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

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

Table 7.1 ♦ Summary of IEEE 802.11 standards

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.

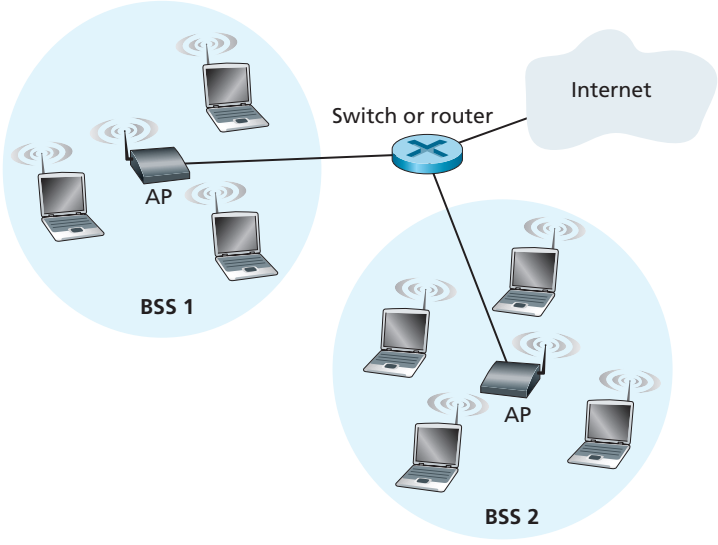


Figure 7.7 ♦ IEEE 802.11 LAN architecture

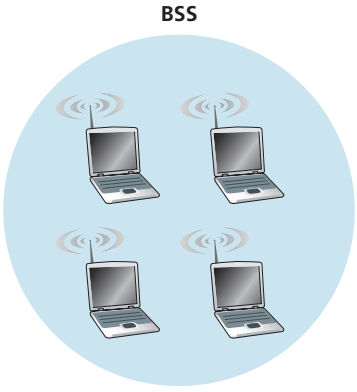


Figure 7.8 ♦ An IEEE 802.11 ad hoc network

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

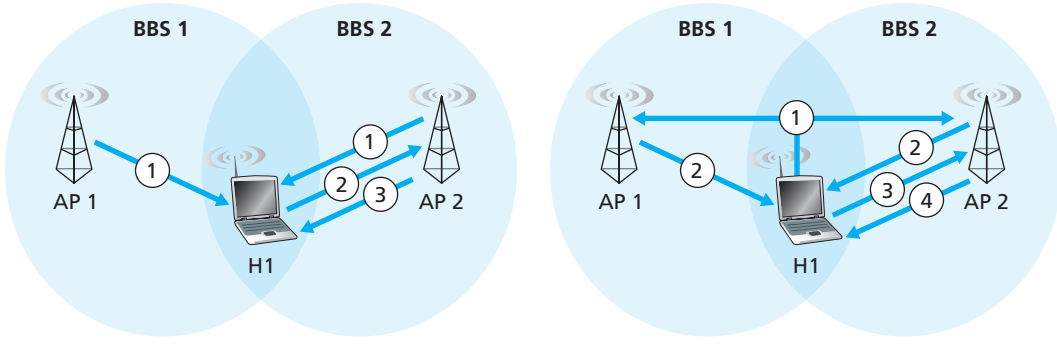
1, 6, and 11 is the only set of three non-overlapping channels. This means that an administrator could create a wireless LAN with an aggregate maximum transmission rate of 33 Mbps by installing three 802.11b APs at the same physical location, assigning channels 1, 6, and 11 to the APs, and interconnecting 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.

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.

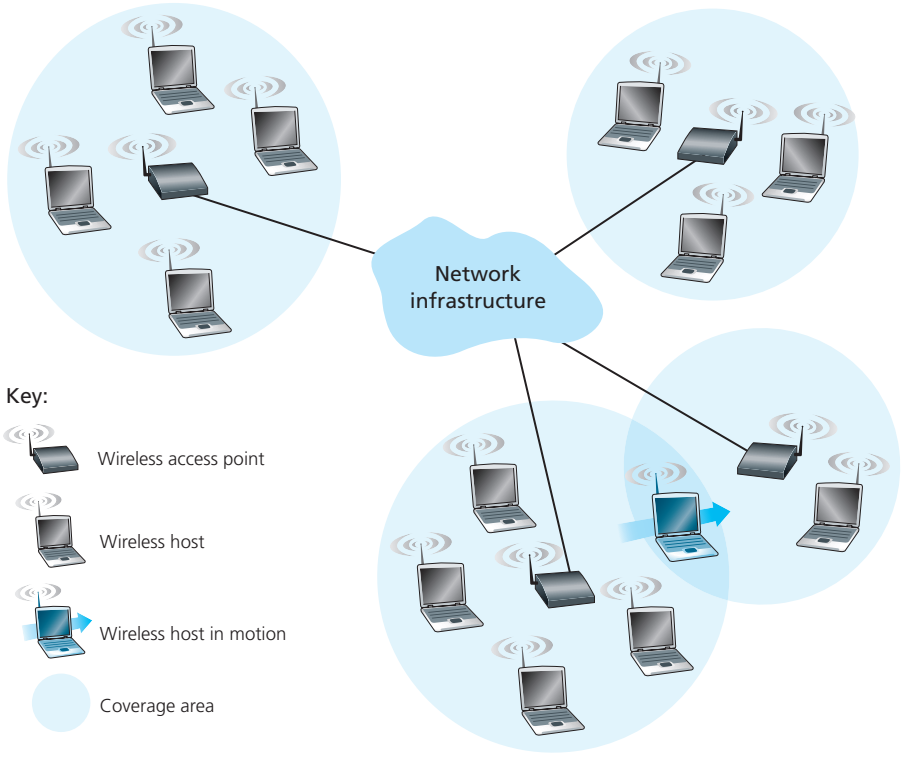


Figure 7.1 ♦ Elements of a wireless network

- *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

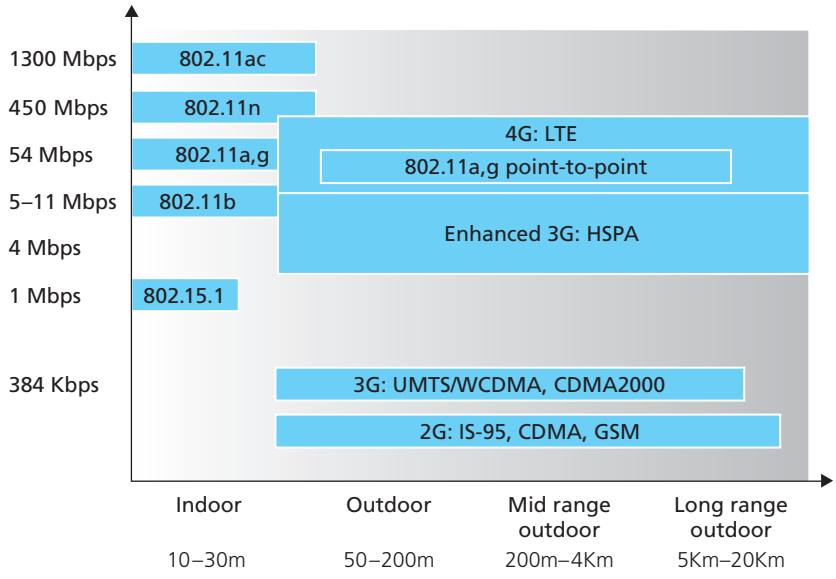


Figure 7.2 ♦ Link characteristics of selected wireless network standards

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

PUBLIC WIFI ACCESS: COMING SOON TO A LAMP POST NEAR YOU?

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

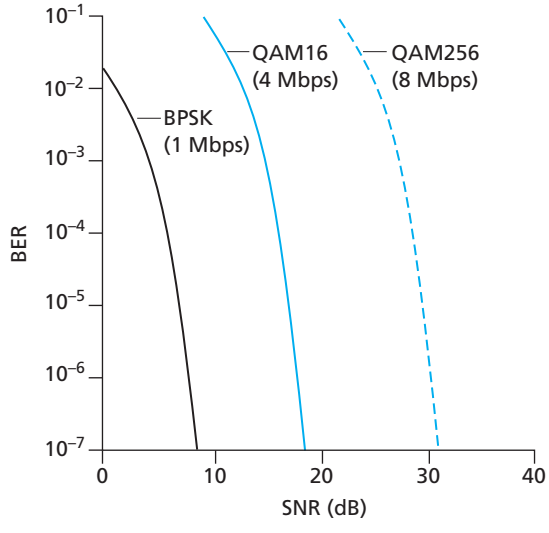


Figure 7.3 ♦ Bit error rate, transmission rate, and SNR

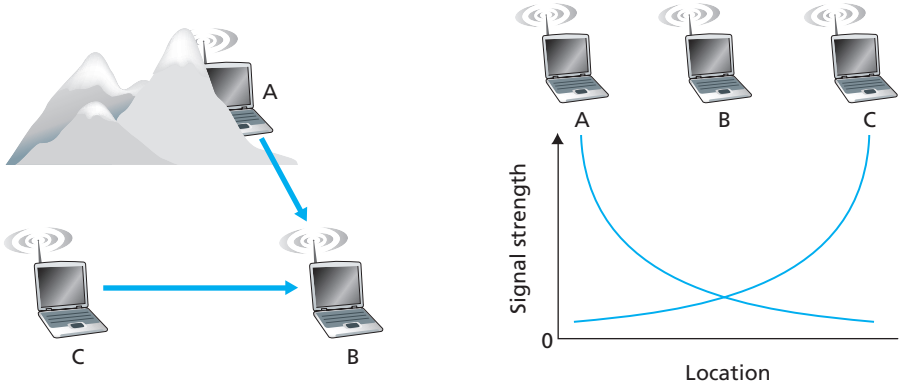


Figure 7.4 ♦ Hidden terminal problem caused by obstacle (a) and fading (b)

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, $M = 8$,