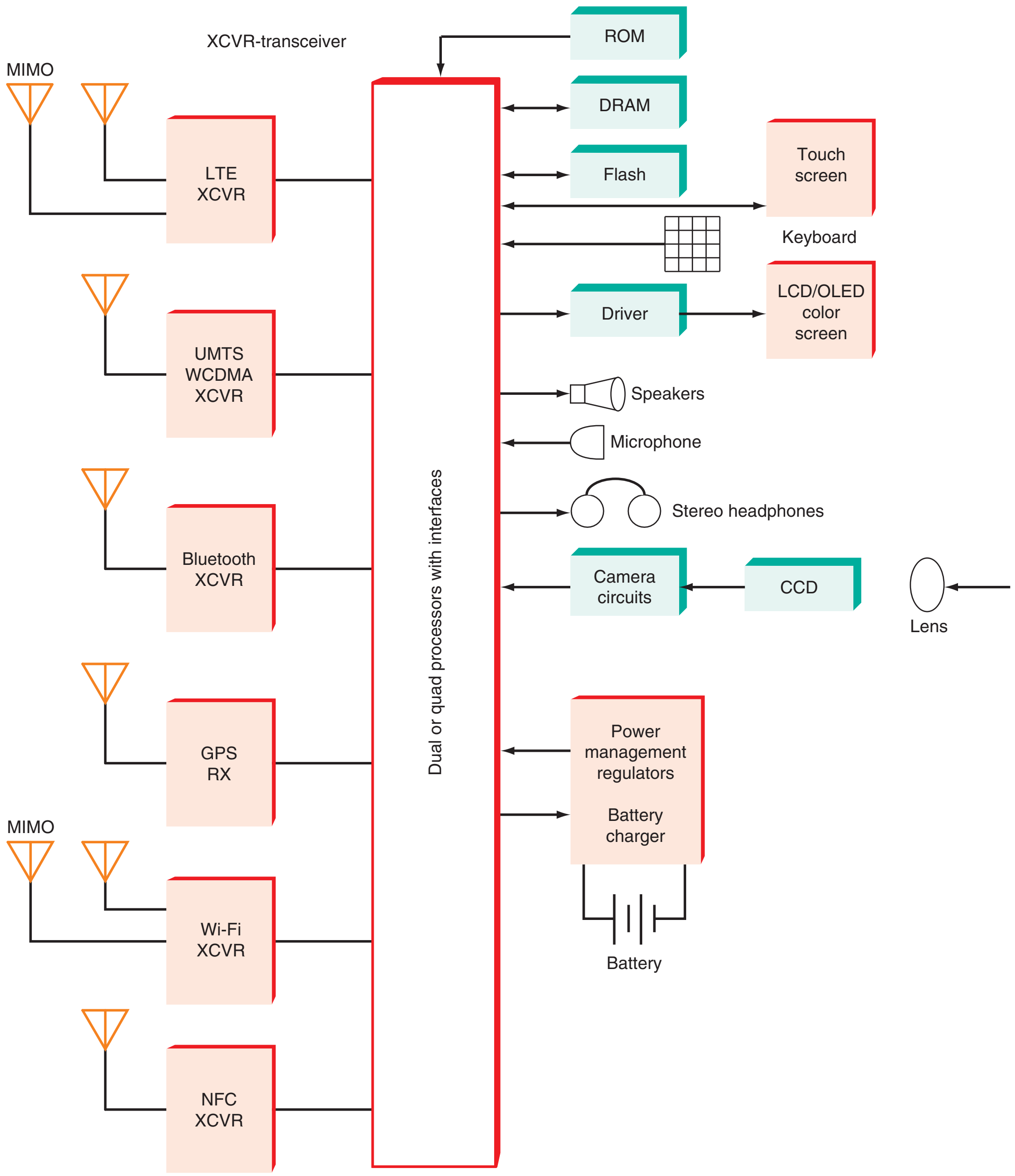
Smartphone Analysis

The most sophisticated cell phone available today is called a smart phone. It incorporates LTE and a wide range of other wireless technologies. Chances are that you already own smartphone. Here is a brief analysis of what's inside the typical modern smart phone.

Refer to the block diagram of a typical smart phone as shown in Fig. 20-15. Most cell phones today are no longer just two-way radios for making phone calls. Instead, at the core of the smart phone is a dual processor or quad processor microcomputer that implements all of the various functions. Today's smart phone is in reality a general-purpose microcomputer that just happens to have cell phone with other communications capabilities built in. The available computing power available has enabled the development of a wide range of software applications (apps). These apps give the smart phone capability far beyond its original function.

Color Touch Screens. The prominent feature of every smart phone today is its large color screen. These high-resolution displays are made with different technologies, such as LCD or OLED. All of them today are touch screens, meaning that all controls such as buttons, keyboards, and other operational tools are operated by pressing or swiping the screen.

Figure 20-15 Block diagram of a generic 4G LTE smart phone.



Cameras. Most cell phones and most smart phones contain a digital camera. These cameras use a CCD or CMOS light sensor and a lens to capture a scene and store it in flash memory. These cameras have resolutions from 5 to 40 megapixels, therefore rivaling stand-alone cameras. Many of the cameras are accompanied by an LED flash. While these cameras are primarily for still photos, most are capable of recording real-time video. Many smart phones also have a second, front-facing camera for making video phone calls and taking selfies.

Radio Modems. Virtually all smart phones today contain LTE 4G technology. The newer phones use a two-antenna MIMO arrangement. The phone also usually contains a 2G and/or 3G radio for voice calls as well as backward capability for calls in a region without LTE service.

Figure 20-16 The Samsung Gear smart watch communicates with a smart phone with Bluetooth wireless technology.

Bluetooth. Bluetooth is a short-range radio technology to be discussed in the next section. However, its primary function in most cell phones is to implement a wireless headset and microphone. The Bluetooth radio can also be used with iBeacon technology that allows cell phones to read nearby information tags and Bluetooth location devices. It could also possibly be used with cashless payment systems that replace credit cards. Bluetooth is also used as a connecting device for smart watches, a wearable accessory to many smart phones. The smart watch provides call, text, or e-mail alerts, time, and other information without taking the smartphone out of your pocket or purse. See Fig. 20-16.

Wi-Fi. Wi-Fi is the wireless local area network (WLAN) technology widely used throughout the world to implement Internet connections. Virtually all smart phones contain a Wi-Fi transceiver, and many include two antennas for MIMO. The Wi-Fi capability permits smart phones to connect to any available access point or hot spot, including wireless routers that are part of many home broadband Internet connections today. Wi-Fi is covered in Chap. 21.

GPS. Another radio inside of most smart phones is a GPS receiver. This gives the smart phone navigation capability. The smart phone is usually accompanied by mapping software that provides vivid visual displays of maps tied to the GPS navigation satellites.

NFC. NFC is near field communications, another short-range radio technology built in to some smart phones. It is used in payment systems that eliminate cash and credit cards. NFC is not in all cell phones.

Functional Features. In addition to being able to make a phone call to any other phone anywhere in the world, all smart phones have Internet access. The operating system software includes a browser to allows you to access the Internet just as you would from a desktop PC or laptop. The only disadvantage is the small screen.

Another common feature is e-mail. Since you can access the Internet, you can easily access your regular e-mail account from any location. Texting is another common feature that is used more often than e-mail.

Music playback is a part of all smart phones. Virtually all smart phones have the ability to store songs and music videos in compressed form for playback on built-in speakers or through headphones.

One of the most popular features of modern smart phones is the ability to play videos. Thanks to digital compression technology, video presentation is very common. By way of an Internet connection, you can watch videos from multiple sources, such as Google, YouTube, Netflix, Hulu, and other video sources for movies and other short subjects.

Another application that is possible thanks to video a and high-resolution display is games. There are literally thousands of games available for smart phones today, and these are widely used.

All of these features are possible because of the internal processing power. Most smart phones contain a processor that contains two cores, each core being a full 32-bit microcontroller. Some phones also have larger quad core processors, and many incorporate 64-bit processing power as well as 32-bit processing power. These multiple processors implement the DSP required of most phones today. All cell phones are software-defined radios, and virtually all of the modulation, demodulation, encoding, decoding, voice and video compression, and other functions are handled by the processors. The processors also run the operating system and any applications software that is added later. The processors are usually accompanied by standard DRAM and flash memory. A variety of special serial and parallel interfaces are provided to connect to the display, cameras, and other peripherals.

Battery and Charger. A key part of every cell phone is the battery power supply and its power management hardware. The lithium-ion battery operates a whole array of multiple voltage regulators and DC-DC converters that supply all of the different operating voltages to the ICs, interfaces, and peripheral devices. The power management system also shuts down unneeded circuits, such as the display, when they are not in use.

In addition, all phones include a battery charger. The battery charger operates from an external AC power source. Some newer phones include wireless battery charging. This system uses magnetic induction to connect the cell phone to its charger. Both the charger and the cell phone have built-in coils that serve as windings on a transformer. By putting the coils close together, transformer action transfers the AC power from the charger to the charging circuitry inside the cell phone by magnetic induction, so that no wire connection is needed.

What Is 5G?

It will take a decade or more for LTE and especially LTE-A to dominate in cellular coverage. Furthermore, new LTE releases from 3GPP are yet to come. In addition, some provisions of current LTE releases have yet to be implemented. An example is self-organizing networks (SONs), a feature that makes networks easier to plan, configure, optimize, and manage. With a SON, all base stations would be self-configuring, taking into account nearby base stations and using internal algorithms to heal, self-optimize, and adapt to new nearby stations and other conditions. The small-cell movement to be discussed in the next section is definitely LTE-based, and extensive deployment with SON is yet to come.

In the meantime, research continues with what is the fifth generation (5G) of cellular wireless. It is possible that 5G will simply stay on the same path as 4G and LTE—that is, that 5G will use higher frequencies and wider bandwidths to achieve even higher data rates. With semiconductor technology still viable at ever smaller IC feature sizes, operation well into the hundreds of GHz is possible. Already, advanced millimeter wave (30- to 300-GHz) systems are functioning with advanced chip sets in short-range personal area networks (PANs) for home video transfer (60 GHz), automotive radar (77 GHz), and cellular/hot spot backhaul (80 GHz). Some think the 28-GHz and 38-GHz spectrum segments offer good opportunities for cellular. Because of the higher frequencies, range is shorter, meaning that there are more but smaller cell sites. However, by using higher-level MIMO, higher-gain antenna arrays and beamforming, coverage will be reliable and the available bandwidth will permit download data rates as high as 10 Gbps. In summary, 5G will most likely be many small cells operating in one or more millimeter wave bands using smart, steerable, high-gain antennas.

20-5 Base Stations and Small Cells

Base stations, also called cell sites or macro cells, form the heart of the cellular network. They implement all radio connectivity and operational and control functions and connect to the carrier's telephone network as well as the Internet by way of backhaul equipment. A key trend today is the incorporation of small cells to complement the existing base stations to improve coverage and data speeds.

Base Stations

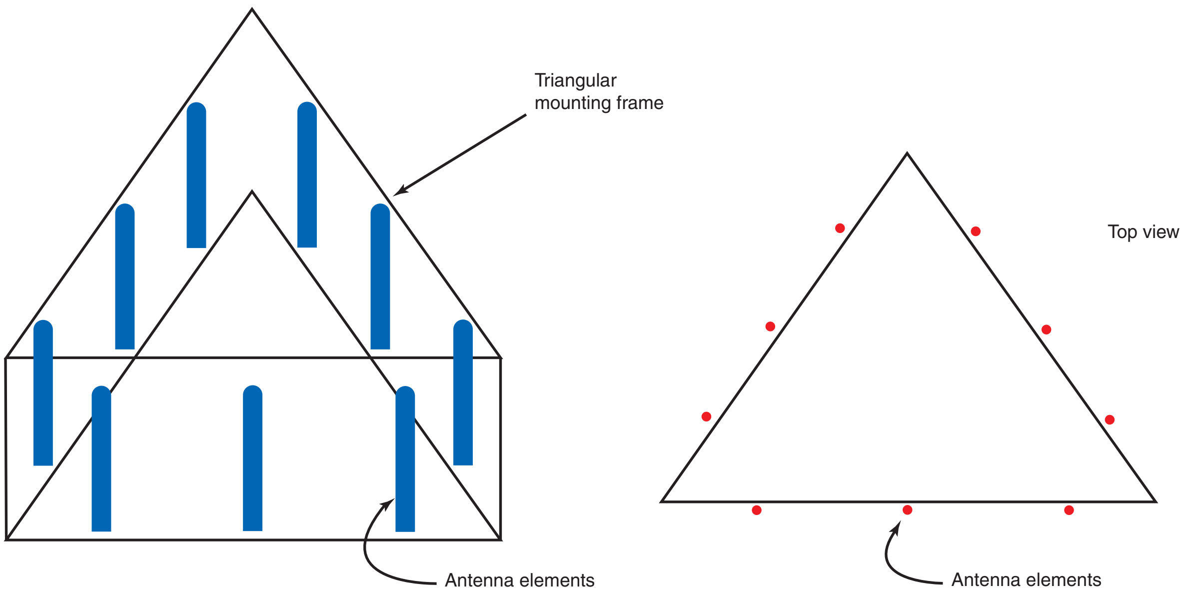
The most complex and expensive part of any cellular telephone system is the network of *base stations* that carriers must have to make it all work. Over the years, carriers have added many more base stations to handle the constantly growing number of subscribers. In addition, each base station has expanded and become more complex because of the growing number and variety of radio standards it must handle. Base stations must continue to support 2G technologies, 2.5G enhancements, and now 3G systems. Support for multiple standards has led to considerably more equipment. An effort has been made by base station manufacturers to consolidate the equipment by using software-defined radio techniques and DSP. These methods permit the base station receivers to accommodate existing multiple standards and to be able to work with new standards by reprogramming rather than replacing equipment.

Base stations consist of multiple receivers and transmitters so that many calls can be handled on many different channels simultaneously. The transmitters in the cell site are much more powerful than those in the handsets. Power levels up to 40 W are typical. These power levels are achieved with highly linear broadband class A or class AB power amplifiers. Since LTE and CDMA systems require linear amplification, base stations are using digital pre-distortion (DPD) and envelope tracking (ET) to improve efficiency. Superior linearity is critical, especially in CDMA and LTE systems that cover a broad spectrum. Nonlinearities produce intermodulation and spurious signals that can make a system inoperable.

The most visible feature of a base station, of course, is its antenna on a tower. The antennas used by base stations must serve many transmitters and receivers by means of isolators, combiners, and splitters. Base station antennas have become directional rather omnidirectional, as the cell patterns suggest. This "sectorization" of the cell site has helped to increase subscriber capacity with minimal cost. Most base stations use a triangular antenna array that looks like the one shown in Fig. 20-17. On

Section 20-5 is largely derived from the original article "Understanding the Small Cell and Het Net Movement," by Louis E. Frenzel, published by *Electronic Design* magazine (Penton Media Inc.) in September and October, 2013, www.electronicdesign.com.

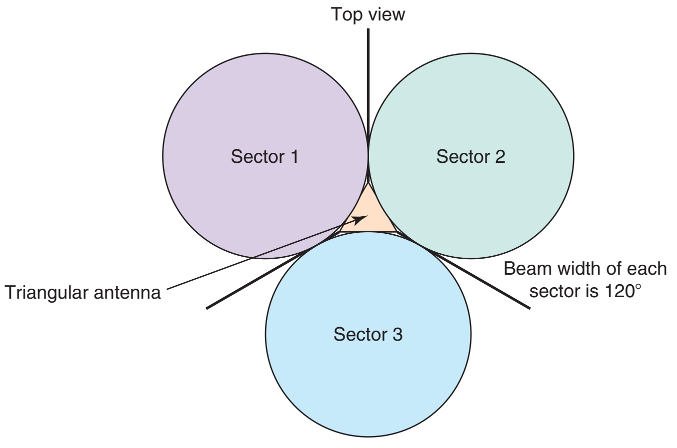
Figure 20-17 Typical triangular cell site antenna.



each side of the triangular frame is an array of three vertical antennas forming a broadside or collinear array that may also use reflectors. Each of the three arrays produces a gain of about 8 dB and an antenna pattern with a beam width of 120°. This divides the cell coverage into three equal sectors. See Fig. 20-18. This directional capability provides excellent isolation of the three sectors, which in turn permits the same channel frequencies to be used in each of three 120° sectors. Some sites also use two supplementary antennas that provide spatial diversity, which greatly improves the reception of weak signals from the handset. Carriers are beginning to use more sophisticated "smart" beam-forming antennas with more elements, arrays, and sectors to further improve capacity.

A key trend is packaging all the RF transmit and receive circuitry, including power amplifiers, into a small housing that is mounted at the antennas at the top of the tower. These are called remote radio heads (RRHs). They eliminate the long, expensive, and

Figure 20-18 Horizontal radiation and reception pattern of a typical cell site antenna.



high-loss transmission lines, thereby greatly improving base station power efficiency. The base station equipment is connected to the RRH by way of a digital fiber interface called the Common Public Radio Interface (CPRI).

Small Cells and HetNet Rationale

A small cell is a miniature cellular basestation with limited power and range. Its function is to complement the larger macro basestations now the most common form of cell site. This permits greater subscriber capacity as well as higher data speeds for all concerned. Small cells are a growing trend that is expected to have its greatest impact in the future.

Currently, cell phone traffic is handled by a huge network of cell sites called macro basestations (BS). With their high power, tall towers with multiple antenna arrays, long range, and backup power sources, these macro BS cover most of the United States except for some very rural and geographically challenged areas. There are nearly 300,000 such basestations in the United States. It is getting increasingly more difficult to find and secure suitable locations for such BS. The solution is the small cell.

In addition, the success of the smartphone and the growing subscriber demand for more and faster service are putting the pressure on cellular carriers to expand and upgrade their BS deployments. The carriers' response has been to upgrade their systems with the 4G LTE technology that offers significantly faster download speeds demanded by the major increase in video consumption. LTE is still being installed with full coverage not expected for several more years. One clear solution is the LTE small cell.

While the adoption of LTE will boost capacity and speed, limits are being reached. The OFDM of LTE along with advanced modulation methods and MIMO have pushed the spectral efficiency (bits/Hz/Hz) of the cellular system to the Shannon limit. LTE Advanced will improve speeds by providing more bandwidth through carrier aggregation. The ultimate limit is the spectrum available to the carrier. Again small cells and frequency reuse can provide an interim solution until more spectrum is freed up.

Another major issue is indoor performance of cell phones. It has been shown that over 80 percent or all cell phone calls are carried out indoors, in homes, offices, shopping malls, hotels and other venues. Indoor performance is significantly poorer than outdoor performance as the radio signals are seriously attenuated, distorted and redirected by walls, ceilings, floors, furniture and other obstacles. Indoor situations limit the range of the radio and furthermore greatly curtails data speeds. LTE is helpful in overcoming this problem, but the real solution is the small cell.

As it turns out, public and private Wi-Fi hotspots and access points fit the basic definition of a small cell. They can connect to a user smartphone, tablet, or laptop and provide access to the video and other information and media demanded by the user. You don't have to use the cellular network to download video or access other big data applications if a Wi-Fi hotspot is nearby. Most cellular small cells will include a Wi-Fi access point.

Groups of physically small cells can be installed anywhere, indoors or out. They can sit on a desk or be mounted on a wall, roof, lamp post or light pole. The small cells fill in the gaps in coverage and provide service where macrocell coverage is poor. In high density population, cities with tall buildings are examples.

It is estimated there will be from 5 to 25 small cells per macro cell in most networks. Networks of small cells overlay, or as some say underlay, the macro network to provide an overall boost not only in data speeds but also subscriber capacity. The general customer performance is greatly improved with more reliable connections and significantly higher download speeds.

Another piece of the small cell trend is distributed antenna systems (DAS). DAS uses fiber optic cable from a macro BS to an array of antennas spread over a wide area to extend the reach and improve connection reliability. It is used in large buildings, airports, convention centers, sports complexes, and other large public venues. The collection of macro BS, small cells, Wi-Fi hotspots, and DAS is now referred to as heterogeneous network or HetNet.

Table 20-2 A Summary of the Main Categories of Licensed Small Cells with their Defining Characteristics

	Femto	Pico	Micro/Metro	Macro
Indoor/outdoor	Indoor	Indoor or outdoor	Outdoor	Outdoor
Number of users	4–16	32–100	200	200–1000+
Max output power	20–100 mW	250 mW	2–10 W	40–100 W
Max cell radius	10–50 m	200 m	2 km	10–40 km
Bandwidth	10 MHz	20 MHz	20, 40 MHz	60–75 MHz
Technology	3G/4G/Wi-Fi	3G/4G/Wi-Fi	3G/4G/Wi-Fi	3G/4G
MIMO	2×2	2×2	4×4	4×4
Backhaul	DSL, cable, fiber	Microwave, mm	Fiber, microwave	Fiber, microwave

All small cells with use the existing licensed spectrum assigned to the carrier's networks. The limited spectrum is shared by the method of frequency reuse and spatial diversity. Frequency reuse refers to the use of the same band by multiple cell sites. Spatial diversity means that these sites are spaced from one another so that coverage areas do not overlap and power levels are controlled to eliminate or minimize interference to adjacent cells and those on the same frequency.

Small Cells Defined

There are several different sizes and versions of small cells. They vary in the number of users they can handle, their power and range. In virtually all cases, they all include the essential 3G technologies of the carrier, LTE and Wi-Fi. They have a power source and a backhaul connection to the cellular network. Table 20-2 shows the general names and capabilities of each major classification.

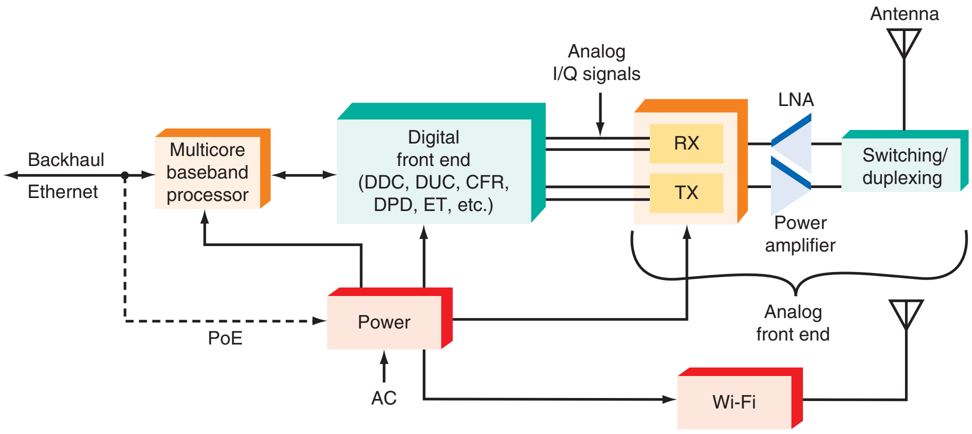
The smallest is the femto cell. A femtocell is a single box BS used by the consumer or small offices to improve local cellular service. Femtos have been around for years, and millions have been installed by most of the larger carriers. Backhaul is by way of the customer's high-speed Internet connection via a cable TV or DSL telecom provider. There are also enterprise femtos that handle more users and provide a significant boost in indoor accessibility.

There are progressively larger small cells such as the picocell, microcell, and metrocell, each with increasing capacity, power and range. Virtually all handle legacy 3G, LTE and include Wi-Fi. Many of the future small cells will also feature LTE-Advanced, the faster version of this 4G technology. See Table 20-2 for details.

Inside the Small Cell

A small cell is still a cellular basestation but boiled down to only a few key chips and circuits. Thanks to super fast multicore processors, most 3G and LTE baseband operations are easily handled by a single IC. This baseband IC is then connected to the RF circuitry making up the radio transceiver. A general block diagram is shown in Fig. 20-19.

Figure 20-19 This general block diagram of a small cell indicates that it is essentially a multicore baseband digital processor connected to the analog RF front-end made up of the transmitter and receiver. Backhaul is usually via Ethernet.



The RF transceiver called the analog front-end consists of the receiver (RX) and transmitter (TX). The receiver gets its signal from the antenna amplifies it in a low noise amplifier (LNA) and sends the signal to I/Q mixers forming a demodulator that recovers the signal. The signals are passed to analog-to-digital converters (ADCs) that create the input to the digital front-end processor.

Between the RF front-end and the baseband processor is additional circuitry that performs decimation, digital upconversion (DUC), and digital downconversion (DDC). Other digital processing includes crest factor reduction (CFR), digital predistortion (DPD) and envelope tracking (ET). DPD and ET are used for linearization of the RF power amplifiers to improve efficiency. All this circuitry may be in a separate ASIC or FPGA or may be included in the baseband chip or front-end RF circuitry.

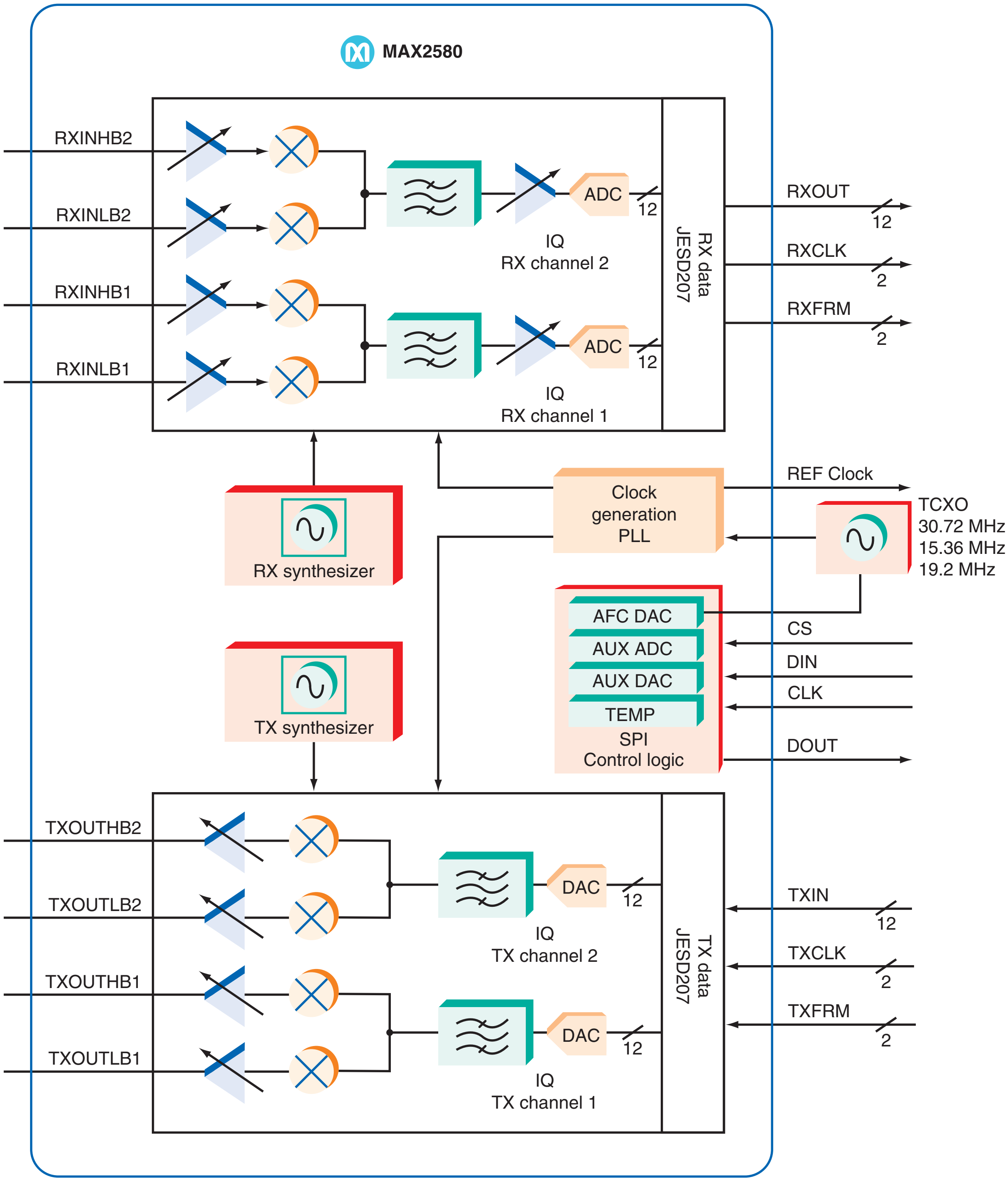
The baseband processor creates the digital I/Q signals for the transmitter. These go to digital-to-analog converters (DACs) in the analog front-end that produce the analog equivalent signals. These are sent to I/Q mixers that form a modulator. The modulator output is then sent to one or more power amplifiers (PAs) and then to the antenna.

The baseband processor has both multiple standard CPUs and digital signal processors (DSP) and handles all the modulation and demodulation and other process involved with the various cellular standards. The I/O to the backhaul is typically by Ethernet. Power comes from a power over Ethernet (PoE) connection if available or by some other source.

Fig. 20-20 shows an example of single chip analog front-end. This is the MAX2580 by Maxim Integrated. It contains the I/Q modulator and demodulator as well as their fractional-N frequency synthesizers for channel selection. The multiple circuits support 2 × 2 MIMO. The synthesizers cover all LTE bands 1 to 41 and provide for bandwidth selection from 1.4 MHz to 20 MHz. The ADCs and DACs are included on chip. The digital interfaces to the baseband processor are the JESD207. The receiver section contains the LNAs however additional external LNAs could be added if necessary. The transmitter output amplifiers provide 0 dBm. If more power is needed external power amplifiers can be added. Maxim makes a wide range of other RF circuits including the MAX2550-MAX2553 3G femtocell transceivers for CDMA systems.

The baseband functions in a base station or small cell is implemented by a single chip containing multiple processors, memory, logic and interface circuits. An example from Texas Instruments is the KeyStone line these processors contain a mix of ARM A15 RISC processors as well as TIs C66x DSPs. One typical unit is the TCI6630K2L

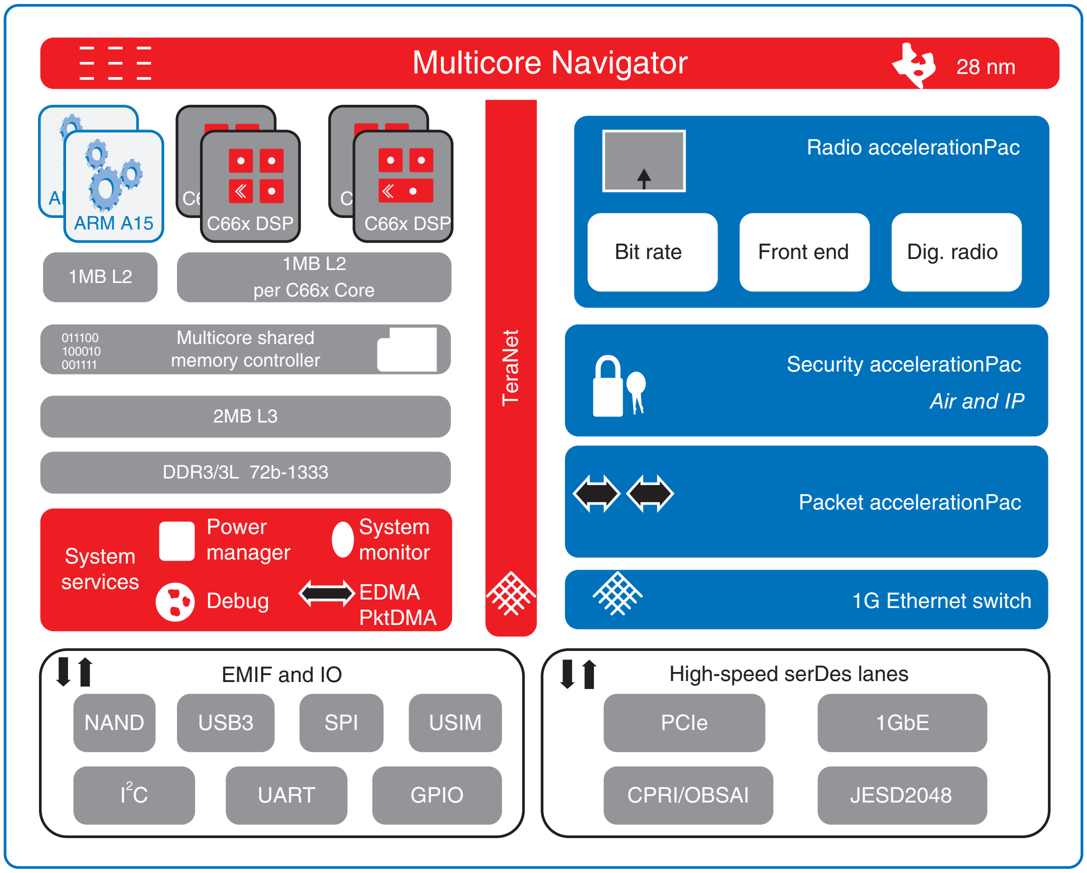
Figure 20-20 The Maxim Integrated MAX2580 RF transceiver features two full radios to implement 2 × 2 MIMO.



shown in Fig. 20-21. It contains two ARM cores and four C66x DSPs. It also contains multiple logic accelerators to speed up operations, minimize the number of cores and reduce power consumption. This chip also includes the digital front-end circuits like DUC/DDC/DPD/CFR. Multiple interfaces include the JESD240B, PCIe, SPI, USB, and a gigabit Ethernet switch.

Finally, most small cells will generally contain Wi-Fi and GPS. Power will come from Power over Ethernet (PoE) plus a mix of DC-DC converters and regulators. Most power is consumed by the RF power amplifiers and the baseband processor SoC.

Figure 20-21 The Texas Instruments TCi6630K2L is a small-cell baseband processor with two ARM CPUs and four C66x DSPs, plus accelerators, the digital front-end components, and multiple interfaces including a gigabit Ethernet switch.



Timing and Synchronization

A key requirement of all LTE basestations, macro or small cell, is timing and synchronization of all the radios in the network. Timing and synchronization is essential to achieve the specifications of the Third Generation Partnership Project (3GPP), the organization establishing the LTE standards. The timing and synchronizations is implemented by delivering a formatted clock signal to the radio circuits of the base station. These signals are then used to create the phase and frequency components of the LTE modulation. Timing and synchronization is also essential for proper handoff and backhaul coordination.

Several timing and synchronization methods have been developed including synchronous Ethernet (SyncE) or G.8262 by the ITU and the IEEE's Precision Time Protocol (PTP) 1588–2008. The latter seems to be the preferred method, but both are used. The PTP can be delivered with a grandmaster clock in the form of a time stamp over the packet network. An alternative is Network Time Protocol (NTP) that is designed to synchronize clock to some time reference over a variable latency data network.

The timing requirements for implementing LTE in the network are severe. The typical clock precision required is 16 parts per billion (ppb) in the transport network and 50 ppb in the air interface. For TDD and Advanced versions of LTE, the phase requirements are also critical. In addition, the method of backhaul will vary with different types of small cells. Many will use microwave, others will use fiber and in residential femtos DSL or cable TV provide the backhaul. Different timing schemes are needed to optimize the performance.

The LTE Advanced small cells to come also have strict timing and synchronization requirements to implement the key features of enhanced inter-cell interference coordination (eICIC) and coordinated multipoint transmission/reception (CoMP) both a type of interference management technology required for self-organizing networks (SON).

Wi-Fi Offload

The concept of Wi-Fi offload is simple. It is the formal use of available hotspots and access points to carry the high-speed data relieving the cellular network of that burden. Since all smartphones have Wi-Fi, it is possible to create a system that automatically selects Wi-Fi for a fast download if a hot spot is nearby. While a subscriber could voluntarily access the data with Wi-Fi, he or she may not be aware of a useable hotspot. By offloading the cellular system, that network can handle more users with high-speed data needs that cannot be addressed with Wi-Fi. Today, the users can automatically offload the network themselves by actively seeking an available hotspot to avoid the cost of using the cellular network. Otherwise, an automatic carrier-driven approach can be implemented to make the offload work seamlessly when a user access a high-volume download.

While the ultimate solution is to roll out a small cell underlay to increase capacity and coverage, Wi-Fi offers an immediate solution to the demand for faster downloads. Since high-speed traffic like video is growing faster than the carriers can implement a full small cell system, Wi-Fi offers a fast and inexpensive way to deal with the problem.

To make this work, several things must happen. First, cellular operators will have to partner with existing Wi-Fi providers in their coverage areas. Alternately, the cellular operators will need to build out their own Wi-Fi networks. Many have already constructed their own Wi-Fi networks to ensure the desired coverage. Wi-Fi networks are significantly less expensive to install than cellular base stations, including small cells. And they are usually faster than most even 4G networks. These cellular operator Wi-Fi networks are referred to as carrier-grade networks

Second, some mechanism is needed to initiate an automatic selection of Wi-Fi vs. cellular network when a subscriber attempts to access some source of video or other big data. A subscriber's smartphone or tablet will seek out the available networks then select the best option mostly favoring Wi-Fi if it is available. It has been estimated that up to 50 percent of cellular data traffic will eventually be offloaded to Wi-Fi giving carriers time to roll out more small cells, expand their LTE networks, or add new spectrum while minimizing capital expenditures (CAPEX).

The mechanism for this is now available in the form of the Wi-Fi Alliance's Hotspot 2.0 and the IEEE 802.11u standard. First, 802.11u is a relatively recent enhancement to the 802.11 WLAN standards. It enables Wi-Fi to work with other networks including cellular networks. The enhancement essentially automates the connection between a smartphone, tablet or laptop to different Wi-Fi networks. It replaces the process of discovering nearby hotspots, entering passwords, performing authentication, and connecting. Next, Hotspot 2.0 is an addition to the basic standard that uses 802.11u to automate access point discovery, registration, and provisioning and connection. This not only enables roaming between hotspots but also provides a mechanism to link to cellular networks to perform automated handoff between the cellular network and available Wi-Fi hotspots.

Virtually all 3G/4G small cells will also include carrier-grade Wi-Fi either in the same enclosure or in an adjacent box. Furthermore, the newer cell phone models will incorporate Hotspot 2.0/802.11u to make the offload option function. And no doubt the cellular operators see the offload strategy as a way to buy time until more wireless spectrum is available or as funds are available to acquire it. Wi-Fi is covered in Chap. 21.

Backhaul

Backhaul is the name of the connection of a cell site to the core network. Older original base stations used T1 or T2 lines, but today most macro BS in the United States use fiber optic cable. Some in harder to reach areas use a microwave link. Fiber is preferred, of course, as it is fast and reliable. However, it is costly to install as it requires access to property, digging in the ground, or permission to use power poles. Microwave is simply line of sight (LOS) point and shoot wireless. It is not as fast but that limitation is gradually going away with the new systems. With most microwave links, a data capacity up to 1 Gb/s is usually available.

Small cell backhaul will most likely be a mix of fiber and wireless. If fiber is available and affordable it will be used. Otherwise, a wireless link will be the backhaul of choice.

Small cell backhaul will sometimes be tricky. With small cells on lamp posts, sides of buildings and in other odd locations, fiber or even AC power may be hard to come by. A wireless link may be the only choice. And even that could be a challenge in large cities with tall buildings and other structures blocking most paths back to the core network. Multiple hop links may be used in some instances.

The most popular wireless backhaul frequencies are 6, 11, 18, and 23 GHz. These frequencies require a license to use, and equipment is generally expensive. However, other potential bands are the 60 GHz band and 70/80 GHz E-band. The 80 GHz band does also require a license, but the 60 GHz band does not. The 60 GHz band (57-64 GHz) is an industrial-scientific-medical (ISM) band that is open to any service.

The millimeter wave bands above 30 GHz offer lots of bandwidth to support higher data rates; their range is severely limited by the physics of their short wavelength. However, with high gain directional antennas and higher power, ranges can extend to several kilometers. Just recently the FCC modified the Part 15 rules and regulations to permit higher power and antenna gains in the 60 GHz band to make it more useful for small cell backhaul.

Fig. 20-22 shows one kind of small cell backhaul unit. It mounts next to the small cell enclosure.

Self-Organizing Networks

Self-organizing networks (SON) are a software solution to managing a HetNet. While the interaction between macrocells is usually managed manually, with multiple small cells such a manual task is overwhelming. With SON, the HetNet will essentially manage

Figure 20-22 The Ceragon FibeAir IP-20C is typical of the small-cell backhaul units available. This one packages the radio, interfaces, and dish antenna into a single unit and is available in standard licensed band frequencies from 6 to 42 GHz. Typical data rate is 1 Gbps in a single Ethernet channel. It uses 2048 QAM.

itself. SON can automate configuration and dynamically optimize the network based on the traffic loads.

SONs can be categorized by their three basic functions: self-configuration, self-optimization, and self-healing. Self-configuration refers to the system as one that adjusts the small cell frequency, power level, interfaces automatically as it is added into the system. It works with the automatic neighbor relations (ANR) software that builds and maintains a list of all cells in the network and the location and physical characteristics of each. If any new cell is added, the configuration is automatic and the list is updated. The same occurs if a cell is removed.

Self-optimization refers to the ability of the network to adapt itself to surrounding conditions and optimize its performance based on coverage, capacity, handover between cells, and interference. Two key functions are load balancing and interference mitigation. Load balancing is dividing the traffic between the cells so that no one cell becomes too overloaded if adjacent cells are within range and have available capacity. Load balancing occurs automatically. And this ability also helps balance the backhaul traffic load.

Interference management is essential in a HetNet as the small cells are generally closely spaced and could potentially interfere with one another. SON software uses the cells to measure the characteristics of nearby cells to make a determination if interference is a possibility the makes adjustments dynamically to change frequency or power level as necessary to minimize interference.

Self-healing refers to SONs ability to adjust to changing conditions such as cell failure.

SON is a key part of a HetNet, and LTE makes provision for it in the standard. Tests have shown that SON can monitor and update a network within milliseconds in some cases and dynamically adapt. Overall throughput can be improved by 10 to 45 percent in many cases.

Distributed Antenna Systems

A key part of the HetNet movement is distributed antenna systems (DAS). DAS is not exactly a small cell, but its effect is similar in that it provides improved coverage and performance in a given region. What a DAS does is expand the coverage on a given basestation by distributing the signal over a wider area using a network of antennas. DAS is useful for improving coverage in multi-floor office buildings, stadiums, hotels, malls, airports, subways, as well as tunnels and roadways. They can be used indoors or outdoors, although indoor coverage is more common.

A DAS system essentially makes a connection to one or more existing macro basestations either by direct connection or by a wireless link. It then distributes this service over fiber optic cable or coax cable or some combination. Typically the unit connected to the basestation involves a repeater or controller that amplifies the RF signal and converts it to an optical signal and sends it to various regions in the coverage area by way of fiber optic cables. The fiber connects to distribution boxes that convert the optical signals to RF for coax cable distribution to an array of antennas. These antennas must be separated from one another by several wavelengths to be effective. The array essentially divides the transmitted power among the antennas. DAS effectively eliminates dead zones caused by the huge attenuation with distance and through walls and ceiling and other obstructions. It provides a more direct line of sight connection to the cell phone or other user device.

DAS may be either passive or active. Passive systems are simplest and use a mix of filter, splitters and couplers to distribute the signals. Active system uses amplifiers and repeaters to boost signal levels.

The DAS is usually owned by the facility owner instead of the cellular carrier as are all other small cells. A distribution agreement with the carrier is necessary. DAS may be carrier specific or generic to handle any 2G/3G/4G signals. Some DAS work with Wi-Fi as well.

CHAPTER REVIEW

Online Activity

20-1 Investigate the SIM Card

Objective: To determine the presence and function of a SIM card in a cell phone.

Procedure:

1. Search on the term *SIM* as it relates to cell phones.
2. Answer the following questions.

Questions:

1. What does *SIM* stand for?
2. Where in the cell phone is the SIM card?
3. Do all cell phones have a SIM card?
4. What circuitry is on a SIM card?
5. Can SIM cards be used to reconfigure a cell phone from one user to another?

20-2 Explore the Remote Radio Head Concept

Objective: To determine the benefits and specifications of a remote radio head.

Procedure:

1. Search on the terms *remote radio head, RRH, CPRI*, and similar terms.
2. Answer the following questions.

Questions:

1. What is an RRH?
2. What is inside an RRH?
3. Where is the RRH located?
4. How is DC power connected?
5. Define *CPRI*.
6. What are the specifications of CPRI?

20-3 Investigate the base station

Objective: Explore the Terminology of Cellular Base Stations

Procedure:

1. Search on the terms *base station, cell site, Node B, eNode B*, and *RAN*.
2. Answer the following questions.

Questions:

1. Define *Node B*.
2. Define *eNode B*.
3. Define *RAN*.
4. Which of the above is associated with LTE?

Questions

1. What key communication technology is referred to when the term *wireless* is used?
2. What is the current latest generation of cell phone technology?
3. Name the two main frequency bands used for cell phones in the United States.
4. What primary characteristic determines cell site range of coverage?
5. What segment of the frequency spectrum is used mostly by the cellular industry? State approximate upper and lower ranges.
6. Name five access methods used in cellular systems.
7. True or false? Cellular telephone radios operate full duplex.
8. True or false? Cell site coverage areas are not all the same size.
9. Name the four major U.S. cellular carriers.
10. True or false? There are more wire line telephone subscribers than cellular subscribers.
11. What major challenge keeps carriers from expanding their capacity and data speed?
12. What one application has forced cellular data rates to increase?
13. What is the primary radio technology of 3G phones?
14. Which type of duplexing is the most widely used?
15. What circuit in the cellular telephone allows a transmitter and receiver to share an antenna?
16. What is the benefit of TDD over FDD?
17. State the relationship between data rate and bandwidth as it applies to the cellular system.
18. What technique allows multiple base stations to share a common channel?
19. What is a vocoder?
20. List the two primary 2G digital cell phone systems used worldwide. Which is the most widely used?
21. Name the two primary functions of a vocoder.
22. What unit of measure is used to determine the spectral efficiency of a modulation scheme?

23. What is the bandwidth of a GSM channel?
24. How many users can share a channel in GSM?
25. True or false? GSM uses TDMA.
26. What modulation is used in GSM?
27. What type of multiuser access is available in IS-95 CDMA and WCDMA?
28. What is the bandwidth of a typical CDMA and WCDMA channel? State the maximum number of subscribers that can use the channel.
29. What feature of CDMA is critical to its success in reception?
30. By what method is a CDMA channelized?
31. What two receiver architectures are common in most modern 2G cell phones? State why they are preferred over the older superheterodyne architectures.
32. Why is the *I/Q* circuit arrangement used in cell phones?
33. List four functions typically performed by a DSP chip in the baseband part of a cell phone.
34. At what point in most receivers are the A/D converters placed?
35. Describe the basic antenna structure of a typical cell site base station.
36. Describe the antenna radiation pattern and explain how it permits sectorization.
37. How does the antenna permit frequency reuse?
38. What types of amplifiers are used in base stations? What is their power level?
39. Why is power amplifier linearity so important?
40. Is CDMA2000 a 2G or 3G technology? Explain. Who developed it?
41. What are the names of the fastest versions of CDMA2000? What are their maximum data rates?
42. Name the technology that makes WCDMA faster. What modulation methods are used?
43. True or false? A WCDMA 3G handset can communicate with a CDMA2000 base station.
44. What is the maximum data rate of the most common form of HSPA, and what modulation is used?
45. Name the U.S. carriers that use GSM/GPRS/EDGE and WCDMA/HSPA.
46. Name the U.S. carriers that use CDMA2000.
47. What antenna technology permits increased subscriber growth on existing base stations?
48. What is the name of the latest cell phone technology that is marketed as 4G?
49. What modulation methods are used with 4G cell phones?
50. Define the term *resource block* and give its specifications.
51. Does LTE use FDD or TDD?
52. Will an LTE phone from AT&T work on the Verizon network? Explain.
53. What is the maximum LTE channel bandwidth? What other bandwidths are popular?
54. What feature of LTE compensates for multipath and Doppler shift problems?
55. What is the maximum MIMO configuration for LTE? for LTE-A?
56. What limits the MIMO configuration in a smart phone? What is the maximum practical?
57. What is the approximate maximum data rate of LTE? What rate is more typical?
58. What access method is used with LTE? How does it work?
59. How does LTE-Advanced implement data rates to 1 Gbps?
60. What is a remote radio head? What are its benefits?
61. Do LTE phones have 3G or 2G technology?
62. List at least five different radios used in smart phones.
63. How are voice calls handled in the typical 3G or 4G cell phone?
64. How are voice calls handled in LTE?
65. What is a HetNet?
66. Name four basic small-cell sizes and their specifications.
67. What is a macrocell?
68. How do small cells improve the cellular network?
69. What techniques make small cells feasible?
70. What is backhaul? What are the most common types?
71. What is Wi-Fi offload, and why is it beneficial?
72. What is an alternative to an array of small cells to improve cellular coverage?
73. What are expected to be the three basic technical features or specifications of 5G cellular technology?

Problems

1. Compute the spectral efficiency of modulation that gives a data rate of 2.4 Mbps in a bandwidth of 1.5 MHz. ◆
2. Without any special modulation methods, approximately what bandwidth is needed to transmit a data rate of 1.2 Mbps?
3. How many GSM channels can exist in the spectrum of Fig. 20-4(*b*)?
4. How many LTE resource blocks fit into a 20-MHz channel?
5. What is the bandwidth of an LTE subcarrier?
6. What is the maximum number of users on a femtocell?

◆ *Answers to Selected Problems follow Chap. 22.*