of data to pass through a very large number of nodes without experiencing degradation. Only having this capability allows the use of high levels of network redundancy, and the high reliability that comes with high redundancy.

Even in the absence of catastrophic failures of the network, it is vital to have this type of robustness. Hardware can malfunction; human error can wreak havoc (think of Homer Simpson), etc. The packet-switching scheme allows us to build a reliable system with unreliable components. As Baran said in 2001, "You can get any reliability you want—far, far greater than the reliability of the components." In his early design, he decided "to have a half-second delay maximum from one point to another. Then at every one of these nodes we would keep a carbon copy of the message until we were sure it got through intact to the next node. So the carbon copy with error detection allowed repeated transmission of any message block, now called a packet." Baran still marvels at the advantages of this system that he uncovered using his computer simulations, "Packet switching had all these wonderful properties that weren't invented—they were discovered."

16.7 WIRELESS MOBILE CELL PHONE NETWORKS

One of the biggest impacts of digital communications on people's lives was the recent rapid rise of cell phone use. Cell, or cellular, phone systems are an example of wireless networks, and are especially interesting in that they are also mobile—you can carry the phone with you. The main physics idea behind cellular phone systems is the fact that the strength of radio waves falls off with increasing distance. Although this may be a disadvantage if you want to communicate directly by radio over a long distance, it has a great benefit: separate stations broadcasting radio waves will not interfere with each other if they are far enough apart. This is illustrated in **Figure 16.21**. The broadcasting station labeled S1 sends out radio waves that are easily picked up by people at locations labeled A and B. These waves decrease in strength with increasing distance, so that people at C, D, or E cannot detect them. Likewise, the station S2 sends out waves that can be detected at D and E, but not at A, B, or C. The advantage of this situation is that each broadcasting station can use the same set of frequencies to broadcast to a local group of listeners, without interfering with other groups of listeners. In this simple example, which avoids interference between stations S1 and S2, a person at C is not able to communicate. This problem can be remedied by using a slightly more involved strategy, described next.

The implementation of a cell phone system is illustrated in **Figure 16.22**. It is based on the idea that each broadcasting station has a limited range. The countryside or a city is separated into small geographical areas, called cells, represented in the figure by hexagons. Each ***cell*** contains one broadcasting and receiving station, called a base

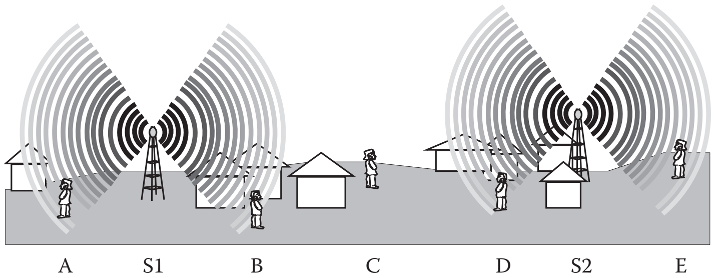

FIGURE 16.21 Radio wave propagation covering a small region around each broadcasting station (cell phone tower). This creates isolated regions within which cell phone users can communicate only with the nearest tower.

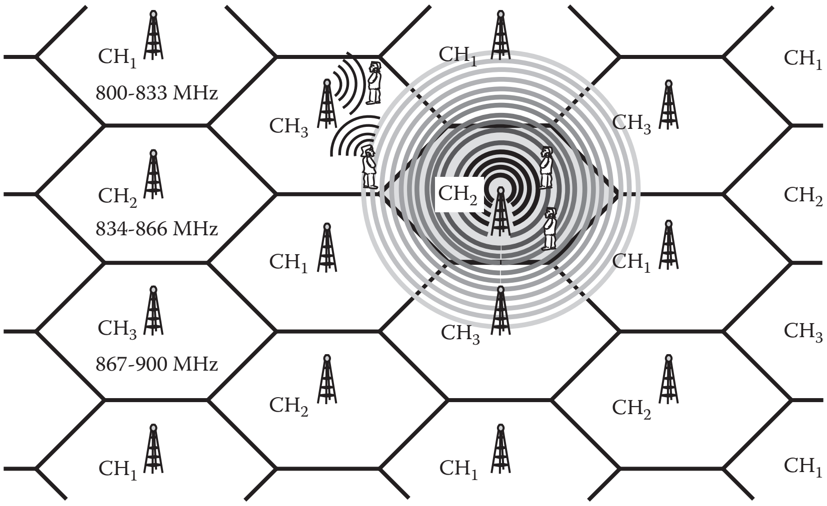

FIGURE 16.22 A large region is divided into regions called cells, within which a specific range of frequencies is used for radio communication. No two adjacent cells use the same frequency range.

station, which can be one of three types, labeled CH$_1$, CH$_2$, and CH$_3$. Each cell is surrounded by six cells, which are of different types from its own type. Each type uses a different range of frequencies or channels for broadcasting radio waves. For example, CH$_1$-type stations could use channels in the range 800–833 MHz; CH$_2$-type stations could use channels in the range 834–866 MHz; and CH$_3$-type stations could use channels in the range 867–900 MHz, as shown in **Figure 16.23**. Because these frequency ranges are not overlapping, this allows some overlapping of the geographical areas being reached by each station. For example, in the figure, one station (a CH$_2$-type) is shown emitting waves that partly leak into the nearest adjacent cells, but no farther. Every telephone communicating with this station is using frequencies in the CH$_2$-type frequency range of 834–866 MHz. The key point is that each cell adjacent to this broadcasting cell is either CH$_1$-type or CH$_3$-type. Therefore no phone users in those cells are receiving radio waves in the CH$_2$-type frequency range. They are using the other frequency ranges, CH$_1$-type or CH$_3$-type. We conclude that by using three separate broadcasting frequency ranges, we can cover the countryside with adjacent but not interfering cells, in which users can receive and send signals with their own local station without suffering interference from other nearby stations.

Every base station in a given area is connected by high-speed data links to a Mobile Telephone Switching Office, or MTSO, as shown in **Figure 16.24**. These links (cables or satellite channels) allow a base station to simultaneously handle many phone connections. Each MTSO is connected to both the Public Telephone Network for voice,

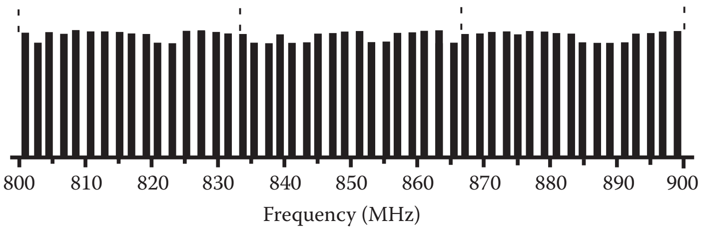

FIGURE 16.23 An example showing the full spectral region used for cell phone communication (800–900 MHz) broken into three separate regions, only one of which is active within a given cell.

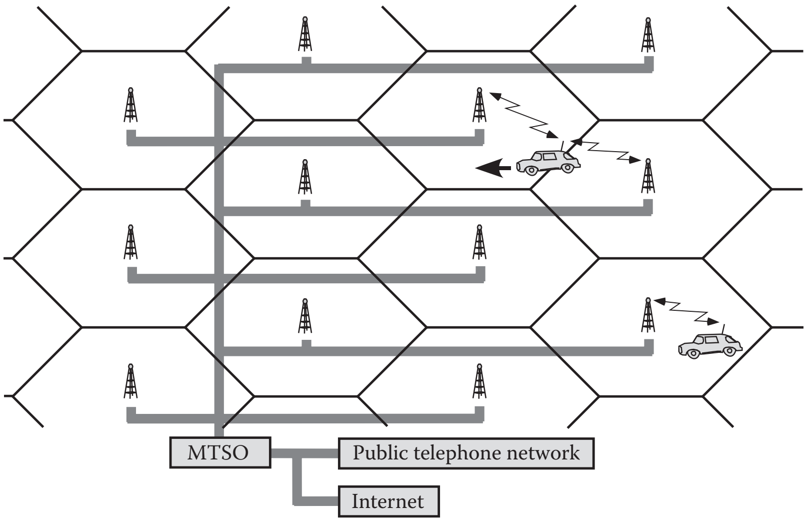

FIGURE 16.24 Every base station within a certain area is connected by high-speed links to a Mobile Telephone Switching Office, or MTSO, which is connected to the public phone network and to the Internet. When a user passes from one cell to another, the MTSO instructs one base station to hand off the user's connection to the next base station.

and the Internet for other data. The MTSO controls the operation of each base station in its area. An important operation is the handing-off of any phone connection between base stations when a moving phone user crosses a boundary between cells. This gives rise to the name *Mobile Phone System*. As the user moves between cells, her phone must quickly reconfigure itself to start using a different frequency range, for example from CH_2-type to CH_3-type. This explains why calls are sometimes dropped when a user is traveling. If she enters a new cell in which all frequency channels are already being used, the MTSO has no choice but to order that call be disconnected.

This provides an example of an internetwork, which is a network comprised of different types of networks connected together. The mobile phone system, the public telephone network, and the Internet are entirely separate networks and operate using different hardware types and protocols for handling data. Yet to a user they behave as a single communication network.

How many phone users can be accommodated within a single cell at any given time? This depends on the particulars of each system, so we can discuss only a representative example. Say that each single-user channel has a bandwidth (the width of the user's spectral region) equal to 100 kHz. For example, one channel might occupy a narrow portion between 80.0 and 80.1 MHz of the spectrum shown in Figure 16.23. If the base station in that cell can handle broadcasting frequencies between 800 and 833 MHz, then the number of single-user channels that can be accommodated equals the ratio of the total frequency range to the frequency range of a single channel:

$$\frac{833\text{ MHz-}800\text{ MHz}}{100\text{ kHz}} = \frac{33\text{ MHz}}{100\text{ kHz}} = \frac{33\times10^6\text{Hz}}{100\times10^3\text{Hz}} = 330$$

This relatively small number explains why a densely populated city needs many cell-phone towers per square mile.

In practice, the manner in which the spectral ranges are allocated to different users is far more complicated than described above. For example, the frequency being used by a single user might change in time according to some set pattern. Or, the bandwidth being used by a user might change in time according to what the user is doing at the moment—just talking requires little bandwidth, whereas downloading an MP3 file requires larger bandwidth. The bandwidth detected by a user might be much larger than the 100 kHz needed, but the user's phone may reject most of the data it receives and select the correct data needed by that user. These topics are discussed in the advanced suggested reading at the chapter's end.

16.8 PROPAGATION OF WIRELESS WAVES IN TERRAIN

As an example of using physics theory in cell phone systems, consider the complicated problem of designing the optimum shapes of the cells in a particular city. In the absence of any obstructions, radio signals tend to travel in straight lines from their source. When radio signals strike a building wall, they are partially reflected and partially absorbed. The reflected part is useful, because it may carry the signal farther by, for example, reflecting many times from building fronts as it travels down a narrow street. Also, radio signals, being waves, experience *diffraction*, or bending around sharp corners. (Think of an ocean wave being bent around a jetty.)

In open space, radio-wave strength decreases with increasing distance as the wave spreads out. In a city, you might have noticed that the strength of your cell phone connection can vary during a call. This decrease of signal is called fading, and is caused by several phenomena, including shadowing, reflection, guiding, diffraction, and wave interference. These are illustrated in **Figure 16.25**. Shadowing is simple—a large building blocks the line of sight between you and the cell tower, decreasing the signal. Shadowing is the direct loss of signal that occurs when a wave encounters a solid object. Reflection from a hard, solid object redirects a wave in a different direction. Guiding occurs when a wave traveling between two reflecting surfaces is guided a long distance without losing strength. Diffraction occurs at edges of hard objects, bending the wave around it. As you drive through the city, these effects are interacting and are changing with time, causing fading.

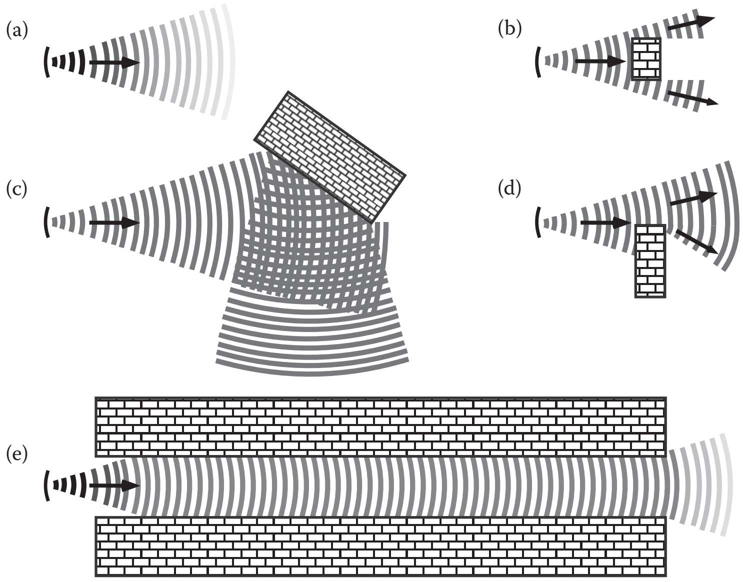

FIGURE 16.25 Radio wave propagation, shown both as circular waves and as directional arrows, called rays. (a) In open space, (b) shadowing, (c) reflection, (d) diffraction, and (e) guiding.