Chapter 7 Wireless and Mobile Networks

In the telephony world, the past 20 years have arguably been the golden years of cellular telephony. The number of worldwide mobile cellular subscribers increased from 34 million in 1993 to nearly 7.0 billion subscribers by 2014, with the number of cellular subscribers now surpassing the number of wired telephone lines. There are now a larger number of mobile phone subscriptions than there are people on our planet. The many advantages of cell phones are evident to all—anywhere, anytime, untethered access to the global telephone network via a highly portable lightweight device. More recently, laptops, smartphones, and tablets are wirelessly connected to the Internet via a cellular or WiFi network. And increasingly, devices such as gaming consoles, thermostats, home security systems, home appliances, watches, eye glasses, cars, traffic control systems and more are being wirelessly connected to the Internet.

From a networking standpoint, the challenges posed by networking these wireless and mobile devices, particularly at the link layer and the network layer, are so different from traditional wired computer networks that an individual chapter devoted to the study of wireless and mobile networks (i.e., *this* chapter) is appropriate.

We'll begin this chapter with a discussion of mobile users, wireless links, and networks, and their relationship to the larger (typically wired) networks to which they connect. We'll draw a distinction between the challenges posed by the *wireless* nature of the communication links in such networks, and by the *mobility* that these wireless links enable. Making this important distinction—between wireless and mobility—will allow us to better isolate, identify, and master the key concepts in each area. Note that there are indeed many networked environments in which the network nodes are wireless but not mobile (e.g., wireless home or office networks with stationary workstations and large displays), and that there are limited forms of mobility that do not require wireless links (e.g., a worker who uses a wired laptop at home, shuts down the laptop, drives to work, and attaches the laptop to the company's wired network). Of course, many of the most exciting networked environments are those in which users are both wireless *and* mobile—for example, a scenario in which a mobile user (say in the back seat of car) maintains a Voice-over-IP call and multiple ongoing TCP connections while racing down the autobahn at 160 kilometers per hour, soon in an autonomous vehicle. It is here, at the intersection of wireless and mobility, that we'll find the most interesting technical challenges!

We’ll begin by illustrating the setting in which we’ll consider wireless communication and mobility—a network in which wireless (and possibly mobile) users are connected into the larger network infrastructure by a wireless link at the network’s edge. We’ll then consider the characteristics of this wireless link in **Section 7.2**. We include a brief introduction to code division multiple access (CDMA), a shared-medium access protocol that is often used in wireless networks, in **Section 7.2**. In **Section 7.3**, we’ll examine the link-level aspects of the IEEE 802.11 (WiFi) wireless LAN standard in some depth; we’ll also say a few words about Bluetooth and other wireless personal area networks. In **Section 7.4**, we’ll provide an overview of cellular Internet access, including 3G and emerging 4G cellular technologies that provide both voice and high-speed Internet access. In **Section 7.5**, we’ll turn our attention to mobility, focusing on the problems of locating a mobile user, routing to the mobile user, and “handing off” the mobile user who dynamically moves from one point of attachment to the network to another. We’ll examine how these mobility services are implemented in the mobile IP standard in enterprise 802.11 networks, and in LTE cellular networks in **Sections 7.6** and **7.7**, respectively. Finally, we’ll consider the impact of wireless links and mobility on transport-layer protocols and networked applications in **Section 7.8**.

7.1 Introduction

Figure 7.1 shows the setting in which we'll consider the topics of wireless data communication and mobility. We'll begin by keeping our discussion general enough to cover a wide range of networks, including both wireless LANs such as IEEE 802.11 and cellular networks such as a 4G network; we'll drill down into a more detailed discussion of specific wireless architectures in later sections. We can identify the following elements in a wireless network:

- **Wireless hosts.** As in the case of wired networks, hosts are the end-system devices that run applications. A **wireless host** might be a laptop, tablet, smartphone, or desktop computer. The hosts themselves may or may not be mobile.

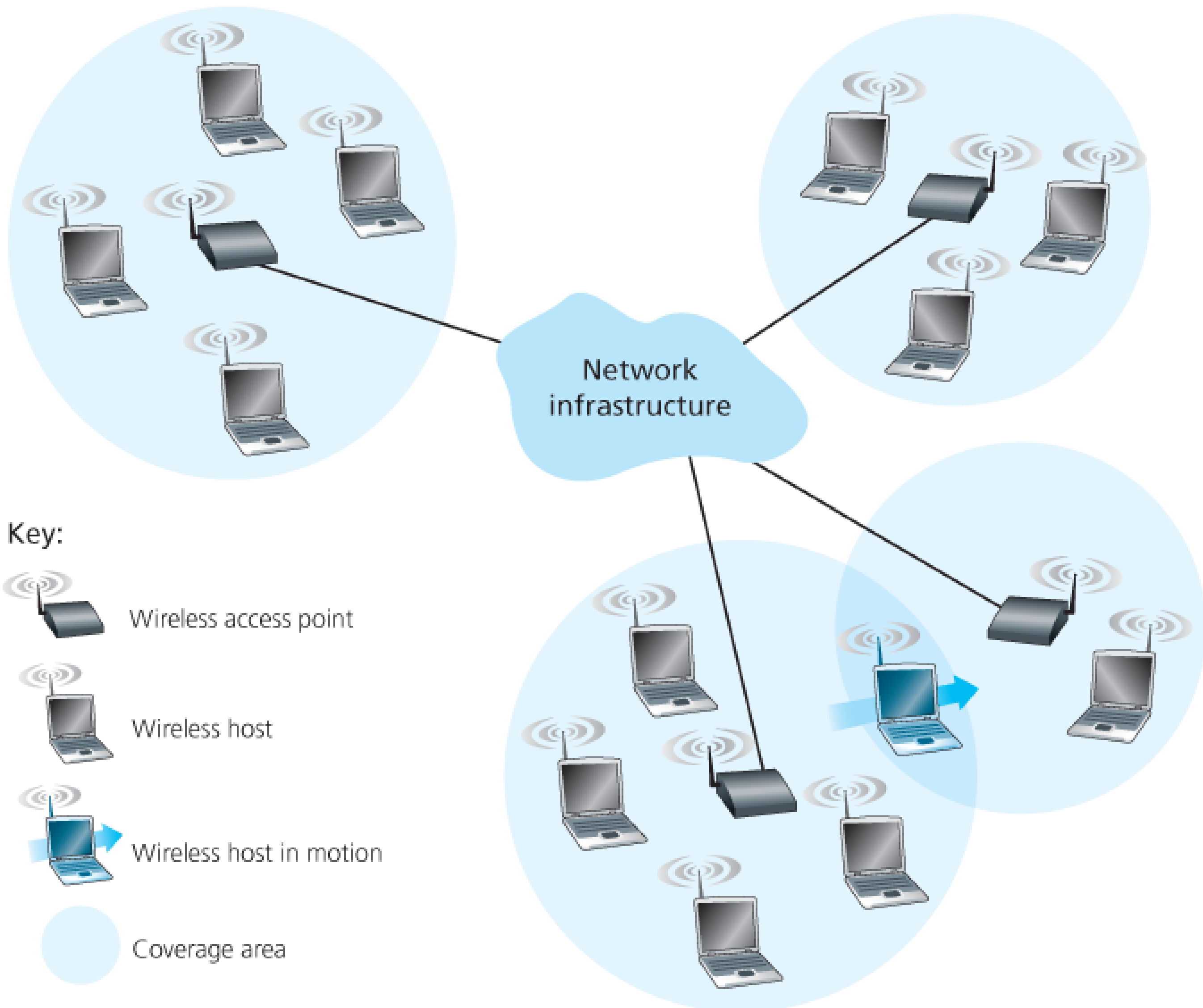

Figure 7.1 Elements of a wireless network

- **Wireless links.** A host connects to a base station (defined below) or to another wireless host through a **wireless communication link**. Different wireless link technologies have different transmission rates and can transmit over different distances. **Figure 7.2** shows two key characteristics (coverage area and link rate) of the more popular wireless network standards. (The figure is only meant to provide a rough idea of these characteristics. For example, some of these types of networks are only now being deployed, and some link rates can increase or decrease beyond the values shown depending on distance, channel conditions, and the number of users in the wireless network.) We'll cover these standards later in the first half of this chapter; we'll also consider other wireless link characteristics (such as their bit error rates and the causes of bit errors) in **Section 7.2**.

In **Figure 7.1**, wireless links connect wireless hosts located at the edge of the network into the larger network infrastructure. We hasten to add that wireless links are also sometimes used *within* a network to connect routers, switches, and

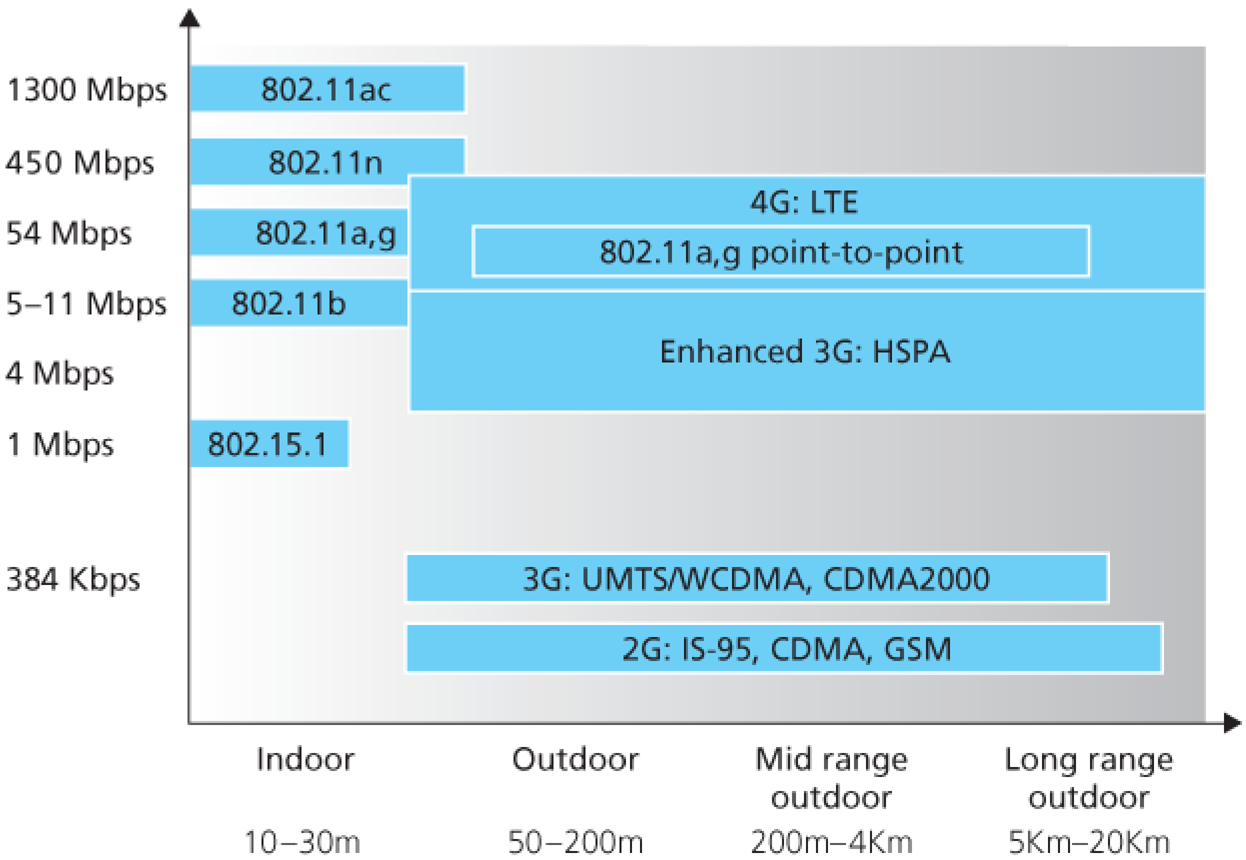

Figure 7.2 Link characteristics of selected wireless network standards

other network equipment. However, our focus in this chapter will be on the use of wireless communication at the network edge, as it is here that many of the most exciting technical challenges, and most of the growth, are occurring.

- **Base station.** The **base station** is a key part of the wireless network infrastructure. Unlike the wireless host and wireless link, a base station has no obvious counterpart in a wired network. A base station is responsible for sending and receiving data (e.g., packets) to and from a wireless host that is associated with that base station. A base station will often be responsible for coordinating the transmission of multiple wireless hosts with which it is associated. When we say a wireless host is “associated” with a base station, we mean that (1) the host is within the wireless communication distance of the base station, and (2) the host uses that base station to relay data between it (the host) and the larger network. **Cell towers** in cellular networks and **access points** in 802.11 wireless LANs are examples of base stations.

In **Figure 7.1**, the base station is connected to the larger network (e.g., the Internet, corporate or home network, or telephone network), thus functioning as a link-layer relay between the wireless host and the rest of the world with which the host communicates.

Hosts associated with a base station are often referred to as operating in **infrastructure mode**, since all traditional network services (e.g., address assignment and routing) are provided by the network to which a host is connected via

> CASE HISTORY
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> PUBLIC WIFI ACCESS: COMING SOON TO A LAMP POST NEAR YOU?
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> WiFi hotspots—public locations where users can find 802.11 wireless access—are becoming increasingly common in hotels, airports, and cafés around the world. Most college campuses offer ubiquitous wireless access, and it’s hard to find a hotel that doesn’t offer wireless Internet access.
>
> Over the past decade a number of cities have designed, deployed, and operated municipal WiFi networks. The vision of providing ubiquitous WiFi access to the community as a public service (much like streetlights)—helping to bridge the digital divide by providing Internet access to all citizens and to promote economic development—is compelling. Many cities around the world, including Philadelphia, Toronto, Hong Kong, Minneapolis, London, and Auckland, have plans to provide ubiquitous wireless within the city, or have already done so to varying degrees. The goal in Philadelphia was to “turn Philadelphia into the nation’s largest WiFi hotspot and help to improve education, bridge the digital divide, enhance neighborhood development, and reduce the costs of government.” The ambitious program—an agreement between the city, Wireless Philadelphia (a nonprofit entity), and the Internet Service Provider Earthlink—built an operational network of 802.11b hotspots on streetlamp pole arms and traffic control devices that covered 80 percent of the city. But financial and operational concerns caused the network to be sold to a group of private investors in 2008, who later sold the network back to the city in 2010. Other cities, such as Minneapolis, Toronto, Hong Kong, and Auckland, have had success with smaller-scale efforts.
>
> The fact that 802.11 networks operate in the unlicensed spectrum (and hence can be deployed without purchasing expensive spectrum use rights) would seem to make them financially attractive. However, 802.11 access points (see **Section 7.3**) have much shorter ranges than 4G cellular base stations (see **Section 7.4**), requiring a larger number of deployed endpoints to cover the same geographic region. Cellular data networks providing Internet access, on the other hand, operate in the licensed spectrum. Cellular providers pay

> billions of dollars for spectrum access rights for their networks, making cellular data networks a business rather than municipal undertaking.

the base station. In **ad hoc networks**, wireless hosts have no such infrastructure with which to connect. In the absence of such infrastructure, the hosts themselves must provide for services such as routing, address assignment, DNS-like name translation, and more.

When a mobile host moves beyond the range of one base station and into the range of another, it will change its point of attachment into the larger network (i.e., change the base station with which it is associated)—a process referred to as **handoff**. Such mobility raises many challenging questions. If a host can move, how does one find the mobile host's current location in the network so that data can be forwarded to that mobile host? How is addressing performed, given that a host can be in one of many possible locations? If the host moves *during* a TCP connection or phone call, how is data routed so that the connection continues uninterrupted? These and many (many!) other questions make wireless and mobile networking an area of exciting networking research.

- **Network infrastructure.** This is the larger network with which a wireless host may wish to communicate.

Having discussed the "pieces" of a wireless network, we note that these pieces can be combined in many different ways to form different types of wireless networks. You may find a taxonomy of these types of wireless networks useful as you read on in this chapter, or read/learn more about wireless networks beyond this book. At the highest level we can classify wireless networks according to two criteria: *(i)* whether a packet in the wireless network crosses exactly *one wireless hop or multiple wireless hops*, and *(ii)* whether there is *infrastructure* such as a base station in the network:

- **Single-hop, infrastructure-based.** These networks have a base station that is connected to a larger wired network (e.g., the Internet). Furthermore, all communication is between this base station and a wireless host over a single wireless hop. The 802.11 networks you use in the classroom, café, or library; and the 4G LTE data networks that we will learn about shortly all fall in this category. The vast majority of our daily interactions are with single-hop, infrastructure-based wireless networks.
- **Single-hop, infrastructure-less.** In these networks, there is no base station that is connected to a wireless network. However, as we will see, one of the nodes in this single-hop network may coordinate the transmissions of the other nodes. Bluetooth networks (that connect small wireless devices such as keyboards, speakers, and headsets, and which we will study in **Section 7.3.6**) and 802.11 networks in ad hoc mode are single-hop, infrastructure-less networks.
- **Multi-hop, infrastructure-based.** In these networks, a base station is present that is wired to the larger network. However, some wireless nodes may have to relay their communication through other wireless nodes in order to communicate via the base station. Some wireless sensor networks and so-called **wireless mesh networks** fall in this category.
- **Multi-hop, infrastructure-less.** There is no base station in these networks, and nodes may have to relay messages among several other nodes in order to reach a destination. Nodes may also be

mobile, with connectivity changing among nodes—a class of networks known as **mobile ad hoc networks (MANETs)**. If the mobile nodes are vehicles, the network is a **vehicular ad hoc network (VANET)**. As you might imagine, the development of protocols for such networks is challenging and is the subject of much ongoing research.

In this chapter, we'll mostly confine ourselves to single-hop networks, and then mostly to infrastructure-based networks.

Let's now dig deeper into the technical challenges that arise in wireless and mobile networks. We'll begin by first considering the individual wireless link, deferring our discussion of mobility until later in this chapter.

7.2 Wireless Links and Network Characteristics

Let's begin by considering a simple wired network, say a home network, with a wired Ethernet switch (see **Section 6.4**) interconnecting the hosts. If we replace the wired Ethernet with a wireless 802.11 network, a wireless network interface would replace the host's wired Ethernet interface, and an access point would replace the Ethernet switch, but virtually no changes would be needed at the network layer or above. This suggests that we focus our attention on the link layer when looking for important differences between wired and wireless networks. Indeed, we can find a number of important differences between a wired link and a wireless link:

- **Decreasing signal strength.** Electromagnetic radiation attenuates as it passes through matter (e.g., a radio signal passing through a wall). Even in free space, the signal will disperse, resulting in decreased signal strength (sometimes referred to as **path loss**) as the distance between sender and receiver increases.
- **Interference from other sources.** Radio sources transmitting in the same frequency band will interfere with each other. For example, 2.4 GHz wireless phones and 802.11b wireless LANs transmit in the same frequency band. Thus, the 802.11b wireless LAN user talking on a 2.4 GHz wireless phone can expect that neither the network nor the phone will perform particularly well. In addition to interference from transmitting sources, electromagnetic noise within the environment (e.g., a nearby motor, a microwave) can result in interference.
- **Multipath propagation.** **Multipath propagation** occurs when portions of the electromagnetic wave reflect off objects and the ground, taking paths of different lengths between a sender and receiver. This results in the blurring of the received signal at the receiver. Moving objects between the sender and receiver can cause multipath propagation to change over time.

For a detailed discussion of wireless channel characteristics, models, and measurements, see **[Anderson 1995]**.

The discussion above suggests that bit errors will be more common in wireless links than in wired links. For this reason, it is perhaps not surprising that wireless link protocols (such as the 802.11 protocol we'll examine in the following section) employ not only powerful CRC error detection codes, but also link-level reliable-data-transfer protocols that retransmit corrupted frames.

Having considered the impairments that can occur on a wireless channel, let's next turn our attention to the host receiving the wireless signal. This host receives an electromagnetic signal that is a combination of a degraded form of the original signal transmitted by the sender (degraded due to the attenuation and multipath propagation effects that we discussed above, among others) and background noise in the environment. The **signal-to-noise ratio (SNR)** is a relative measure of the strength of the received signal (i.e., the information being transmitted) and this noise. The SNR is typically measured in units of decibels (dB), a unit of measure that some think is used by electrical engineers primarily to confuse computer scientists. The SNR, measured in dB, is twenty times the ratio of the base-10 logarithm of the amplitude of the received signal to the amplitude of the noise. For our purposes here, we need only know that a larger SNR makes it easier for the receiver to extract the transmitted signal from the background noise.

Figure 7.3 (adapted from **[Holland 2001]**) shows the bit error rate (BER)—roughly speaking, the probability that a transmitted bit is received in error at the receiver—versus the SNR for three different modulation techniques for encoding information for transmission on an idealized wireless channel. The theory of modulation and coding, as well as signal extraction and BER, is well beyond the scope of

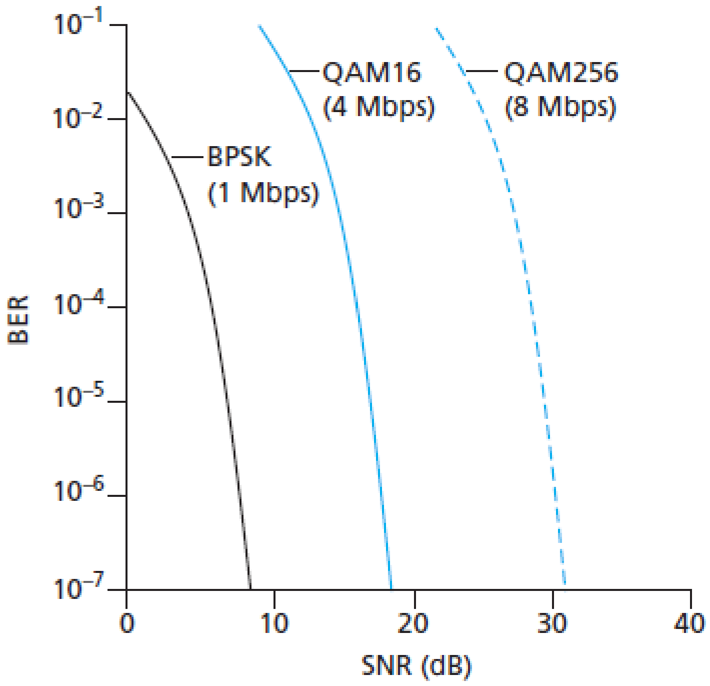
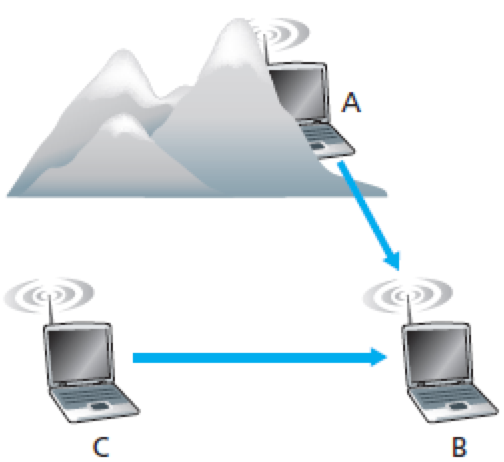
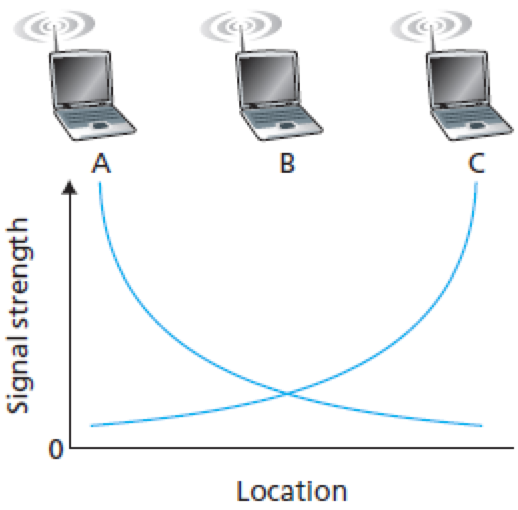


Figure 7.3 Bit error rate, transmission rate, and SNR



a.

Figure 7.4 Hidden terminal problem caused by obstacle (a) and fading (b)



this text (see [Schwartz 1980] for a discussion of these topics). Nonetheless, Figure 7.3 illustrates several physical-layer characteristics that are important in understanding higher-layer wireless communication protocols:

- **For a given modulation scheme, the higher the SNR, the lower the BER.** Since a sender can increase the SNR by increasing its transmission power, a sender can decrease the probability that a frame is received in error by increasing its transmission power. Note, however, that there is arguably little practical gain in increasing the power beyond a certain threshold, say to decrease the BER from 10^{-12} to 10^{-13}. There are also *disadvantages* associated with increasing the transmission power: More energy must be expended by the sender (an important concern for battery-powered mobile users), and the sender's transmissions are more likely to interfere with the transmissions of another sender (see Figure 7.4(b)).
- **For a given SNR, a modulation technique with a higher bit transmission rate (whether in error or not) will have a higher BER.** For example, in Figure 7.3, with an SNR of 10 dB, BPSK modulation with a transmission rate of 1 Mbps has a BER of less than 10−7, while with QAM16 modulation with a transmission rate of 4 Mbps, the BER is 10−1, far too high to be practically useful. However, with an SNR of 20 dB, QAM16 modulation has a transmission rate of 4 Mbps and a BER of 10−7, while BPSK modulation has a transmission rate of only 1 Mbps and a BER that is so low as to be (literally) "off the charts." If one can tolerate a BER of 10−7, the higher transmission rate offered by QAM16 would make it the preferred modulation technique in this situation. These considerations give rise to the final characteristic, described next.
- **Dynamic selection of the physical-layer modulation technique can be used to adapt the modulation technique to channel conditions.** The SNR (and hence the BER) may change as a result of mobility or due to changes in the environment. Adaptive modulation and coding are used in cellular data systems and in the 802.11 WiFi and 4G cellular data networks that we'll study in Sections 7.3 and 7.4. This allows, for example, the selection of a modulation technique that provides the highest transmission rate possible subject to a constraint on the BER, for given channel characteristics.

A higher and time-varying bit error rate is not the only difference between a wired and wireless link. Recall that in the case of wired broadcast links, all nodes receive the transmissions from all other nodes. In the case of wireless links, the situation is not as simple, as shown in **Figure 7.4**. Suppose that Station A is transmitting to Station B. Suppose also that Station C is transmitting to Station B. With the so-called **hidden terminal problem**, physical obstructions in the environment (for example, a mountain or a building) may prevent A and C from hearing each other's transmissions, even though A's and C's transmissions are indeed interfering at the destination, B. This is shown in **Figure 7.4(a)**. A second scenario that results in undetectable collisions at the receiver results from the **fading** of a signal's strength as it propagates through the wireless medium. **Figure 7.4(b)** illustrates the case where A and C are placed such that their signals are not strong enough to detect each other's transmissions, yet their signals *are* strong enough to interfere with each other at station B. As we'll see in **Section 7.3**, the hidden terminal problem and fading make multiple access in a wireless network considerably more complex than in a wired network.

7.2.1 CDMA

Recall from **Chapter 6** that when hosts communicate over a shared medium, a protocol is needed so that the signals sent by multiple senders do not interfere at the receivers. In **Chapter 6** we described three classes of medium access protocols: channel partitioning, random access, and taking turns. Code division multiple access (CDMA) belongs to the family of channel partitioning protocols. It is prevalent in wireless LAN and cellular technologies. Because CDMA is so important in the wireless world, we'll take a quick look at CDMA now, before getting into specific wireless access technologies in the subsequent sections.

In a CDMA protocol, each bit being sent is encoded by multiplying the bit by a signal (the code) that changes at a much faster rate (known as the **chipping rate**) than the original sequence of data bits. **Figure 7.5** shows a simple, idealized CDMA encoding/decoding scenario. Suppose that the rate at which original data bits reach the CDMA encoder defines the unit of time; that is, each original data bit to be transmitted requires a one-bit slot time. Let d_i be the value of the data bit for the ith bit slot. For mathematical convenience, we represent a data bit with a 0 value as −1. Each bit slot is further subdivided into M mini-slots; in **Figure 7.5**, $M=8$,

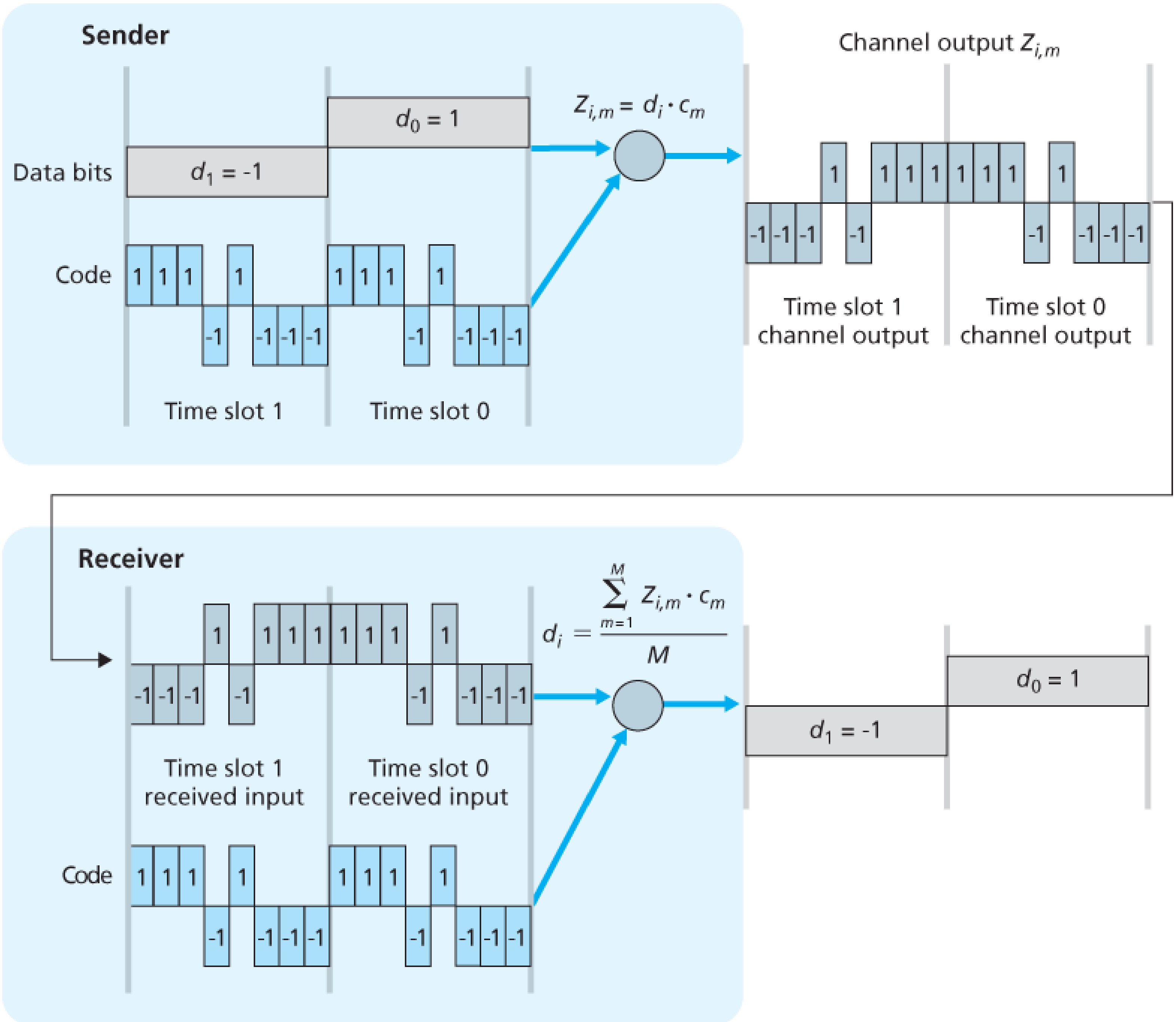


Figure 7.5 A simple CDMA example: Sender encoding, receiver decoding

although in practice *M* is much larger. The CDMA code used by the sender consists of a sequence of *M* values, c_m, $m=1,\ldots, M$, each taking a $+1$ or -1 value. In the example in **Figure 7.5**, the *M*-bit CDMA code being used by the sender is (1,1,1,−1,1,−1,−1,−1).

To illustrate how CDMA works, let us focus on the *i*th data bit, d_i. For the *m*th mini-slot of the bit-transmission time of d_i, the output of the CDMA encoder, $Z_{i,m}$, is the value of d_i multiplied by the *m*th bit in the assigned CDMA code, c_m:

$$Z_{i,m}=d_i\cdot c_m \tag{7.1}$$

In a simple world, with no interfering senders, the receiver would receive the encoded bits, $Z_{i,m}$, and recover the original data bit, d_i, by computing:

$$d_i = \frac{1}{M}\sum_{m=1}^{M} Z_{i,m} \cdot c_m \tag{7.2}$$

The reader might want to work through the details of the example in **Figure 7.5** to see that the original data bits are indeed correctly recovered at the receiver using **Equation 7.2**.

The world is far from ideal, however, and as noted above, CDMA must work in the presence of interfering senders that are encoding and transmitting their data using a different assigned code. But how can a CDMA receiver recover a sender's original data bits when those data bits are being tangled with bits being transmitted by other senders? CDMA works under the assumption that the interfering transmitted bit signals are additive. This means, for example, that if three senders send a 1 value, and a fourth sender sends a −1 value during the same mini-slot, then the received signal at all receivers during that mini-slot is a 2 (since $1+1+1-1=2$). In the presence of multiple senders, sender *s* computes its encoded transmissions, $Z_{i,m}^{s}$, in exactly the same manner as in **Equation 7.1**. The value received at a receiver during the *m*th mini-slot of the *i*th bit slot, however, is now the *sum* of the transmitted bits from all *N* senders during that mini-slot:

$$Z_{i,m}^{*} = \sum_{s=1}^{N} Z_{i,m}^{s}$$

Amazingly, if the senders' codes are chosen carefully, each receiver can recover the data sent by a given sender out of the aggregate signal simply by using the sender's code in exactly the same manner as in **Equation 7.2**:

$$d_i = \frac{1}{M}\sum_{m=1}^{M} Z_{i,m}^{*} \cdot c_m \tag{7.3}$$

as shown in **Figure 7.6**, for a two-sender CDMA example. The *M*-bit CDMA code being used by the upper sender is (1,1,1,−1,1,−1,−1,−1), while the CDMA code being used by the lower sender is $(1,-1,1,1,1,-1,1,1)$. **Figure 7.6** illustrates a receiver recovering the original data bits from the upper sender. Note that the receiver is able to extract the data from sender 1 in spite of the interfering transmission from sender 2.

Recall our cocktail analogy from **Chapter 6**. A CDMA protocol is similar to having partygoers speaking in multiple languages; in such circumstances humans are actually quite good at locking into the conversation in the language they understand, while filtering out the remaining conversations. We see here that CDMA is a partitioning protocol in that it partitions the codespace (as opposed to time or frequency) and assigns each node a dedicated piece of the codespace.

Our discussion here of CDMA is necessarily brief; in practice a number of difficult issues must be addressed. First, in order for the CDMA receivers to be able

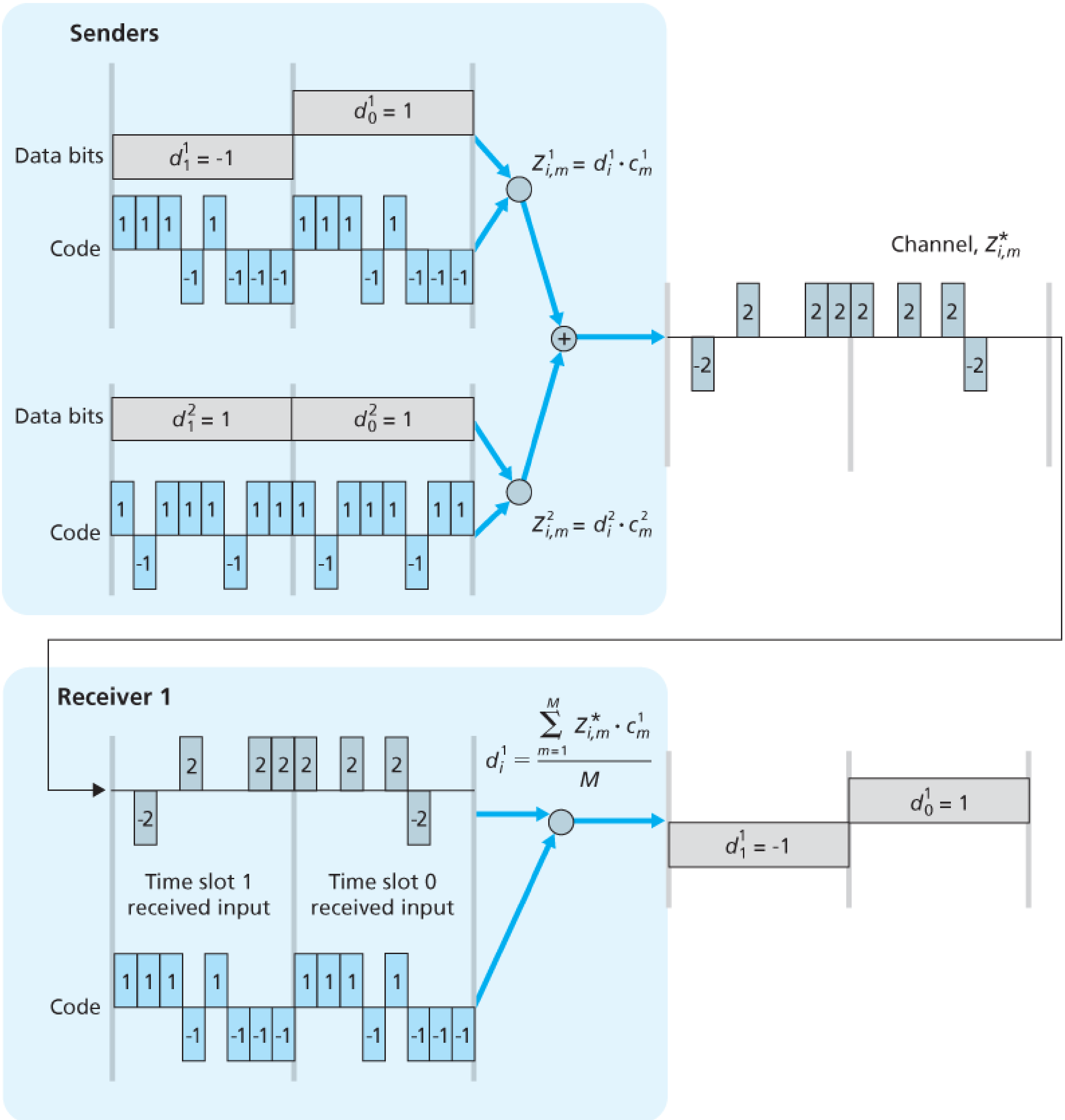


Figure 7.6 A two-sender CDMA example

to extract a particular sender's signal, the CDMA codes must be carefully chosen. Second, our discussion has assumed that the received signal strengths from various senders are the same; in reality this can be difficult to achieve. There is a considerable body of literature addressing these and other issues related to CDMA; see [Pickholtz 1982; Viterbi 1995] for details.

7.3 WiFi: 802.11 Wireless LANs

Pervasive in the workplace, the home, educational institutions, cafés, airports, and street corners, wireless LANs are now one of the most important access network technologies in the Internet today. Although many technologies and standards for wireless LANs were developed in the 1990s, one particular class of standards has clearly emerged as the winner: the **IEEE 802.11 wireless LAN**, also known as **WiFi**. In this section, we'll take a close look at 802.11 wireless LANs, examining its frame structure, its medium access protocol, and its internetworking of 802.11 LANs with wired Ethernet LANs.

There are several 802.11 standards for wireless LAN technology in the IEEE 802.11 ("WiFi") family, as summarized in **Table 7.1**. The different 802.11 standards all share some common characteristics. They all use the same medium access protocol, CSMA/CA, which we'll discuss shortly. All three use the same frame structure for their link-layer frames as well. All three standards have the ability to reduce their transmission rate in order to reach out over greater distances. And, importantly, 802.11 products are also all backwards compatible, meaning, for example, that a mobile capable only of 802.11g may still interact with a newer 802.11ac base station.

However, as shown in **Table 7.1**, the standards have some major differences at the physical layer. 802.11 devices operate in two difference frequency ranges: 2.4–2.485 GHz (referred to as the 2.4 GHz range) and 5.1 – 5.8 GHz (referred to as the 5 GHz range). The 2.4 GHz range is an unlicensed frequency band, where 802.11 devices may compete for frequency spectrum with 2.4 GHz phones and microwave ovens. At 5 GHz, 802.11 LANs have a shorter transmission distance for a given power level and suffer more from multipath propagation. The two most recent standards, 802.11n **[IEEE 802.11n 2012]** and 802.11ac **[IEEE 802.11ac 2013**; Cisco 802.11ac 2015] uses multiple input multiple-output (MIMO) antennas; i.e., two or more antennas on the sending side and two or more antennas on the receiving side that are transmitting/receiving different signals **[Diggavi 2004]**. 802.11ac base

Table 7.1 Summary of IEEE 802.11 standards

Standard	Frequency Range	Data Rate
802.11b	2.4 GHz	up to 11 Mbps
802.11a	5 GHz	up to 54 Mbps
802.11g	2.4 GHz	up to 54 Mbps

802.11n	2.5 GHz and 5 GHz	up to 450 Mbps
802.11ac	5 GHz	up to 1300 Mbps

stations may transmit to multiple stations simultaneously, and use “smart” antennas to adaptively beamform to target transmissions in the direction of a receiver. This decreases interference and increases the distance reached at a given data rate. The data rates shown in **Table 7.1** are for an idealized environment, e.g., a receiver placed 1 meter away from the base station, with no interference —a scenario that we’re unlikely to experience in practice! So as the saying goes, YMMV: Your Mileage (or in this case your wireless data rate) May Vary.

7.3.1 The 802.11 Architecture

Figure 7.7 illustrates the principal components of the 802.11 wireless LAN architecture. The fundamental building block of the 802.11 architecture is the **basic service set (BSS)**. A BSS contains one or more wireless stations and a central **base station**, known as an **access point (AP)** in 802.11 parlance. **Figure 7.7** shows the AP in each of two BSSs connecting to an interconnection device (such as a switch or router), which in turn leads to the Internet. In a typical home network, there is one AP and one router (typically integrated together as one unit) that connects the BSS to the Internet.

As with Ethernet devices, each 802.11 wireless station has a 6-byte MAC address that is stored in the firmware of the station’s adapter (that is, 802.11 network interface card). Each AP also has a MAC address for its wireless interface. As with Ethernet, these MAC addresses are administered by IEEE and are (in theory) globally unique.

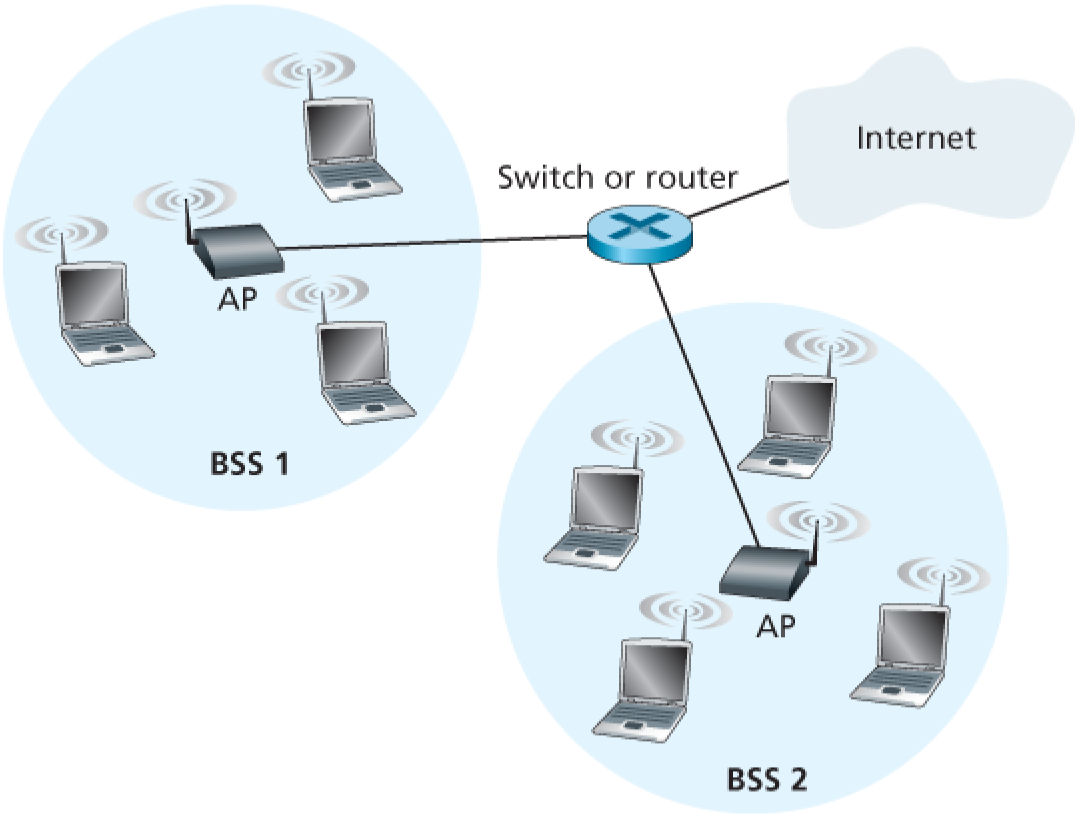


Figure 7.7 IEEE 802.11 LAN architecture

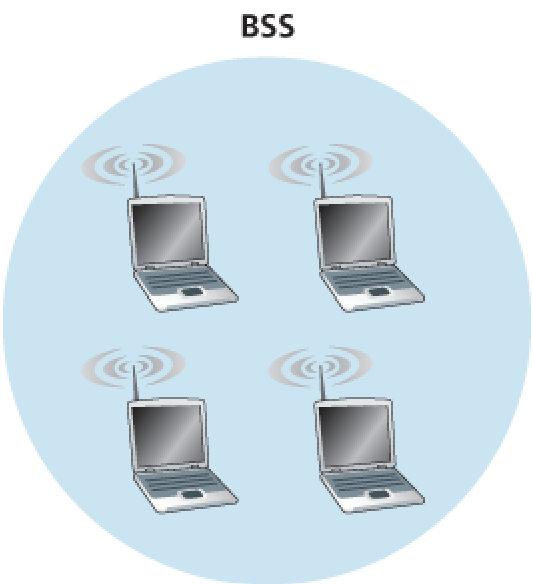


Figure 7.8 An IEEE 802.11 ad hoc network

As noted in **Section 7.1**, wireless LANs that deploy APs are often referred to as **infrastructure wireless LANs**, with the “infrastructure” being the APs along with the wired Ethernet infrastructure that interconnects the APs and a router. **Figure 7.8** shows that IEEE 802.11 stations can also group themselves together to form an ad hoc network—a network with no central control and with no connections to the “outside world.” Here, the network is formed “on the fly,” by mobile devices that have found themselves in proximity to each other, that have a need to communicate, and that find no preexisting network infrastructure in their location. An ad hoc network might be formed when people with laptops get together (for example, in a conference room, a train, or a car) and want to exchange data in the absence of a centralized AP. There has been tremendous interest in ad hoc networking, as communicating portable devices continue to proliferate. In this section, though, we'll focus our attention on infrastructure wireless LANs.

Channels and Association

In 802.11, each wireless station needs to associate with an AP before it can send or receive network-layer data. Although all of the 802.11 standards use association, we'll discuss this topic specifically in the context of IEEE 802.11b/g.

When a network administrator installs an AP, the administrator assigns a one- or two-word **Service Set Identifier (SSID)** to the access point. (When you choose Wi-Fi under Setting on your iPhone, for example, a list is displayed showing the SSID of each AP in range.) The administrator must also assign a channel number to the AP. To understand channel numbers, recall that 802.11 operates in the frequency range of 2.4 GHz to 2.4835 GHz. Within this 85 MHz band, 802.11 defines 11 partially overlapping channels. Any two channels are non-overlapping if and only if they are separated by four or more channels. In particular, the set of channels 1, 6, and 11 is the only set of three non-overlapping channels. This means that an administrator could create a wireless LAN with an aggregate maximum transmission rate of 33 Mbps by installing three 802.11b APs at the same physical location, assigning channels 1, 6, and 11 to the APs, and interconnecting each of the APs with a switch.

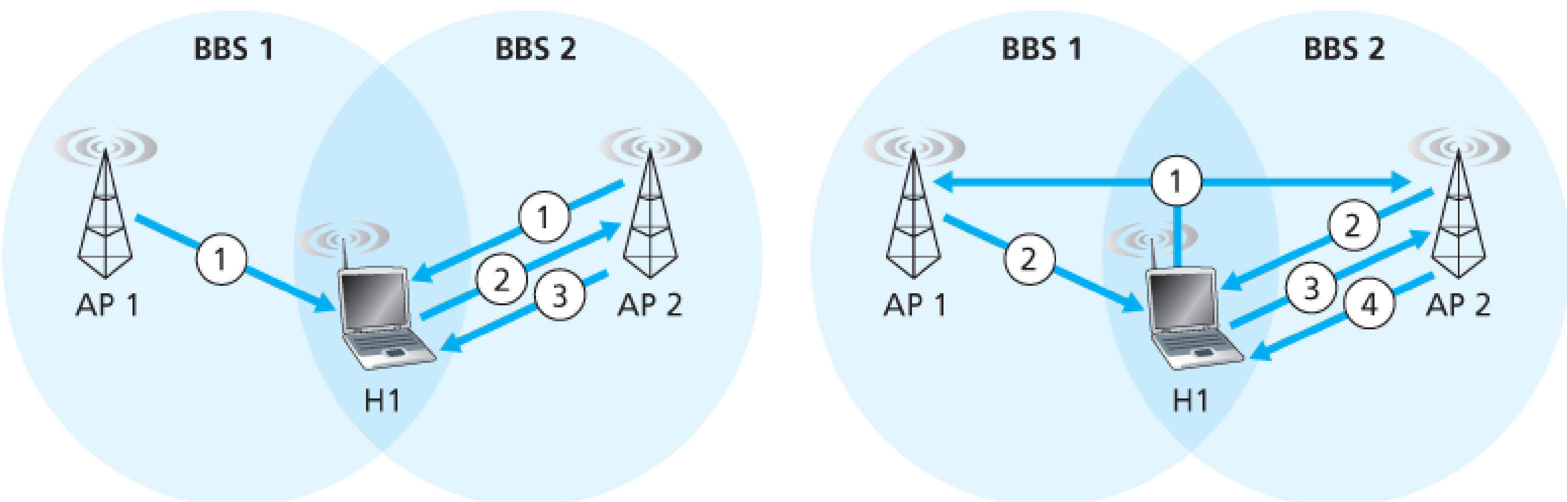
Now that we have a basic understanding of 802.11 channels, let's describe an interesting (and not completely uncommon) situation—that of a WiFi jungle. A **WiFi jungle** is any physical location where a wireless station receives a sufficiently strong signal from two or more APs. For example, in many cafés in New York City, a wireless station can pick up a signal from numerous nearby APs. One of the APs might be managed by the café, while the other APs might be in residential apartments near the café. Each of these APs would likely be located in a different IP subnet and would have been independently assigned a channel.

Now suppose you enter such a WiFi jungle with your phone, tablet, or laptop, seeking wireless Internet access and a blueberry muffin. Suppose there are five APs in the WiFi jungle. To gain Internet access, your wireless device needs to join exactly one of the subnets and hence needs to **associate** with exactly one of the APs. Associating means the wireless device creates a virtual wire between itself and the AP. Specifically, only the associated AP will send data frames (that is, frames containing data, such as a datagram) to your wireless device, and your wireless device will send data frames into the Internet only through the associated AP. But how does your wireless device associate with a particular AP? And more fundamentally, how does your wireless device know which APs, if any, are out there in the jungle?

The 802.11 standard requires that an AP periodically send **beacon frames**, each of which includes the

AP's SSID and MAC address. Your wireless device, knowing that APs are sending out beacon frames, scans the 11 channels, seeking beacon frames from any APs that may be out there (some of which may be transmitting on the same channel—it's a jungle out there!). Having learned about available APs from the beacon frames, you (or your wireless device) select one of the APs for association.

The 802.11 standard does not specify an algorithm for selecting which of the available APs to associate with; that algorithm is left up to the designers of the 802.11 firmware and software in your wireless device. Typically, the device chooses the AP whose beacon frame is received with the highest signal strength. While a high signal strength is good (see, e.g., **Figure 7.3**), signal strength is not the only AP characteristic that will determine the performance a device receives. In particular, it's possible that the selected AP may have a strong signal, but may be overloaded with other affiliated devices (that will need to share the wireless bandwidth at that AP), while an unloaded AP is not selected due to a slightly weaker signal. A number of alternative ways of choosing APs have thus recently been proposed [Vasudevan 2005; **Nicholson 2006**; **Sundaresan 2006]**. For an interesting and down-to-earth discussion of how signal strength is measured, see **[Bardwell 2004]**.



a. Passive scanning
1. Beacon frames sent from APs
2. Association Request frame sent: H1 to selected AP
3. Association Response frame sent: Selected AP to H1

a. Active scanning
1. Probe Request frame broadcast from H1
2. Probes Response frame sent from APs
3. Association Request frame sent: H1 to selected AP
4. Association Response frame sent: Selected AP to H1

Figure 7.9 Active and passive scanning for access points

The process of scanning channels and listening for beacon frames is known as **passive scanning** (see **Figure 7.9a**). A wireless device can also perform **active scanning**, by broadcasting a probe frame that will be received by all APs within the wireless device's range, as shown in **Figure 7.9b**. APs respond to the probe request frame with a probe response frame. The wireless device can then choose the AP with which to associate from among the responding APs.

After selecting the AP with which to associate, the wireless device sends an association request frame to the AP, and the AP responds with an association response frame. Note that this second request/response handshake is needed with active scanning, since an AP responding to the initial probe request frame doesn't know which of the (possibly many) responding APs the device will choose to associate with, in much the same way that a DHCP client can choose from among multiple DHCP servers (see **Figure 4.21**). Once associated with an AP, the device will want to join the subnet (in the IP addressing sense of **Section 4.3.3**) to which the AP belongs. Thus, the device will typically send a DHCP discovery message (see **Figure 4.21**) into the subnet via the AP in order to obtain an IP address on the subnet. Once the address is obtained, the rest of the world then views that device simply as another host with an IP address in that subnet.

In order to create an association with a particular AP, the wireless device may be required to authenticate itself to the AP. 802.11 wireless LANs provide a number of alternatives for authentication and access. One approach, used by many companies, is to permit access to a wireless network based on a device's MAC address. A second approach, used by many Internet cafés, employs usernames and passwords. In both cases, the AP typically communicates with an authentication server, relaying information between the wireless device and the authentication server using a protocol such as RADIUS **[RFC 2865]** or DIAMETER **[RFC 3588]**. Separating the authentication server from the AP allows one authentication server to serve many APs, centralizing the (often sensitive) decisions of authentication and access within the single server, and keeping AP costs and complexity low. We'll see in **Chapter 8** that the new IEEE 802.11i protocol defining security aspects of the 802.11 protocol family takes precisely this approach.

7.3.2 The 802.11 MAC Protocol

Once a wireless device is associated with an AP, it can start sending and receiving data frames to and from the access point. But because multiple wireless devices, or the AP itself may want to transmit data frames at the same time over the same channel, a multiple access protocol is needed to coordinate the transmissions. In the following, we'll refer to the devices or the AP as wireless "stations" that share the multiple access channel. As discussed in **Chapter 6** and **Section 7.2.1**, broadly speaking there are three classes of multiple access protocols: channel partitioning (including CDMA), random access, and taking turns. Inspired by the huge success of Ethernet and its random access protocol, the designers of 802.11 chose a random access protocol for 802.11 wireless LANs. This random access protocol is referred to as **CSMA with collision avoidance**, or more succinctly as **CSMA/CA**. As with Ethernet's CSMA/CD, the "CSMA" in CSMA/CA stands for "carrier sense multiple access," meaning that each station senses the channel before transmitting, and refrains from transmitting when the channel is sensed busy. Although both Ethernet and 802.11 use carrier-sensing random access, the two MAC protocols have important differences. First, instead of using collision detection, 802.11 uses collision-avoidance techniques. Second, because of the relatively high bit error rates of wireless channels, 802.11 (unlike Ethernet) uses a link-layer acknowledgment/retransmission (ARQ) scheme. We'll describe 802.11's collision-avoidance and link-layer acknowledgment schemes below.

Recall from **Sections 6.3.2** and **6.4.2** that with Ethernet's collision-detection algorithm, an Ethernet station listens to the channel as it transmits. If, while transmitting, it detects that another station is also transmitting, it aborts its transmission and tries to transmit again after waiting a small, random amount of time. Unlike the 802.3 Ethernet protocol, the 802.11 MAC protocol does *not* implement collision detection. There are two important reasons for this:

- The ability to detect collisions requires the ability to send (the station's own signal) and receive (to determine whether another station is also transmitting) at the same time. Because the strength of the received signal is typically very small compared to the strength of the transmitted signal at the 802.11 adapter, it is costly to build hardware that can detect a collision.
- More importantly, even if the adapter could transmit and listen at the same time (and presumably abort transmission when it senses a busy channel), the adapter would still not be able to detect all collisions, due to the hidden terminal problem and fading, as discussed in **Section 7.2**.

Because 802.11wireless LANs do not use collision detection, once a station begins to transmit a frame, *it transmits the frame in its entirety*; that is, once a station gets started, there is no turning back. As one might expect, transmitting entire frames (particularly long frames) when collisions are prevalent can significantly degrade a multiple access protocol's performance. In order to reduce the likelihood of collisions, 802.11 employs several collision-avoidance techniques, which we'll shortly discuss.

Before considering collision avoidance, however, we'll first need to examine 802.11's **link-layer acknowledgment** scheme. Recall from **Section 7.2** that when a station in a wireless LAN sends a frame, the frame may not reach the destination station intact for a variety of reasons. To deal with this non-negligible chance of failure, the 802.11 MAC protocol uses link-layer acknowledgments. As shown in **Figure 7.10**, when the destination station receives a frame that passes the CRC, it waits a short period of time known as the **Short Inter-frame Spacing (SIFS)** and then sends back

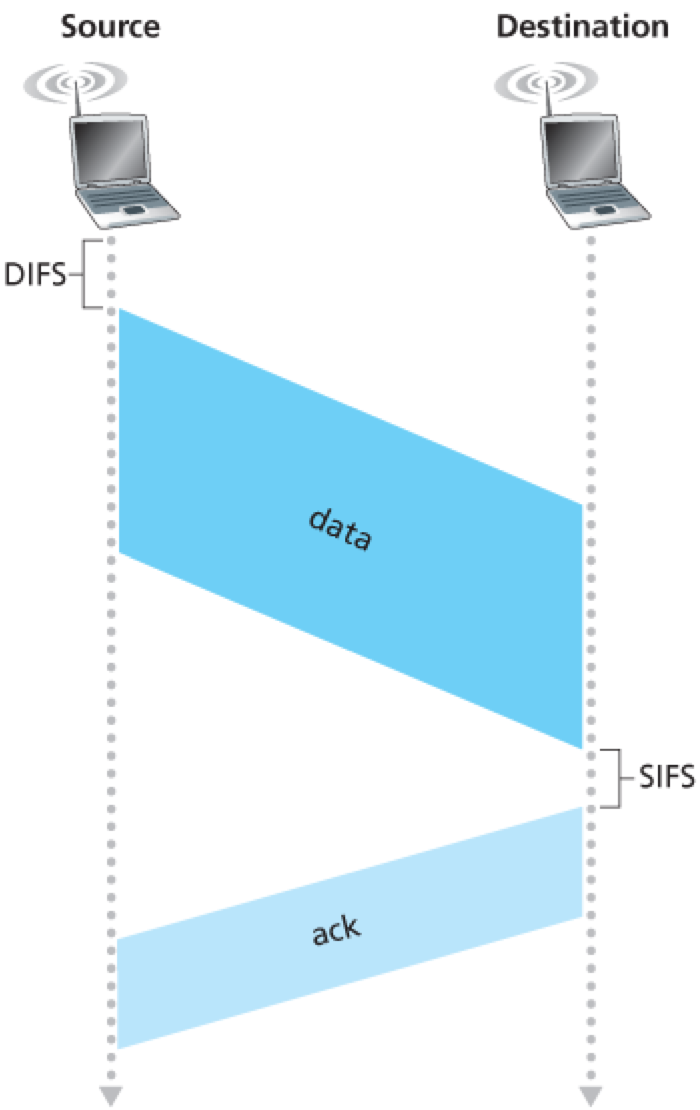


Figure 7.10 802.11 uses link-layer acknowledgments

an acknowledgment frame. If the transmitting station does not receive an acknowledgment within a given amount of time, it assumes that an error has occurred and retransmits the frame, using the CSMA/CA protocol to access the channel. If an acknowledgment is not received after some fixed number of retransmissions, the transmitting station gives up and discards the frame.

Having discussed how 802.11 uses link-layer acknowledgments, we're now in a position to describe the 802.11 CSMA/CA protocol. Suppose that a station (wireless device or an AP) has a frame to transmit.

1. If initially the station senses the channel idle, it transmits its frame after a short period of time known as the **Distributed Inter-frame Space (DIFS)**; see **Figure 7.10**.
2. Otherwise, the station chooses a random backoff value using binary exponential backoff (as we encountered in **Section 6.3.2**) and counts down this value after DIFS when the channel is sensed idle. While the channel is sensed busy, the counter value remains frozen.
3. When the counter reaches zero (note that this can only occur while the channel is sensed idle), the station transmits the entire frame and then waits for an acknowledgment.
4. If an acknowledgment is received, the transmitting station knows that its frame has been correctly received at the destination station. If the station has another frame to send, it begins

the CSMA/CA protocol at step 2. If the acknowledgment isn't received, the transmitting station reenters the backoff phase in step 2, with the random value chosen from a larger interval.

Recall that under Ethernet's CSMA/CD, multiple access protocol (**Section 6.3.2**), a station begins transmitting as soon as the channel is sensed idle. With CSMA/CA, however, the station refrains from transmitting while counting down, even when it senses the channel to be idle. Why do CSMA/CD and CDMA/CA take such different approaches here?

To answer this question, let's consider a scenario in which two stations each have a data frame to transmit, but neither station transmits immediately because each senses that a third station is already transmitting. With Ethernet's CSMA/CD, the two stations would each transmit as soon as they detect that the third station has finished transmitting. This would cause a collision, which isn't a serious issue in CSMA/CD, since both stations would abort their transmissions and thus avoid the useless transmissions of the remainders of their frames. In 802.11, however, the situation is quite different. Because 802.11 does not detect a collision and abort transmission, a frame suffering a collision will be transmitted in its entirety. The goal in 802.11 is thus to avoid collisions whenever possible. In 802.11, if the two stations sense the channel busy, they both immediately enter random backoff, hopefully choosing different backoff values. If these values are indeed different, once the channel becomes idle, one of the two stations will begin transmitting before the other, and (if the two stations are not hidden from each other) the "losing station" will hear the "winning station's" signal, freeze its counter, and refrain from transmitting until the winning station has completed its transmission. In this manner, a costly collision is avoided. Of course, collisions can still occur with 802.11 in this scenario: The two stations could be hidden from each other, or the two stations could choose random backoff values that are close enough that the transmission from the station starting first have yet to reach the second station. Recall that we encountered this problem earlier in our discussion of random access algorithms in the context of **Figure 6.12**.

Dealing with Hidden Terminals: RTS and CTS

The 802.11 MAC protocol also includes a nifty (but optional) reservation scheme that helps avoid collisions even in the presence of hidden terminals. Let's investigate this scheme in the context of **Figure 7.11**, which shows two wireless stations and one access point. Both of the wireless stations are within range of the AP (whose coverage is shown as a shaded circle) and both have associated with the AP. However, due to fading, the signal ranges of wireless stations are limited to the interiors of the shaded circles shown in **Figure 7.11**. Thus, each of the wireless stations is hidden from the other, although neither is hidden from the AP.

Let's now consider why hidden terminals can be problematic. Suppose Station H1 is transmitting a frame and halfway through H1's transmission, Station H2 wants to send a frame to the AP. H2, not hearing the transmission from H1, will first wait a DIFS interval and then transmit the frame, resulting in a collision. The channel will therefore be wasted during the entire period of H1's transmission as well as during H2's transmission.

In order to avoid this problem, the IEEE 802.11 protocol allows a station to use a short **Request to Send (RTS)** control frame and a short **Clear to Send (CTS)** control frame to *reserve* access to the channel. When a sender wants to send a DATA

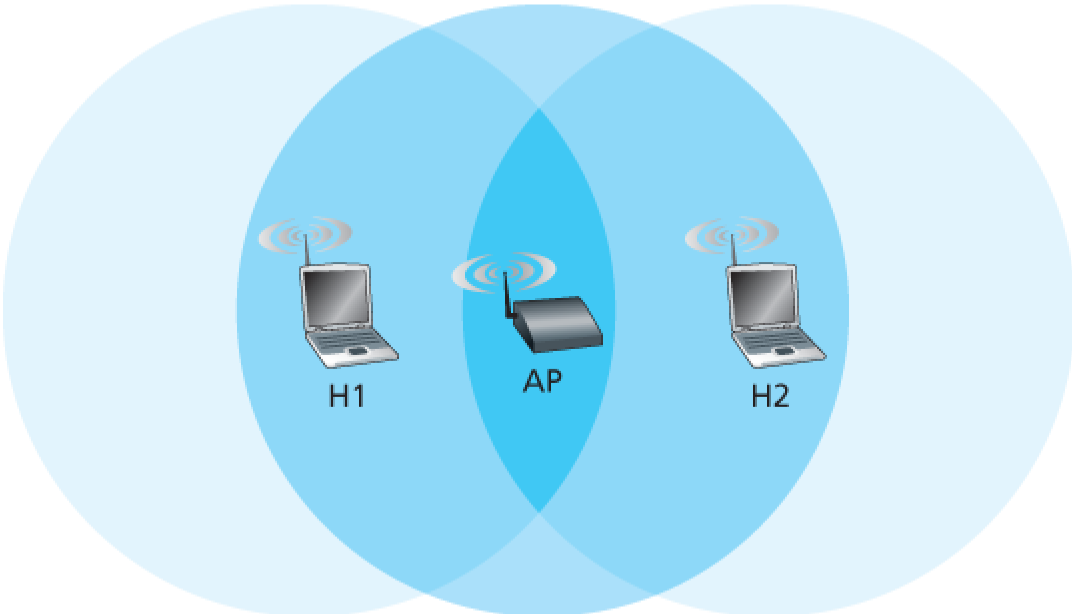


Figure 7.11 Hidden terminal example: H1 is hidden from H2, and vice versa

frame, it can first send an RTS frame to the AP, indicating the total time required to transmit the DATA frame and the acknowledgment (ACK) frame. When the AP receives the RTS frame, it responds by broadcasting a CTS frame. This CTS frame serves two purposes: It gives the sender explicit permission to send and also instructs the other stations not to send for the reserved duration.

Thus, in **Figure 7.12**, before transmitting a DATA frame, H1 first broadcasts an RTS frame, which is heard by all stations in its circle, including the AP. The AP then responds

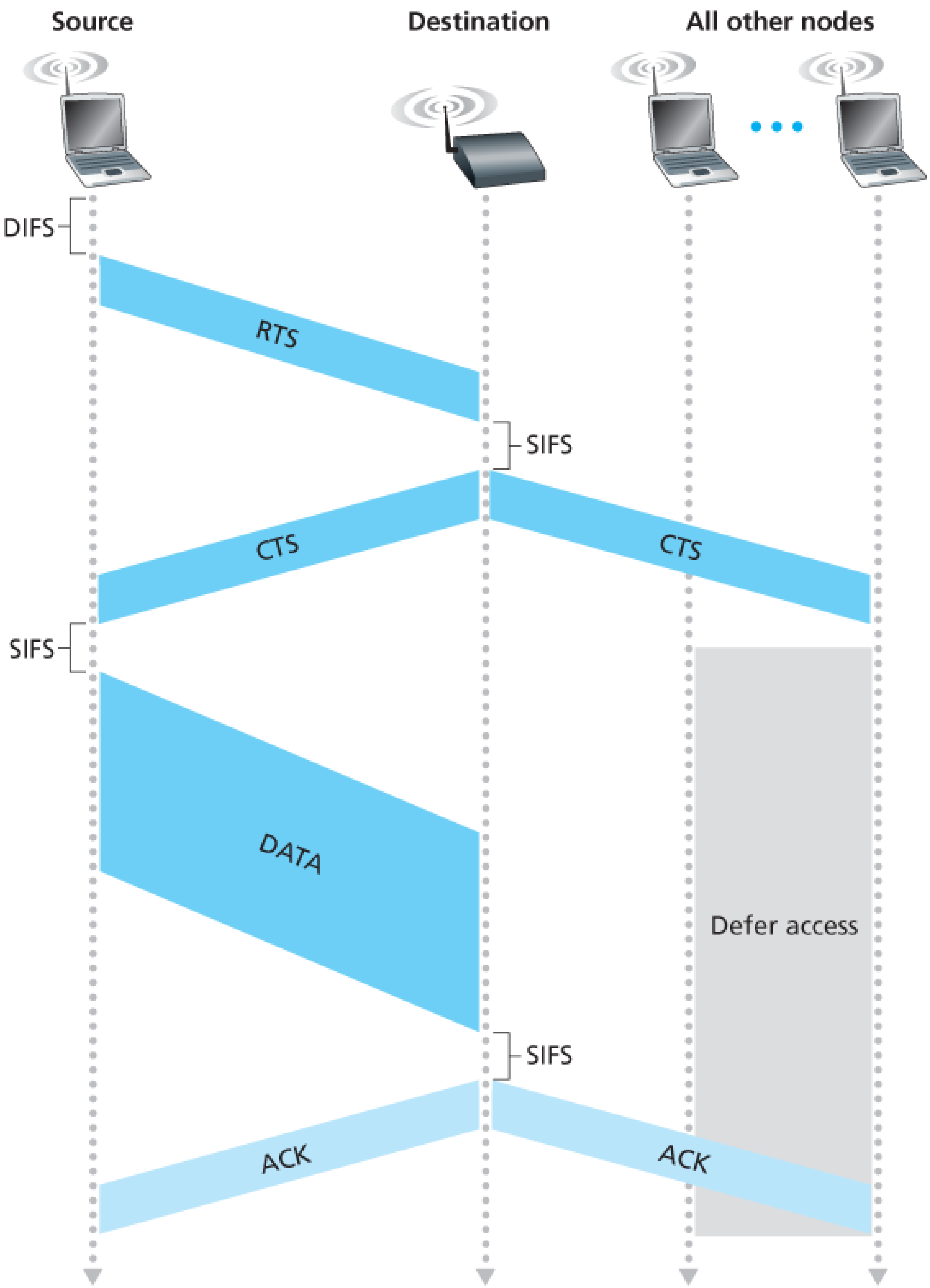


Figure 7.12 Collision avoidance using the RTS and CTS frames

with a CTS frame, which is heard by all stations within its range, including H1 and H2. Station H2, having heard the CTS, refrains from transmitting for the time specified in the CTS frame. The RTS, CTS, DATA, and ACK frames are shown in **Figure 7.12**.

The use of the RTS and CTS frames can improve performance in two important ways:

- The hidden station problem is mitigated, since a long DATA frame is transmitted only after the channel has been reserved.
- Because the RTS and CTS frames are short, a collision involving an RTS or CTS frame will last only

for the duration of the short RTS or CTS frame. Once the RTS and CTS frames are correctly transmitted, the following DATA and ACK frames should be transmitted without collisions.

You are encouraged to check out the 802.11 applet in the textbook's Web site. This interactive applet illustrates the CSMA/CA protocol, including the RTS/CTS exchange sequence.

Although the RTS/CTS exchange can help reduce collisions, it also introduces delay and consumes channel resources. For this reason, the RTS/CTS exchange is only used (if at all) to reserve the channel for the transmission of a long DATA frame. In practice, each wireless station can set an RTS threshold such that the RTS/CTS sequence is used only when the frame is longer than the threshold. For many wireless stations, the default RTS threshold value is larger than the maximum frame length, so the RTS/CTS sequence is skipped for all DATA frames sent.

Using 802.11 as a Point-to-Point Link

Our discussion so far has focused on the use of 802.11 in a multiple access setting. We should mention that if two nodes each have a directional antenna, they can point their directional antennas at each other and run the 802.11 protocol over what is essentially a point-to-point link. Given the low cost of commodity 802.11 hardware, the use of directional antennas and an increased transmission power allow 802.11 to be used as an inexpensive means of providing wireless point-to-point connections over tens of kilometers distance. **[Raman 2007]** describes one of the first such multi-hop wireless networks, operating in the rural Ganges plains in India using point-to-point 802.11 links.

7.3.3 The IEEE 802.11 Frame

Although the 802.11 frame shares many similarities with an Ethernet frame, it also contains a number of fields that are specific to its use for wireless links. The 802.11 frame is shown in **Figure 7.13**. The numbers above each of the fields in the frame represent the lengths of the fields in *bytes*; the numbers above each of the subfields in the frame control field represent the lengths of the subfields in *bits*. Let's now examine the fields in the frame as well as some of the more important subfields in the frame's control field.

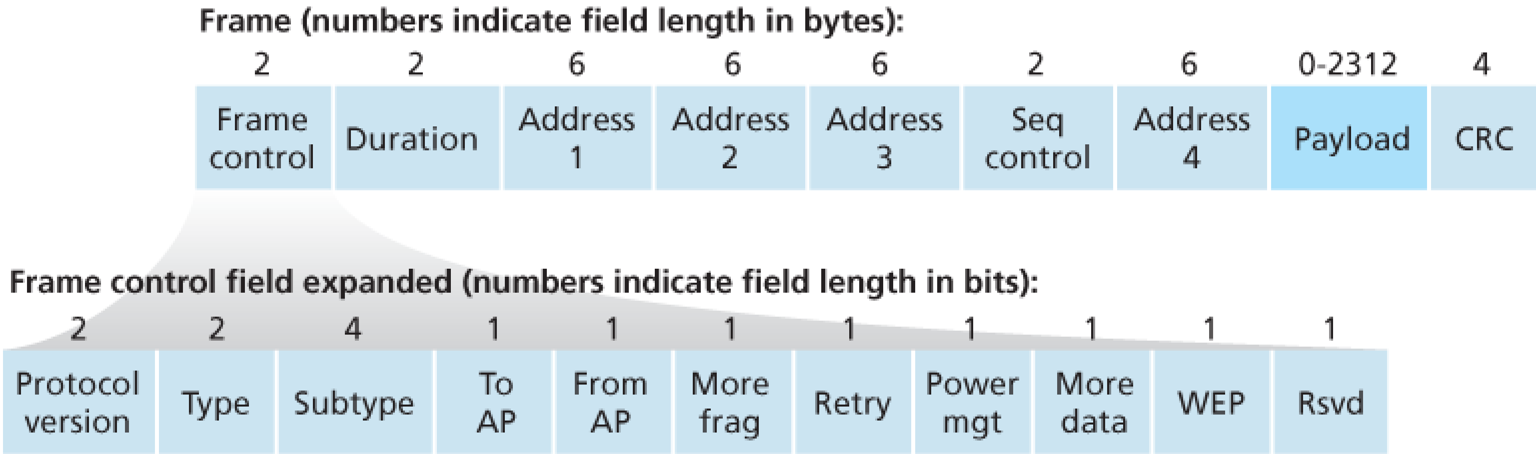


Figure 7.13 The 802.11 frame

Payload and CRC Fields

At the heart of the frame is the payload, which typically consists of an IP datagram or an ARP packet. Although the field is permitted to be as long as 2,312 bytes, it is typically fewer than 1,500 bytes, holding an IP datagram or an ARP packet. As with an Ethernet frame, an 802.11 frame includes a 32-bit cyclic redundancy check (CRC) so that the receiver can detect bit errors in the received frame. As we've seen, bit errors are much more common in wireless LANs than in wired LANs, so the CRC is even more useful here.

Address Fields

Perhaps the most striking difference in the 802.11 frame is that it has *four* address fields, each of which can hold a 6-byte MAC address. But why four address fields? Doesn't a source MAC field and destination MAC field suffice, as they do for Ethernet? It turns out that three address fields are needed for internetworking purposes—specifically, for moving the network-layer datagram from a wireless station through an AP to a router interface. The fourth address field is used when APs forward frames to each other in ad hoc mode. Since we are only considering infrastructure networks here, let's focus our attention on the first three address fields. The 802.11 standard defines these fields as follows:

- Address 2 is the MAC address of the station that transmits the frame. Thus, if a wireless station transmits the frame, that station's MAC address is inserted in the address 2 field. Similarly, if an AP transmits the frame, the AP's MAC address is inserted in the address 2 field.
- Address 1 is the MAC address of the wireless station that is to receive the frame. Thus if a mobile wireless station transmits the frame, address 1 contains the MAC address of the destination AP. Similarly, if an AP transmits the frame, address 1 contains the MAC address of the destination wireless station.

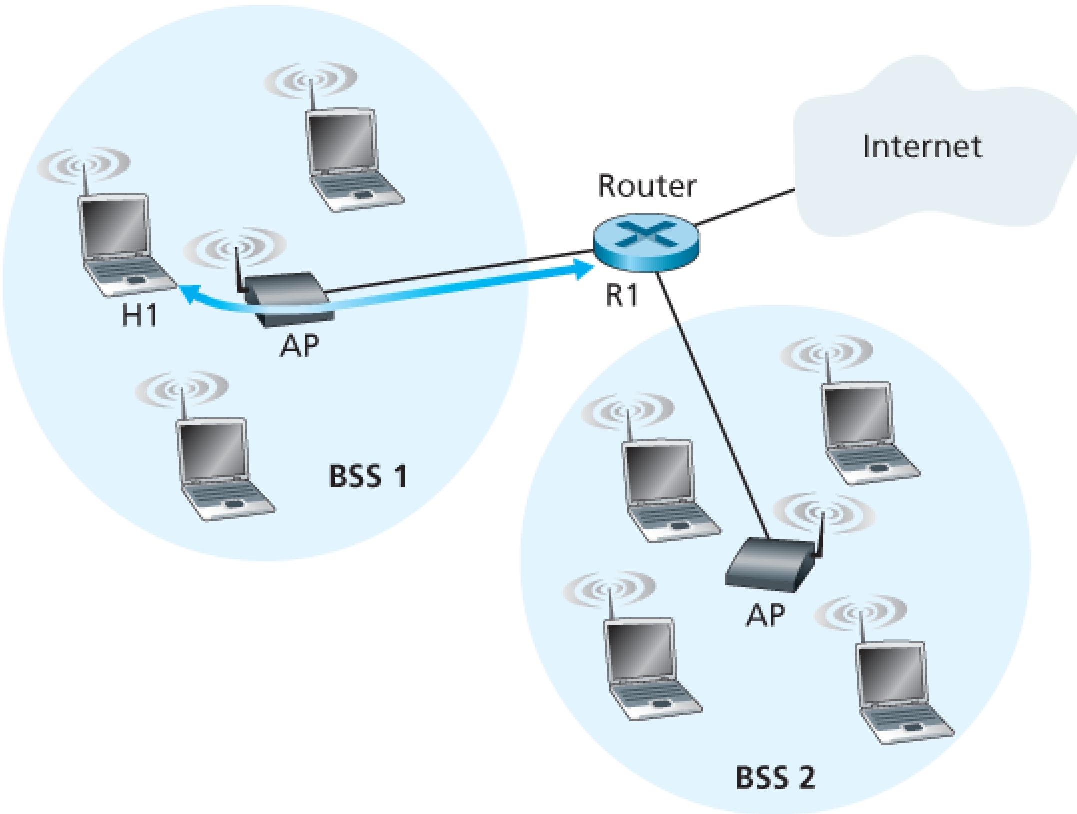


Figure 7.14 The use of address fields in 802.11 frames: Sending frames between H1 and R1

- To understand address 3, recall that the BSS (consisting of the AP and wireless stations) is part of a subnet, and that this subnet connects to other subnets via some router interface. Address 3 contains the MAC address of this router interface.

To gain further insight into the purpose of address 3, let's walk through an internetworking example in the context of **Figure 7.14**. In this figure, there are two APs, each of which is responsible for a number of wireless stations. Each of the APs has a direct connection to a router, which in turn connects to the global Internet. We should keep in mind that an AP is a link-layer device, and thus neither "speaks" IP nor understands IP addresses. Consider now moving a datagram from the router interface R1 to the wireless Station H1. The router is not aware that there is an AP between it and H1; from the router's perspective, H1 is just a host in one of the subnets to which it (the router) is connected.

- The router, which knows the IP address of H1 (from the destination address of the datagram), uses ARP to determine the MAC address of H1, just as in an ordinary Ethernet LAN. After obtaining H1's MAC address, router interface R1 encapsulates the datagram within an Ethernet frame. The source address field of this frame contains R1's MAC address, and the destination address field contains H1's MAC address.
- When the Ethernet frame arrives at the AP, the AP converts the 802.3 Ethernet frame to an 802.11 frame before transmitting the frame into the wireless channel. The AP fills in address 1 and address 2 with H1's MAC address and its own MAC address, respectively, as described above. For address 3, the AP inserts the MAC address of R1. In this manner, H1 can determine (from address 3) the MAC address of the router interface that sent the datagram into the subnet.

Now consider what happens when the wireless station H1 responds by moving a datagram from H1 to R1.

- H1 creates an 802.11 frame, filling the fields for address 1 and address 2 with the AP's MAC address and H1's MAC address, respectively, as described above. For address 3, H1 inserts R1's MAC address.
- When the AP receives the 802.11 frame, it converts the frame to an Ethernet frame. The source address field for this frame is H1's MAC address, and the destination address field is R1's MAC address. Thus, address 3 allows the AP to determine the appropriate destination MAC address when constructing the Ethernet frame.

In summary, address 3 plays a crucial role for internetworking the BSS with a wired LAN.

Sequence Number, Duration, and Frame Control Fields

Recall that in 802.11, whenever a station correctly receives a frame from another station, it sends back an acknowledgment. Because acknowledgments can get lost, the sending station may send multiple copies of a given frame. As we saw in our discussion of the rdt2.1 protocol (**Section 3.4.1**), the use of sequence numbers allows the receiver to distinguish between a newly transmitted frame and the retransmission of a previous frame. The sequence number field in the 802.11 frame thus serves exactly the same purpose here at the link layer as it did in the transport layer in **Chapter 3**.

Recall that the 802.11 protocol allows a transmitting station to reserve the channel for a period of time that includes the time to transmit its data frame and the time to transmit an acknowledgment. This duration value is included in the frame's duration field (both for data frames and for the RTS and CTS frames).

As shown in **Figure 7.13**, the frame control field includes many subfields. We'll say just a few words about some of the more important subfields; for a more complete discussion, you are encouraged to consult the 802.11 specification **[Held 2001**; **Crow 1997**; **IEEE 802.11 1999]**. The *type* and *subtype* fields are used to distinguish the association, RTS, CTS, ACK, and data frames. The *to* and *from* fields are used to define the meanings of the different address fields. (These meanings change depending on whether ad hoc or infrastructure modes are used and, in the case of infrastructure mode, whether a wireless station or an AP is sending the frame.) Finally the WEP field indicates whether encryption is being used or not (WEP is discussed in **Chapter 8**).

7.3.4 Mobility in the Same IP Subnet

In order to increase the physical range of a wireless LAN, companies and universities will often deploy multiple BSSs within the same IP subnet. This naturally raises the issue of mobility among the BSSs—how do wireless stations seamlessly move from one BSS to another while maintaining ongoing TCP sessions? As we'll see in this subsection, mobility can be handled in a relatively straightforward manner when the BSSs are part of the subnet. When stations move between subnets, more sophisticated mobility management protocols will be needed, such as those we'll study in **Sections 7.5** and **7.6**.

Let's now look at a specific example of mobility between BSSs in the same subnet. **Figure 7.15** shows two interconnected BSSs with a host, H1, moving from BSS1 to BSS2. Because in this example the interconnection device that connects the two BSSs is *not* a router, all of the stations in the two BSSs, including the APs, belong to the same IP subnet. Thus, when H1 moves from BSS1 to BSS2, it may keep its IP address and all of its ongoing TCP connections. If the interconnection device were a router, then H1 would have to obtain a new IP address in the subnet in which it was moving. This address change would disrupt (and eventually terminate) any on-going TCP connections at H1. In **Section 7.6**, we'll see how a network-layer mobility protocol, such as mobile IP, can be used to avoid this problem.

But what specifically happens when H1 moves from BSS1 to BSS2? As H1 wanders away from AP1, H1 detects a weakening signal from AP1 and starts to scan for a stronger signal. H1 receives beacon frames from AP2 (which in many corporate and university settings will have the same SSID as AP1). H1 then disassociates with AP1 and associates with AP2, while keeping its IP address and maintaining its ongoing TCP sessions.

This addresses the handoff problem from the host and AP viewpoint. But what about the switch in **Figure 7.15**? How does it know that the host has moved from one AP to another? As you may recall from **Chapter 6**, switches are "self-learning" and automatically build their forwarding tables. This self-learning feature nicely handles

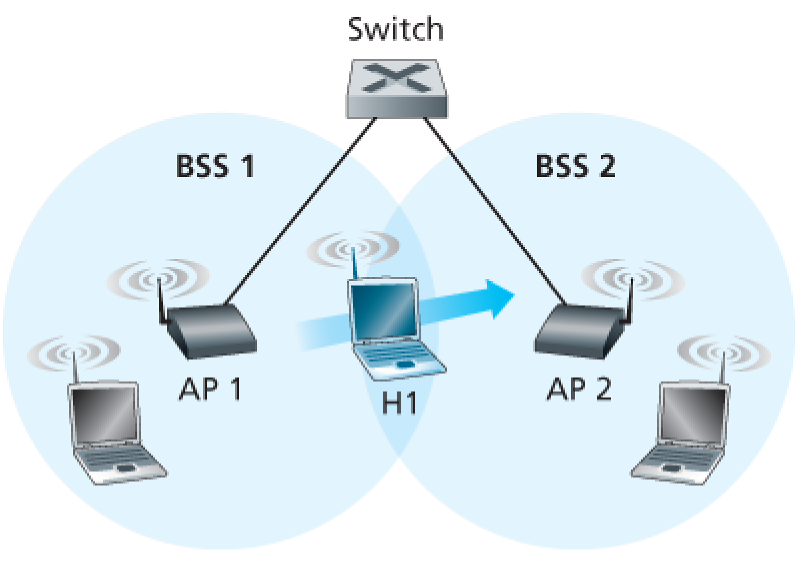


Figure 7.15 Mobility in the same subnet

occasional moves (for example, when an employee gets transferred from one department to another); however, switches were not designed to support highly mobile users who want to maintain TCP connections while moving between BSSs. To appreciate the problem here, recall that before the move, the switch has an entry in its forwarding table that pairs H1's MAC address with the outgoing switch interface through which H1 can be reached. If H1 is initially in BSS1, then a datagram destined to H1 will be directed to H1 via AP1. Once H1 associates with BSS2, however, its frames should be directed to AP2. One solution (a bit of a hack, really) is for AP2 to send a broadcast Ethernet frame with H1's source address to the switch just after the new association. When the switch receives the frame, it updates its forwarding table, allowing H1 to be reached via AP2. The 802.11f standards group is developing an inter-AP protocol to handle these and related issues.

Our discussion above has focused on mobility with the same LAN subnet. Recall that VLANs, which we studied in **Section 6.4.4**, can be used to connect together islands of LANs into a large virtual LAN that can span a large geographical region. Mobility among base stations within such a VLAN can be handled in exactly the same manner as above **[Yu 2011]**.

7.3.5 Advanced Features in 802.11

We'll wrap up our coverage of 802.11 with a short discussion of two advanced capabilities found in 802.11 networks. As we'll see, these capabilities are *not* completely specified in the 802.11 standard, but rather are made possible by mechanisms specified in the standard. This allows different vendors to implement these capabilities using their own (proprietary) approaches, presumably giving them an edge over the competition.

802.11 Rate Adaptation

We saw earlier in **Figure 7.3** that different modulation techniques (with the different transmission rates that they provide) are appropriate for different SNR scenarios. Consider for example a mobile 802.11 user who is initially 20 meters away from the base station, with a high signal-to-noise ratio. Given the high SNR, the user can communicate with the base station using a physical-layer modulation technique that provides high transmission rates while maintaining a low BER. This is one happy user! Suppose now that the user becomes mobile, walking away from the base station, with the SNR falling as the distance from the base station increases. In this case, if the modulation technique used in the 802.11 protocol operating between the base station and the user does not change, the BER will become unacceptably high as the SNR decreases, and eventually no transmitted frames will be received correctly.

For this reason, some 802.11 implementations have a rate adaptation capability that adaptively selects the underlying physical-layer modulation technique to use based on current or recent channel characteristics. If a node sends two frames in a row without receiving an acknowledgment (an implicit indication of bit errors on the channel), the transmission rate falls back to the next lower rate. If 10 frames in a row are acknowledged, or if a timer that tracks the time since the last fallback expires, the transmission rate increases to the next higher rate. This rate adaptation mechanism shares the same "probing" philosophy as TCP's congestion-control mechanism—when conditions are good (reflected by ACK receipts), the transmission rate is increased until something "bad" happens (the lack of ACK receipts); when something "bad" happens, the transmission rate is reduced. 802.11 rate adaptation and TCP congestion control are thus similar to the young child who is constantly pushing his/her parents for more and more (say candy for a young child, later curfew hours for the teenager) until the parents finally say "Enough!" and the child backs off (only to try again later after conditions have hopefully improved!). A number of other schemes have also been proposed to improve on this basic automatic rate-adjustment scheme **[Kamerman 1997**; **Holland 2001**; **Lacage 2004]**.

Power Management

Power is a precious resource in mobile devices, and thus the 802.11 standard provides power-management capabilities that allow 802.11 nodes to minimize the amount of time that their sense, transmit, and receive functions and other circuitry need to be "on." 802.11 power management operates as follows. A node is able to explicitly alternate between sleep and wake states (not unlike a sleepy student in a classroom!). A node indicates to the access point that it will be going to sleep by setting the power-management bit in the header of an 802.11 frame to 1. A timer in the node is then set to wake up the node just before the AP is scheduled to send its beacon frame (recall that an AP typically sends a beacon frame every 100 msec). Since the AP knows from the set power-transmission bit that the node is going to sleep, it (the AP) knows that it should not send any frames to that node, and will buffer any frames destined for the sleeping host for later transmission.

A node will wake up just before the AP sends a beacon frame, and quickly enter the fully active state (unlike the sleepy student, this wakeup requires only 250 microseconds **[Kamerman 1997]**!). The beacon frames sent out by the AP contain a list of nodes whose frames have been buffered at the AP. If there are no buffered frames for the node, it can go back to sleep. Otherwise, the node can explicitly request that the buffered frames be sent by sending a polling message to the AP. With an inter-beacon time of 100 msec, a wakeup time of 250 microseconds, and a similarly small time to receive a beacon frame and check to ensure that there are no buffered frames, a node that has no frames to send or receive can be asleep 99% of the time, resulting in a significant energy savings.

7.3.6 Personal Area Networks: Bluetooth and Zigbee

As illustrated in **Figure 7.2**, the IEEE 802.11 WiFi standard is aimed at communication among devices separated by up to 100 meters (except when 802.11 is used in a point-to-point configuration with a