CHAPTER 17

WIRELESS LANS

Investigators have published numerous reports of birds taking turns vocalizing; the bird spoken to gave its full attention to the speaker and never vocalized at the same time, as if the two were holding a conversation. Researchers and scholars who have studied the data on avian communication carefully write the (a) the communication code of birds such has crows has not been broken by any means; (b) probably all birds have wider vocabularies than anyone realizes; and (c) greater complexity and depth are recognized in avian communication as research progresses.

—*The Human Nature of Birds*, Theodore Barber

KEY POINTS

- The principal technologies used for wireless LANs are infrared, spread spectrum, and narrowband microwave.
- The IEEE 802.11 standard defines a set of services and physical layer options for wireless LANs.
- The IEEE 802.11 services include managing associations, delivering data, and security.
- The IEEE 802.11 physical layer includes infrared and spread spectrum and covers a range of data rates.

In just the past few years, wireless LANs have come to occupy a significant niche in the local area network market. Increasingly, organizations are finding that wireless LANs are an indispensable adjunct to traditional wired LANs, to satisfy requirements for mobility, relocation, ad hoc networking, and coverage of locations difficult to wire.

This chapter provides a survey of wireless LANs. We begin with an overview that looks at the motivations for using wireless LANs and summarize the various approaches in current use. The next section examines the three principal types of wireless LANs, classified according to transmission technology: infrared, spread spectrum, and narrowband microwave.

The most prominent specification for wireless LANs was developed by the IEEE 802.11 working group. The remainder of the chapter focuses on this standard.

17.1 OVERVIEW

As the name suggests, a wireless LAN is one that makes use of a wireless transmission medium. Until relatively recently, wireless LANs were little used. The reasons

for this included high prices, low data rates, occupational safety concerns, and licensing requirements. As these problems have been addressed, the popularity of wireless LANs has grown rapidly.

In this section, we survey the key wireless LAN application areas and then look at the requirements for and advantages of wireless LANs.

Wireless LAN Applications

[PAHL95] lists four application areas for wireless LANs: LAN extension, cross-building interconnect, nomadic access, and ad hoc networks. Let us consider each of these in turn.

LAN Extension Early wireless LAN products, introduced in the late 1980s, were marketed as substitutes for traditional wired LANs. A wireless LAN saves the cost of the installation of LAN cabling and eases the task of relocation and other modifications to network structure. However, this motivation for wireless LANs was overtaken by events. First, as awareness of the need for LANs became greater, architects designed new buildings to include extensive prewiring for data applications. Second, with advances in data transmission technology, there is an increasing reliance on twisted pair cabling for LANs and, in particular, Category 3 and Category 5 unshielded twisted pair. Most older buildings are already wired with an abundance of Category 3 cable, and many newer buildings are prewired with Category 5. Thus, the use of a wireless LAN to replace wired LANs has not happened to any great extent.

However, in a number of environments, there is a role for the wireless LAN as an alternative to a wired LAN. Examples include buildings with large open areas, such as manufacturing plants, stock exchange trading floors, and warehouses; historical buildings with insufficient twisted pair and where drilling holes for new wiring is prohibited; and small offices where installation and maintenance of wired LANs is not economical. In all of these cases, a wireless LAN provides an effective and more attractive alternative. In most of these cases, an organization will also have a wired LAN to support servers and some stationary workstations. For example, a manufacturing facility typically has an office area that is separate from the factory floor but that must be linked to it for networking purposes. Therefore, typically, a wireless LAN will be linked into a wired LAN on the same premises. Thus, this application area is referred to as LAN extension.

Figure 17.1 indicates a simple wireless LAN configuration that is typical of many environments. There is a backbone wired LAN, such as Ethernet, that supports servers, workstations, and one or more bridges or routers to link with other networks. In addition, there is a control module (CM) that acts as an interface to a wireless LAN. The control module includes either bridge or router functionality to link the wireless LAN to the backbone. It includes some sort of access control logic, such as a polling or token-passing scheme, to regulate the access from the end systems. Note that some of the end systems are standalone devices, such as a workstation or a server. Hubs or other user modules (UMs) that control a number of stations off a wired LAN may also be part of the wireless LAN configuration.

The configuration of Figure 17.1 can be referred to as a single-cell wireless LAN; all of the wireless end systems are within range of a single control module.

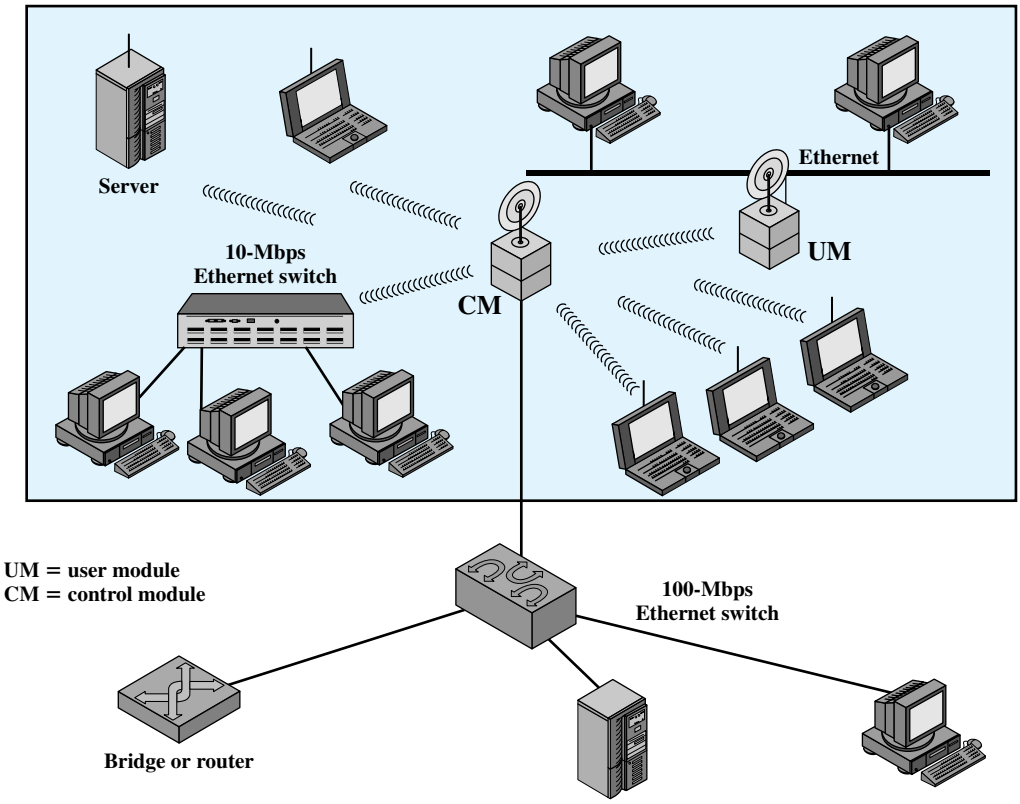


Figure 17.1 Example Single-Cell Wireless LAN Configuration

Another common configuration, suggested by Figure 17.2, is a multiple-cell wireless LAN. In this case, there are multiple control modules interconnected by a wired LAN. Each control module supports a number of wireless end systems within its transmission range. For example, with an infrared LAN, transmission is limited to a single room; therefore, one cell is needed for each room in an office building that requires wireless support.

Cross-Building Interconnect Another use of wireless LAN technology is to connect LANs in nearby buildings, be they wired or wireless LANs. In this case, a point-to-point wireless link is used between two buildings. The devices so connected are typically bridges or routers. This single point-to-point link is not a LAN per se, but it is usual to include this application under the heading of wireless LAN.

Nomadic Access Nomadic access provides a wireless link between a LAN hub and a mobile data terminal equipped with an antenna, such as a laptop computer or notepad computer. One example of the utility of such a connection is to enable an employee returning from a trip to transfer data from a personal portable computer to a server in the office. Nomadic access is also useful in an extended environment such as a campus or a business operating out of a cluster of buildings. In both of

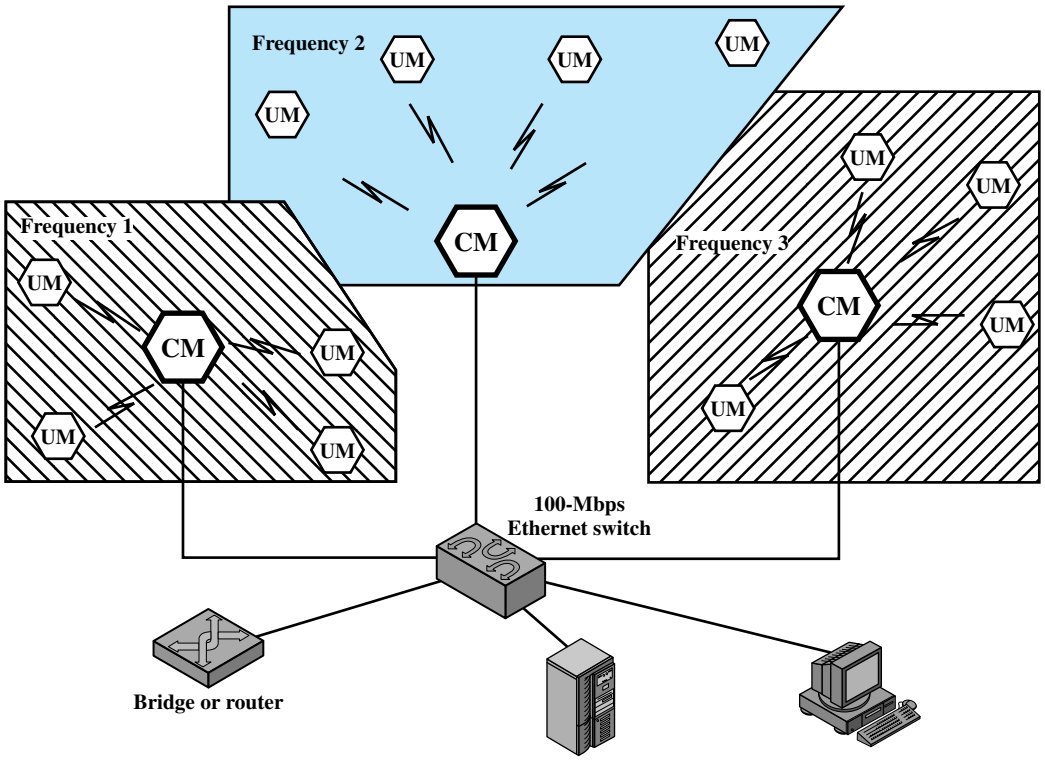


Figure 17.2 Example Multiple-Cell Wireless LAN Configuration

these cases, users may move around with their portable computers and may wish access to the servers on a wired LAN from various locations.

Ad Hoc Networking An ad hoc network is a peer-to-peer network (no centralized server) set up temporarily to meet some immediate need. For example, a group of employees, each with a laptop or palmtop computer, may convene in a conference room for a business or classroom meeting. The employees link their computers in a temporary network just for the duration of the meeting.

Figure 17.3 suggests the differences between a wireless LAN that supports LAN extension and nomadic access requirements and an ad hoc wireless LAN. In the former case, the wireless LAN forms a stationary infrastructure consisting of one or more cells with a control module for each cell. Within a cell, there may be a number of stationary end systems. Nomadic stations can move from one cell to another. In contrast, there is no infrastructure for an ad hoc network. Rather, a peer collection of stations within range of each other may dynamically configure themselves into a temporary network.

Wireless LAN Requirements

A wireless LAN must meet the same sort of requirements typical of any LAN, including high capacity, ability to cover short distances, full connectivity among attached stations, and broadcast capability. In addition, there are a number of

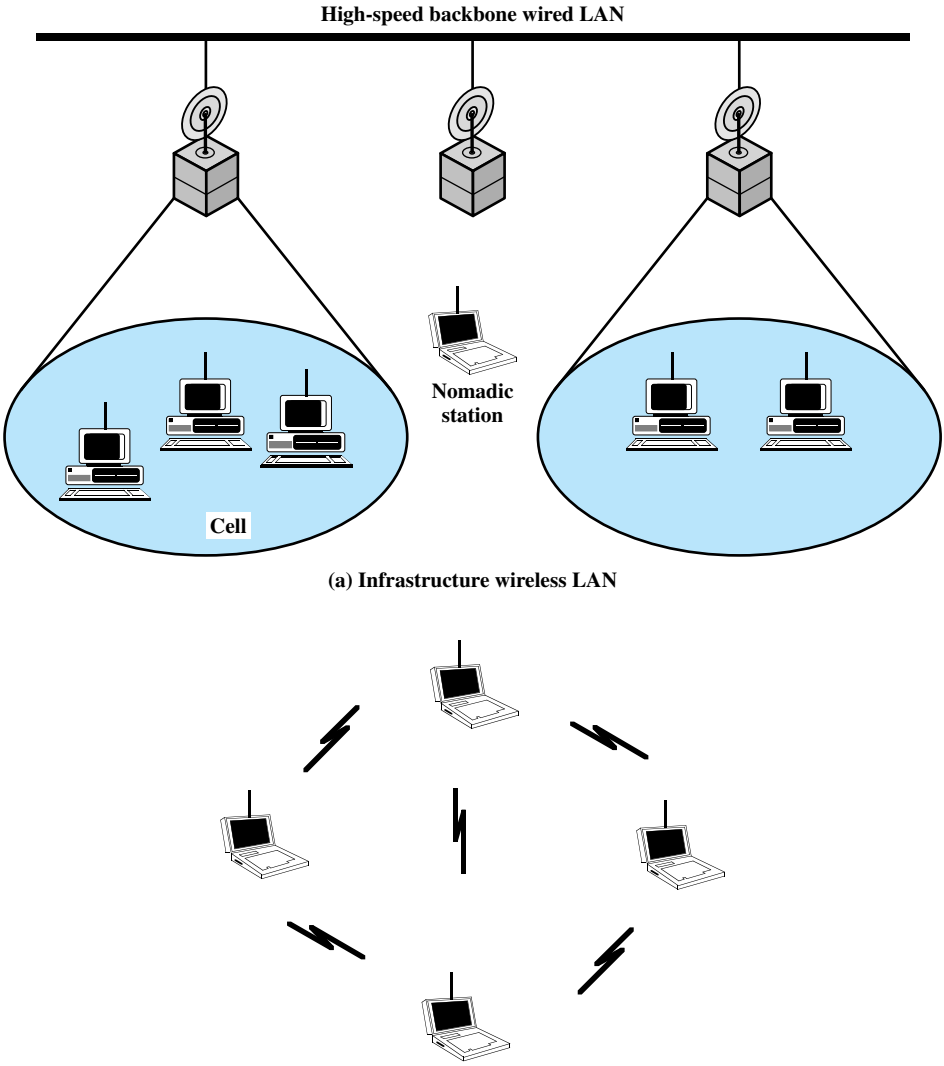


Figure 17.3 Wireless LAN Configurations

requirements specific to the wireless LAN environment. The following are among the most important requirements for wireless LANs:

- **Throughput:** The medium access control protocol should make as efficient use as possible of the wireless medium to maximize capacity.
- **Number of nodes:** Wireless LANs may need to support hundreds of nodes across multiple cells.
- **Connection to backbone LAN:** In most cases, interconnection with stations on a wired backbone LAN is required. For infrastructure wireless LANs, this is easily accomplished through the use of control modules that connect to both

types of LANs. There may also need to be accommodation for mobile users and ad hoc wireless networks.

- **Service area:** A typical coverage area for a wireless LAN has a diameter of 100 to 300 m.
- **Battery power consumption:** Mobile workers use battery-powered workstations that need to have a long battery life when used with wireless adapters. This suggests that a MAC protocol that requires mobile nodes to monitor access points constantly or engage in frequent handshakes with a base station is inappropriate. Typical wireless LAN implementations have features to reduce power consumption while not using the network, such as a sleep mode.
- **Transmission robustness and security:** Unless properly designed, a wireless LAN may be especially vulnerable to interference and eavesdropping. The design of a wireless LAN must permit reliable transmission even in a noisy environment and should provide some level of security from eavesdropping.
- **Collocated network operation:** As wireless LANs become more popular, it is quite likely for two or more wireless LANs to operate in the same area or in some area where interference between the LANs is possible. Such interference may thwart the normal operation of a MAC algorithm and may allow unauthorized access to a particular LAN.
- **License-free operation:** Users would prefer to buy and operate wireless LAN products without having to secure a license for the frequency band used by the LAN.
- **Handoff/roaming:** The MAC protocol used in the wireless LAN should enable mobile stations to move from one cell to another.
- **Dynamic configuration:** The MAC addressing and network management aspects of the LAN should permit dynamic and automated addition, deletion, and relocation of end systems without disruption to other users.

17.2 WIRELESS LAN TECHNOLOGY

Wireless LANs are generally categorized according to the transmission technique that is used. All current wireless LAN products fall into one of the following categories:

- **Infrared (IR) LANs:** An individual cell of an IR LAN is limited to a single room, because infrared light does not penetrate opaque walls.
- **Spread spectrum LANs:** This type of LAN makes use of spread spectrum transmission technology. In most cases, these LANs operate in the ISM (industrial, scientific, and medical) microwave bands so that no Federal Communications Commission (FCC) licensing is required for their use in the United States.

Infrared LANs

Optical wireless communication in the infrared portion of the spectrum is commonplace in most homes, where it is used for a variety of remote control devices.

More recently, attention has turned to the use of infrared technology to construct wireless LANs. In this section, we begin with a comparison of the characteristics of infrared LANs with those of radio LANs and then look at some of the details of infrared LANs.

Strengths and Weaknesses Infrared offers a number of significant advantages over microwave approaches. The spectrum for infrared is virtually unlimited, which presents the possibility of achieving extremely high data rates. The infrared spectrum is unregulated worldwide, which is not true of some portions of the microwave spectrum.

In addition, infrared shares some properties of visible light that make it attractive for certain types of LAN configurations. Infrared light is diffusely reflected by light-colored objects; thus it is possible to use ceiling reflection to achieve coverage of an entire room. Infrared light does not penetrate walls or other opaque objects. This has two advantages: First, infrared communications can be more easily secured against eavesdropping than microwave; and second, a separate infrared installation can be operated in every room in a building without interference, enabling the construction of very large infrared LANs.

Another strength of infrared is that the equipment is relatively inexpensive and simple. Infrared data transmission typically uses intensity modulation, so that IR receivers need to detect only the amplitude of optical signals, whereas most microwave receivers must detect frequency or phase.

The infrared medium also exhibits some drawbacks. Many indoor environments experience rather intense infrared background radiation, from sunlight and indoor lighting. This ambient radiation appears as noise in an infrared receiver, requiring the use of transmitters of higher power than would otherwise be required and also limiting the range. However, increases in transmitter power are limited by concerns of eye safety and excessive power consumption.

Transmission Techniques Three alternative transmission techniques are in common use for IR data transmission: the transmitted signal can be focused and aimed (as in a remote TV control); it can be radiated omnidirectionally; or it can be reflected from a light-colored ceiling.

Directed-beam IR can be used to create point-to-point links. In this mode, the range depends on the emitted power and on the degree of focusing. A focused IR data link can have a range of kilometers. Such ranges are not needed for constructing indoor wireless LANs. However, an IR link can be used for cross-building interconnect between bridges or routers located in buildings within a line of sight of each other.

One indoor use of point-to-point IR links is to set up a ring LAN. A set of IR transceivers can be positioned so that data circulate around them in a ring configuration. Each transceiver supports a workstation or a hub of stations, with the hub providing a bridging function.

An **omnidirectional configuration** involves a single base station that is within line of sight of all other stations on the LAN. Typically, this station is mounted on the ceiling. The base station acts as a multiport repeater. The ceiling transmitter broadcasts an omnidirectional signal that can be received by all of the other IR transceivers in the area. These other transceivers transmit a directional beam aimed at the ceiling base unit.

In a **diffused** configuration, all of the IR transmitters are focused and aimed at a point on a diffusely reflecting ceiling. IR radiation striking the ceiling is reradiated omnidirectionally and picked up by all of the receivers in the area.

Spread Spectrum LANs

Currently, the most popular type of wireless LAN uses spread spectrum techniques.

Configuration Except for quite small offices, a spread spectrum wireless LAN makes use of a multiple-cell arrangement, as was illustrated in Figure 17.2. Adjacent cells make use of different center frequencies within the same band to avoid interference.

Within a given cell, the topology can be either hub or peer to peer. The hub topology is indicated in Figure 17.2. In a hub topology, the hub is typically mounted on the ceiling and connected to a backbone wired LAN to provide connectivity to stations attached to the wired LAN and to stations that are part of wireless LANs in other cells. The hub may also control access, as in the IEEE 802.11 point coordination function, described subsequently. The hub may also control access by acting as a multiport repeater with similar functionality to Ethernet multiport repeaters. In this case, all stations in the cell transmit only to the hub and receive only from the hub. Alternatively, and regardless of access control mechanism, each station may broadcast using an omnidirectional antenna so that all other stations in the cell may receive; this corresponds to a logical bus configuration.

One other potential function of a hub is automatic handoff of mobile stations. At any time, a number of stations are dynamically assigned to a given hub based on proximity. When the hub senses a weakening signal, it can automatically hand off to the nearest adjacent hub.

A peer-to-peer topology is one in which there is no hub. A MAC algorithm such as CSMA is used to control access. This topology is appropriate for ad hoc LANs.

Transmission Issues A desirable, though not necessary, characteristic of a wireless LAN is that it be usable without having to go through a licensing procedure. The licensing regulations differ from one country to another, which complicates this objective. Within the United States, the FCC has authorized two unlicensed applications within the ISM band: spread spectrum systems, which can operate at up to 1 watt, and very low power systems, which can operate at up to 0.5 watts. Since the FCC opened up this band, its use for spread spectrum wireless LANs has become popular.

In the United States, three microwave bands have been set aside for unlicensed spread spectrum use: 902–928 MHz (915-MHz band), 2.4–2.4835 GHz (2.4-GHz band), and 5.725–5.825 GHz (5.8-GHz band). Of these, the 2.4 GHz is also used in this manner in Europe and Japan. The higher the frequency, the higher the potential bandwidth, so the three bands are of increasing order of attractiveness from a capacity point of view. In addition, the potential for interference must be considered. There are a number of devices that operate at around 900 MHz, including cordless telephones, wireless microphones, and amateur radio. There are fewer devices operating at 2.4 GHz; one notable example is the microwave oven, which tends to have greater leakage of radiation with increasing age. At present there is little competition at the 5.8-GHz-band; however, the higher the frequency band, in general the more expensive the equipment.

17.3 IEEE 802.11 ARCHITECTURE AND SERVICES

In 1990, the IEEE 802 Committee formed a new working group, IEEE 802.11, specifically devoted to wireless LANs, with a charter to develop a MAC protocol and physical medium specification. The initial interest was in developing a wireless LAN operating in the ISM (industrial, scientific, and medical) band. Since that time, the demand for WLANs, at different frequencies and data rates, has exploded. Keeping pace with this demand, the IEEE 802.11 working group has issued an ever-expanding list of standards (Table 17.1). Table 17.2 briefly defines key terms used in the IEEE 802.11 standard.

Table 17.1 IEEE 802.11 Standards

Standard	Scope
IEEE 802.11	Medium access control (MAC): One common MAC for WLAN applications
	Physical layer: Infrared at 1 and 2 Mbps
	Physical layer: 2.4-GHz FHSS at 1 and 2 Mbps
	Physical layer: 2.4-GHz DSSS at 1 and 2 Mbps
IEEE 802.11a	Physical layer: 5-GHz OFDM at rates from 6 to 54 Mbps
IEEE 802.11b	Physical layer: 2.4-GHz DSSS at 5.5 and 11 Mbps
IEEE 802.11c	Bridge operation at 802.11 MAC layer
IEEE 802.11d	Physical layer: Extend operation of 802.11 WLANs to new regulatory domains (countries)
IEEE 802.11e	MAC: Enhance to improve quality of service and enhance security mechanisms
IEEE 802.11f	Recommended practices for multivendor access point interoperability
IEEE 802.11g	Physical layer: Extend 802.11b to data rates >20 Mbps
IEEE 802.11h	Physical/MAC: Enhance IEEE 802.11a to add indoor and outdoor channel selection and to improve spectrum and transmit power management
IEEE 802.11i	MAC: Enhance security and authentication mechanisms
IEEE 802.11j	Physical: Enhance IEEE 802.11a to conform to Japanese requirements
IEEE 802.11k	Radio resource measurement enhancements to provide interface to higher layers for radio and network measurements
IEEE 802.11m	Maintenance of IEEE 802.11-1999 standard with technical and editorial corrections
IEEE 802.11n	Physical/MAC: Enhancements to enable higher throughput
IEEE 802.11p	Physical/MAC: Wireless access in vehicular environments
IEEE 802.11r	Physical/MAC: Fast roaming (fast BSS transition)
IEEE 802.11s	Physical/MAC: ESS mesh networking
IEEE 802.11,2	Recommended practice for the evaluation of 802.11 wireless performance
IEEE 802.11u	Physical/MAC: Interworking with external networks

Table 17.2 IEEE 802.11 Terminology

Access point (AP)	Any entity that has station functionality and provides access to the distribution system via the wireless medium for associated stations
Basic service set (BSS)	A set of stations controlled by a single coordination function
Coordination function	The logical function that determines when a station operating within a BSS is permitted to transmit and may be able to receive PDUs
Distribution system DS	A system used to interconnect a set of BSSs and integrated LANs to create an (ESS)
Extended service set (ESS)	A set of one or more interconnected BSSs and integrated LANs that appear as a single BSS to the LLC layer at any station associated with one of these BSSs
MAC protocol data unit (MPDU)	The unit of data exchanged between two peer MAC entites using the services of the physical layer
MAC service data unit (MSDU)	Information that is delivered as a unit between MAC users
Station	Any device that contains an IEEE 802.11 conformant MAC and physical layer

The Wi-Fi Alliance

The first 802.11 standard to gain broad industry acceptance was 802.11b. Although 802.11b products are all based on the same standard, there is always a concern whether products from different vendors will successfully interoperate. To meet this concern, the Wireless Ethernet Compatibility Alliance (WECA), an industry consortium, was formed in 1999. This organization, subsequently renamed the Wi-Fi (Wireless Fidelity) Alliance, created a test suite to certify interoperability for 802.11b products. The term used for certified 802.11b products is *Wi-Fi.* Wi-Fi certification has been extended to 802.11g products,. The Wi-Fi Alliance has also developed a certification process for 802.11a products, called *Wi-Fi5.* The Wi-Fi Alliance is concerned with a range of market areas for WLANs, including enterprise, home, and hot spots.

IEEE 802.11 Architecture

Figure 17.4 illustrates the model developed by the 802.11 working group. The smallest building block of a wireless LAN is a **basic service set (BSS)**, which consists of some number of stations executing the same MAC protocol and competing for access to the same shared wireless medium. A BSS may be isolated or it may connect to a backbone **distribution system (DS)** through an **access point (AP)**. The AP functions as a bridge and a relay point. In a BSS, client stations do not communicate directly with one another. Rather, if one station in the BSS wants to communicate with another station in the same BSS, the MAC frame is first sent from the originating station to the AP, and then from the AP to the destination station. Similarly, a MAC frame from a station in the BSS to a remote station is sent from the local station to the AP and then relayed by the AP over the DS on its way to the destination station. The BSS generally corresponds to what is referred to as a cell in the literature. The DS can be a switch, a wired network, or a wireless network.

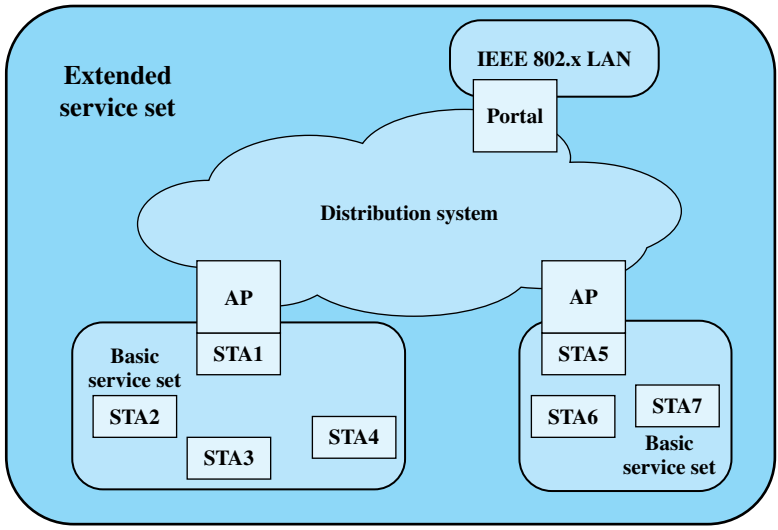


Figure 17.4 IEEE 802.11 Architecture

When all the stations in the BSS are mobile stations, with no connection to other BSSs, the BSS is called an **independent BSS (IBSS)**. An IBSS is typically an ad hoc network. In an IBSS, the stations all communicate directly, and no AP is involved.

A simple configuration is shown in Figure 17.4, in which each station belongs to a single BSS; that is, each station is within wireless range only of other stations within the same BSS. It is also possible for two BSSs to overlap geographically, so that a single station could participate in more than one BSS. Further, the association between a station and a BSS is dynamic. Stations may turn off, come within range, and go out of range.

An **extended service set (ESS)** consists of two or more basic service sets interconnected by a distribution system. Typically, the distribution system is a wired backbone LAN but can be any communications network. The extended service set appears as a single logical LAN to the logical link control (LLC) level.

Figure 17.4 indicates that an access point (AP) is implemented as part of a station; the AP is the logic within a station that provides access to the DS by providing DS services in addition to acting as a station. To integrate the IEEE 802.11 architecture with a traditional wired LAN, a **portal** is used. The portal logic is implemented in a device, such as a bridge or router, that is part of the wired LAN and that is attached to the DS.

IEEE 802.11 Services

IEEE 802.11 defines nine services that need to be provided by the wireless LAN to provide functionality equivalent to that which is inherent to wired LANs. Table 17.3 lists the services and indicates two ways of categorizing them.

Table 17.3 IEEE 802.11 Services

Service	Provider	Used to Support
Association	Distribution system	MSDU delivery
Authentication	Station	LAN access and security
Deauthentication	Station	LAN access and security
Dissassociation	Distribution system	MSDU delivery
Distribution	Distribution system	MSDU delivery
Integration	Distribution system	MSDU delivery
MSDU delivery	Station	MSDU delivery
Privacy	Station	LAN access and security
Reassocation	Distribution system	MSDU delivery

1. The service provider can be either the station or the DS. Station services are implemented in every 802.11 station, including AP stations. Distribution services are provided between BSSs; these services may be implemented in an AP or in another special-purpose device attached to the distribution system.
2. Three of the services are used to control IEEE 802.11 LAN access and confidentiality. Six of the services are used to support delivery of MAC service data units (MSDUs) between stations. The MSDU is a block of data passed down from the MAC user to the MAC layer; typically this is a LLC PDU. If the MSDU is too large to be transmitted in a single MAC frame, it may be fragmented and transmitted in a series of MAC frames. Fragmentation is discussed in Section 17.4.

Following the IEEE 802.11 document, we next discuss the services in an order designed to clarify the operation of an IEEE 802.11 ESS network. **MSDU delivery**, which is the basic service, has already been mentioned. Services related to security are discussed in Section17.6.

Distribution of Messages within a DS The two services involved with the distribution of messages within a DS are distribution and integration. **Distribution** is the primary service used by stations to exchange MAC frames when the frame must traverse the DS to get from a station in one BSS to a station in another BSS. For example, suppose a frame is to be sent from station 2 (STA 2) to STA 7 in Figure 17.4. The frame is sent from STA 2 to STA 1, which is the AP for this BSS. The AP gives the frame to the DS, which has the job of directing the frame to the AP associated with STA 5 in the target BSS. STA 5 receives the frame and forwards it to STA 7. How the message is transported through the DS is beyond the scope of the IEEE 802.11 standard.

If the two stations that are communicating are within the same BSS, then the distribution service logically goes through the single AP of that BSS.

The **integration** service enables transfer of data between a station on an IEEE 802.11 LAN and a station on an integrated IEEE 802.x LAN. The term *integrated*

refers to a wired LAN that is physically connected to the DS and whose stations may be logically connected to an IEEE 802.11 LAN via the integration service. The integration service takes care of any address translation and media conversion logic required for the exchange of data.

Association-Related Services The primary purpose of the MAC layer is to transfer MSDUs between MAC entities; this purpose is fulfilled by the distribution service. For that service to function, it requires information about stations within the ESS that is provided by the association-related services. Before the distribution service can deliver data to or accept data from a station, that station must be *associated.* Before looking at the concept of association, we need to describe the concept of mobility. The standard defines three transition types, based on mobility:

- **No transition:** A station of this type is either stationary or moves only within the direct communication range of the communicating stations of a single BSS.
- **BSS transition:** This is defined as a station movement from one BSS to another BSS within the same ESS. In this case, delivery of data to the station requires that the addressing capability be able to recognize the new location of the station.
- **ESS transition:** This is defined as a station movement from a BSS in one ESS to a BSS within another ESS. This case is supported only in the sense that the station can move. Maintenance of upper-layer connections supported by 802.11 cannot be guaranteed. In fact, disruption of service is likely to occur.

To deliver a message within a DS, the distribution service needs to know where the destination station is located. Specifically, the DS needs to know the identity of the AP to which the message should be delivered in order for that message to reach the destination station. To meet this requirement, a station must maintain an association with the AP within its current BSS. Three services relate to this requirement:

- **Association:** Establishes an initial association between a station and an AP. Before a station can transmit or receive frames on a wireless LAN, its identity and address must be known. For this purpose, a station must establish an association with an AP within a particular BSS. The AP can then communicate this information to other APs within the ESS to facilitate routing and delivery of addressed frames.
- **Reassociation:** Enables an established association to be transferred from one AP to another, allowing a mobile station to move from one BSS to another.
- **Disassociation:** A notification from either a station or an AP that an existing association is terminated. A station should give this notification before leaving an ESS or shutting down. However, the MAC management facility protects itself against stations that disappear without notification.

17.4 IEEE 802.11 MEDIUM ACCESS CONTROL

The IEEE 802.11 MAC layer covers three functional areas: reliable data delivery, access control, and security. This section covers the first two topics.

Reliable Data Delivery

As with any wireless network, a wireless LAN using the IEEE 802.11 physical and MAC layers is subject to considerable unreliability. Noise, interference, and other propagation effects result in the loss of a significant number of frames. Even with error correction codes, a number of MAC frames may not successfully be received. This situation can be dealt with by reliability mechanisms at a higher layer, such as TCP. However, timers used for retransmission at higher layers are typically on the order of seconds. It is therefore more efficient to deal with errors at the MAC level. For this purpose, IEEE 802.11 includes a frame exchange protocol. When a station receives a data frame from another station, it returns an acknowledgment (ACK) frame to the source station. This exchange is treated as an atomic unit, not to be interrupted by a transmission from any other station. If the source does not receive an ACK within a short period of time, either because its data frame was damaged or because the returning ACK was damaged, the source retransmits the frame.

Thus, the basic data transfer mechanism in IEEE 802.11 involves an exchange of two frames. To further enhance reliability, a four-frame exchange may be used. In this scheme, a source first issues a Request to Send (RTS) frame to the destination. The destination then responds with a Clear to Send (CTS). After receiving the CTS, the source transmits the data frame, and the destination responds with an ACK. The RTS alerts all stations that are within reception range of the source that an exchange is under way; these stations refrain from transmission in order to avoid a collision between two frames transmitted at the same time. Similarly, the CTS alerts all stations that are within reception range of the destination that an exchange is under way. The RTS/CTS portion of the exchange is a required function of the MAC but may be disabled.

Medium Access Control

The 802.11 working group considered two types of proposals for a MAC algorithm: distributed access protocols, which, like Ethernet, distribute the decision to transmit over all the nodes using a carrier sense mechanism; and centralized access protocols, which involve regulation of transmission by a centralized decision maker. A distributed access protocol makes sense for an ad hoc network of peer workstations (typically an IBSS) and may also be attractive in other wireless LAN configurations that consist primarily of bursty traffic. A centralized access protocol is natural for configurations in which a number of wireless stations are interconnected with each other and some sort of base station that attaches to a backbone wired LAN; it is especially useful if some of the data is time sensitive or high priority.

The end result for 802.11 is a MAC algorithm called DFWMAC (distributed foundation wireless MAC) that provides a distributed access control mechanism with an optional centralized control built on top of that. Figure 17.5 illustrates the architecture. The lower sublayer of the MAC layer is the distributed coordination function (DCF). DCF uses a contention algorithm to provide access to all traffic. Ordinary asynchronous traffic directly uses DCF. The point coordination function (PCF) is a centralized MAC algorithm used to provide contention-free service. PCF is built on top of DCF and exploits features of DCF to assure access for its users. Let us consider these two sublayers in turn.

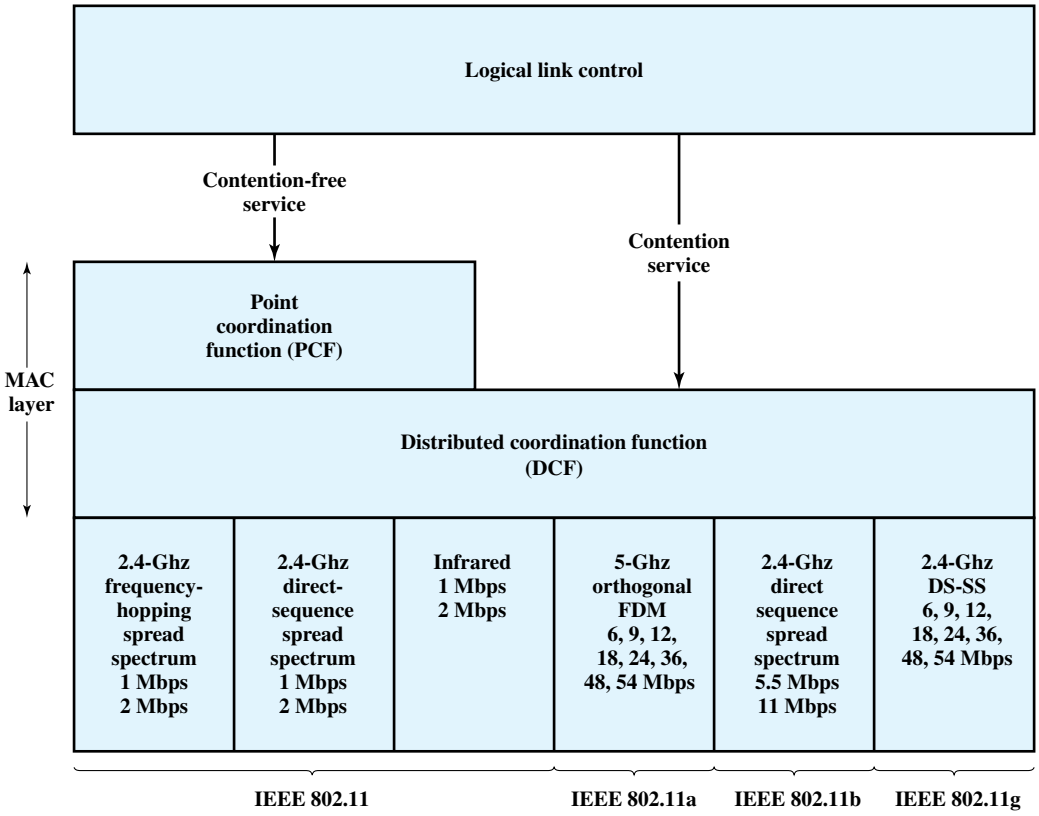


Figure 17.5 IEEE 802.11 Protocol Architecture

Distributed Coordination Function The DCF sublayer makes use of a simple CSMA (carrier sense multiple access) algorithm. If a station has a MAC frame to transmit, it listens to the medium. If the medium is idle, the station may transmit; otherwise the station must wait until the current transmission is complete before transmitting. The DCF does not include a collision detection function (i.e., CSMA/CD) because collision detection is not practical on a wireless network. The dynamic range of the signals on the medium is very large, so that a transmitting station cannot effectively distinguish incoming weak signals from noise and the effects of its own transmission.

To ensure the smooth and fair functioning of this algorithm, DCF includes a set of delays that amounts to a priority scheme. Let us start by considering a single delay known as an interframe space (IFS). In fact, there are three different IFS values, but the algorithm is best explained by initially ignoring this detail. Using an IFS, the rules for CSMA access are as follows (Figure 17.6):

1. A station with a frame to transmit senses the medium. If the medium is idle, it waits to see if the medium remains idle for a time equal to IFS. If so, the station may transmit immediately.

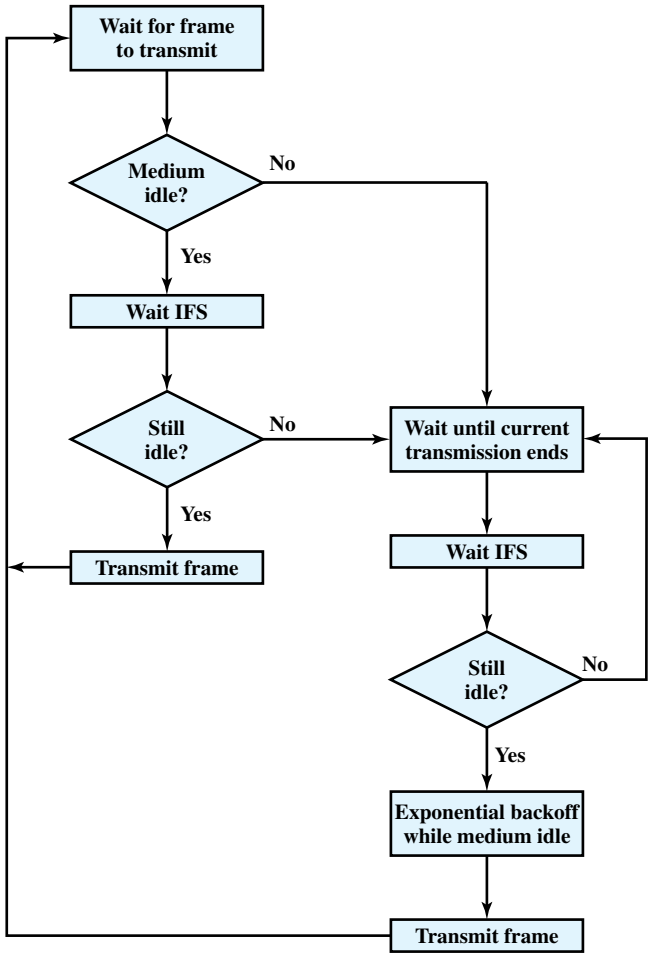


Figure 17.6 IEEE 802.11 Medium Access Control Logic

2. If the medium is busy (either because the station initially finds the medium busy or because the medium becomes busy during the IFS idle time), the station defers transmission and continues to monitor the medium until the current transmission is over.
3. Once the current transmission is over, the station delays another IFS. If the medium remains idle for this period, then the station backs off a random amount of time and again senses the medium. If the medium is still idle, the station may transmit. During the backoff time, if the medium becomes busy, the backoff timer is halted and resumes when the medium becomes idle.
4. If the transmission is unsuccessful, which is determined by the absence of an acknowledgement, then it is assumed that a collision has occurred.

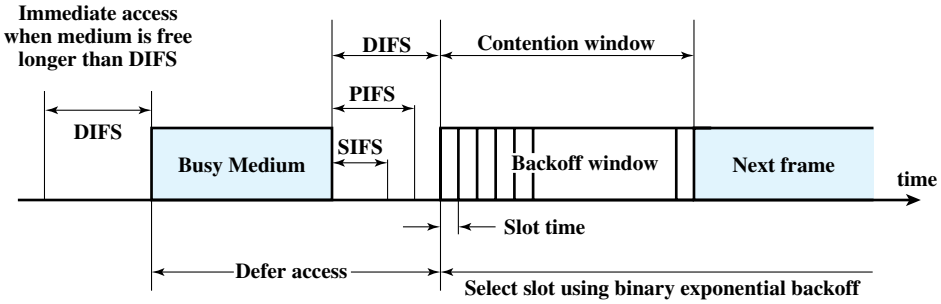
To ensure that backoff maintains stability, binary exponential backoff, described in Chapter 16, is used. Binary exponential backoff provides a means of

handling a heavy load. Repeated failed attempts to transmit result in longer and longer backoff times, which helps to smooth out the load. Without such a backoff, the following situation could occur: Two or more stations attempt to transmit at the same time, causing a collision. These stations then immediately attempt to retransmit, causing a new collision.

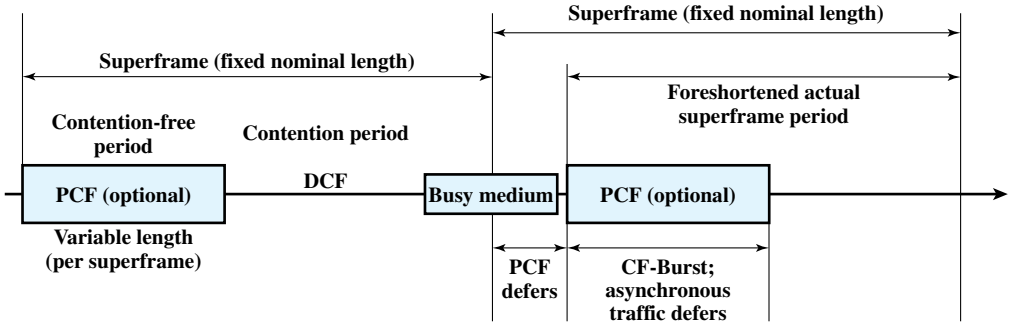
The preceding scheme is refined for DCF to provide priority-based access by the simple expedient of using three values for IFS:

- **SIFS (short IFS):** The shortest IFS, used for all immediate response actions, as explained in the following discussion
- **PIFS (point coordination function IFS):** A midlength IFS, used by the centralized controller in the PCF scheme when issuing polls
- **DIFS (distributed coordination function IFS):** The longest IFS, used as a minimum delay for asynchronous frames contending for access

Figure 17.7a illustrates the use of these time values. Consider first the SIFS. Any station using SIFS to determine transmission opportunity has, in effect, the highest priority, because it will always gain access in preference to a station waiting an amount of time equal to PIFS or DIFS. The SIFS is used in the following circumstances:



(a) Basic access method



(b) PCF superframe construction

Figure 17.7 IEEE 802.11 MAC Timing

- **Acknowledgment (ACK):** When a station receives a frame addressed only to itself (not multicast or broadcast), it responds with an ACK frame after waiting only for an SIFS gap. This has two desirable effects. First, because collision detection is not used, the likelihood of collisions is greater than with CSMA/CD, and the MAC-level ACK provides for efficient collision recovery. Second, the SIFS can be used to provide efficient delivery of an LLC protocol data unit (PDU) that requires multiple MAC frames. In this case, the following scenario occurs. A station with a multiframe LLC PDU to transmit sends out the MAC frames one at a time. Each frame is acknowledged by the recipient after SIFS. When the source receives an ACK, it immediately (after SIFS) sends the next frame in the sequence. The result is that once a station has contended for the channel, it will maintain control of the channel until it has sent all of the fragments of an LLC PDU.
- **Clear to Send (CTS):** A station can ensure that its data frame will get through by first issuing a small Request to Send (RTS) frame. The station to which this frame is addressed should immediately respond with a CTS frame if it is ready to receive. All other stations receive the RTS and defer using the medium.
- **Poll response:** This is explained in the following discussion of PCF.

The next longest IFS interval is the PIFS. This is used by the centralized controller in issuing polls and takes precedence over normal contention traffic. However, those frames transmitted using SIFS have precedence over a PCF poll.

Finally, the DIFS interval is used for all ordinary asynchronous traffic.

Point Coordination Function PCF is an alternative access method implemented on top of the DCF. The operation consists of polling by the centralized polling master (point coordinator). The point coordinator makes use of PIFS when issuing polls. Because PIFS is smaller than DIFS, the point coordinator can seize the medium and lock out all asynchronous traffic while it issues polls and receives responses.

As an extreme, consider the following possible scenario. A wireless network is configured so that a number of stations with time-sensitive traffic are controlled by the point coordinator while remaining traffic contends for access using CSMA. The point coordinator could issue polls in a round-robin fashion to all stations configured for polling. When a poll is issued, the polled station may respond using SIFS. If the point coordinator receives a response, it issues another poll using PIFS. If no response is received during the expected turnaround time, the coordinator issues a poll.

If the discipline of the preceding paragraph were implemented, the point coordinator would lock out all asynchronous traffic by repeatedly issuing polls. To prevent this, an interval known as the superframe is defined. During the first part of this interval, the point coordinator issues polls in a round-robin fashion to all stations configured for polling. The point coordinator then idles for the remainder of the superframe, allowing a contention period for asynchronous access.

Figure 17.7b illustrates the use of the superframe. At the beginning of a superframe, the point coordinator may optionally seize control and issue polls for a given period of time. This interval varies because of the variable frame size issued by responding stations. The remainder of the superframe is available for contention-based access. At the end of the superframe interval, the point coordinator contends

FC = Frame control
D/I = Duration/connection ID
SC = Sequence control

Figure 17.8 IEEE 802.11 MAC Frame Format

for access to the medium using PIFS. If the medium is idle, the point coordinator gains immediate access and a full superframe period follows. However, the medium may be busy at the end of a superframe. In this case, the point coordinator must wait until the medium is idle to gain access; this results in a foreshortened superframe period for the next cycle.

MAC Frame

Figure 17.8 shows the 802.11 frame format. This general format is used for all data and control frames, but not all fields are used in all contexts. The fields are as follows:

- **Frame Control:** Indicates the type of frame (control, management, or data) and provides control information. Control information includes whether the frame is to or from a DS, fragmentation information, and privacy information.
- **Duration/Connection ID:** If used as a duration field, indicates the time (in microseconds) the channel will be allocated for successful transmission of a MAC frame. In some control frames, this field contains an association, or connection, identifier.
- **Addresses:** The number and meaning of the 48-bit address fields depend on context. The **transmitter address** and **receiver address** are the MAC addresses of stations joined to the BSS that are transmitting and receiving frames over the wireless LAN. The **service set ID** (SSID) identifies the wireless LAN over which a frame is transmitted. For an IBSS, the SSID is a random number generated at the time the network is formed. For a wireless LAN that is part of a larger configuration the SSID identifies the BSS over which the frame is transmitted; specifically, the SSID is the MAC-level address of the AP for this BSS (Figure 17.4). Finally the **source address** and **destination address** are the MAC addresses of stations, wireless or otherwise, that are the ultimate source and destination of this frame. The source address may be identical to the transmitter address and the destination address may be identical to the receiver address.
- **Sequence Control:** Contains a 4-bit fragment number subfield, used for fragmentation and reassembly, and a 12-bit sequence number used to number frames sent between a given transmitter and receiver.
- **Frame Body:** Contains an MSDU or a fragment of an MSDU. The MSDU is a LLC protocol data unit or MAC control information.
- **Frame Check Sequence:** A 32-bit cyclic redundancy check.

We now look at the three MAC frame types.

Control Frames Control frames assist in the reliable delivery of data frames. There are six control frame subtypes:

- **Power Save-Poll (PS-Poll):** This frame is sent by any station to the station that includes the AP (access point). Its purpose is to request that the AP transmit a frame that has been buffered for this station while the station was in power-saving mode.
- **Request to Send (RTS):** This is the first frame in the four-way frame exchange discussed under the subsection on reliable data delivery at the beginning of Section 17.3. The station sending this message is alerting a potential destination, and all other stations within reception range, that it intends to send a data frame to that destination.
- **Clear to Send (CTS):** This is the second frame in the four-way exchange. It is sent by the destination station to the source station to grant permission to send a data frame.
- **Acknowledgment:** Provides an acknowledgment from the destination to the source that the immediately preceding data, management, or PS-Poll frame was received correctly.
- **Contention-Free (CF)-end:** Announces the end of a contention-free period that is part of the point coordination function.
- **CF-End + CF-Ack:** Acknowledges the CF-end. This frame ends the contention-free period and releases stations from the restrictions associated with that period.

Data Frames There are eight data frame subtypes, organized into two groups. The first four subtypes define frames that carry upper-level data from the source station to the destination station. The four data-carrying frames are as follows:

- **Data:** This is the simplest data frame. It may be used in both a contention period and a contention-free period.
- **Data + CF-Ack:** May only be sent during a contention-free period. In addition to carrying data, this frame acknowledges previously received data.
- **Data + CF-Poll:** Used by a point coordinator to deliver data to a mobile station and also to request that the mobile station send a data frame that it may have buffered.
- **Data + CF-Ack + CF-Poll:** Combines the functions of the Data + CF-Ack and Data + CF-Poll into a single frame.

The remaining four subtypes of data frames do not in fact carry any user data. The Null Function data frame carries no data, polls, or acknowledgments. It is used only to carry the power management bit in the frame control field to the AP, to indicate that the station is changing to a low-power operating state. The remaining three frames (CF-Ack, CF-Poll, CF-Ack + CF-Poll) have the same functionality as the corresponding data frame subtypes in the preceding list (Data + CF-Ack, Data + CF-Poll, Data + CF-Ack + CF-Poll) but without the data.

Management Frames Management frames are used to manage communications between stations and APs. Functions covered include management of associations (request, response, reassociation, dissociation, and authentication).

17.5 IEEE 802.11 PHYSICAL LAYER

The physical layer for IEEE 802.11 has been issued in four stages. The first part, simply called **IEEE 802.11**, includes the MAC layer and three physical layer specifications, two in the 2.4-GHz band (ISM) and one in the infrared, all operating at 1 and 2 Mbps. **IEEE 802.11a** operates in the 5-GHz band at data rates up to 54 Mbps. **IEEE 802.11b** operates in the 2.4-GHz band at 5.5 and 11 Mbps. **IEEE 802.11g** also operates in the 2.4-GHz band, at data rates up to 54 Mbps. Table 17.4 provides some details. We look at each of these in turn.

Original IEEE 802.11 Physical Layer

Three physical media are defined in the original 802.11 standard:

- **Direct sequence spread spectrum (DSSS)** operating in the 2.4-GHz ISM band, at data rates of 1 Mbps and 2 Mbps. In the United States, the FCC (Federal Communications Commission) requires no licensing for the use of this band. The number of channels available depends on the bandwidth allocated by the various national regulatory agencies. This ranges from 13 in most European countries to just one available channel in Japan.
- **Frequency-hopping spread spectrum (FHSS)** operating in the 2.4-GHz ISM band, at data rates of 1 Mbps and 2 Mbps. The number of channels available ranges from 23 in Japan to 70 in the United States.

Table 17.4 IEEE 802.11 Physical Layer Standards

	802.11	802.11a	802.11b	802.11g
Available bandwidth	83.5 MHz	300 MHz	83.5 MHz	83.5 MHz
Unlicensed frequency of operation	2.4–2.4835 GHz DSSS, FHSS	5.15–5.35 GHz OFDM 5.725–5.825 GHz OFDM	2.4–2.4835 GHz DSSS	2.4–2.4835 GHz DSSS, OFDM
Number of non-overlapping channels	3 (indoor/outdoor)	4 indoor 4 (indoor/outdoor) 4 outdoor	3 (indoor/outdoor)	3 (indoor/outdoor)
Data rate per channel	1, 2 Mbps	6, 9, 12, 18, 24, 36, 48, 54 Mbps	1, 2, 5.5, 11 Mbps	1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, 54 Mbps
Compatibility	802.11	Wi-Fi5	Wi-Fi	Wi-Fi at 11 Mbps and below

- **Infrared** at 1 Mbps and 2 Mbps operating at a wavelength between 850 and 950 nm

Direct Sequence Spread Spectrum Up to three nonoverlapping channels, each with a data rate of 1 Mbps or 2 Mbps, can be used in the DSSS scheme. Each channel has a bandwidth of 5 MHz. The encoding scheme that is used is DBPSK (differential binary phase shift keying) for the 1-Mbps rate and DQPSK for the 2-Mbps rate.

Recall from Chapter 9 that a DSSS system makes use of a chipping code, or pseudonoise sequence, to spread the data rate and hence the bandwidth of the signal. For IEEE 802.11, a Barker sequence is used.

A **Barker sequence** is a binary $\{-1, +1\}$ sequence $\{s(t)\}$ of length n with the property that its autocorrelation values $R(\tau)$ satisfy $|R(\tau)| \leq 1$ for all $|\tau| \leq (n - 1)$. Autocorrelation is defined by the following formula: $R(\tau) = \frac{1}{N} \sum_{k=1}^{N} B_k B_{k-\tau}$, where the B_i are the bits of the sequence.[1]
Further, the Barker property is preserved under the following transformations:

$$s(t) \rightarrow -s(t) \qquad s(t) \rightarrow (-1)^t s(t) \quad \text{and} \quad s(t) \rightarrow -s(n - 1 - t)$$

as well as under compositions of these transformations. Only the following Barker sequences are known:

$n = 2$ $+ +$
$n = 3$ $+ + -$
$n = 4$ $+ + + -$
$n = 5$ $+ + + - +$
$n = 7$ $+ + + - - + -$
$n = 11$ $+ - + + - + + + - - -$
$n = 13$ $+ + + + + - - + + - + - +$

IEEE 802.11 DSSS uses the 11-chip Barker sequence. Each data binary 1 is mapped into the sequence $\{+ - + + - + + + - - -\}$, and each binary 0 is mapped into the sequence $\{- + - - + - - - + + +\}$.

Important characteristics of Barker sequences are their robustness against interference and their insensitivity to multipath propagation.

Frequency-Hopping Spread Spectrum Recall from Chapter 9 that a FHSS system makes use of a multiple channels, with the signal hopping from one channel to another based on a pseudonoise sequence. In the case of the IEEE 802.11 scheme, 1-MHz channels are used.

The details of the hopping scheme are adjustable. For example, the minimum hop rate for the United States is 2.5 hops per second. The minimum

[1]See Appendix J for a discussion of correlation and orthogonality.

hop distance in frequency is 6 MHz in North America and most of Europe and 5 MHz in Japan.

For modulation, the FHSS scheme uses two-level Gaussian FSK for the 1-Mbps system. The bits zero and one are encoded as deviations from the current carrier frequency. For 2 Mbps, a four-level GFSK scheme is used, in which four different deviations from the center frequency define the four 2-bit combinations.

Infrared The IEEE 802.11 infrared scheme is omnidirectional rather than point to point. A range of up to 20 m is possible. The modulation scheme for the 1-Mbps data rate is known as 16-PPM (pulse position modulation). In pulse position modulation (PPM), the input value determines the position of a narrow pulse relative to the clocking time. The advantage of PPM is that it reduces the output power required of the infrared source. For 16-PPM, each group of 4 data bits is mapped into one of the 16-PPM symbols; each symbol is a string of 16 pulse positions. Each 16-pulse string consists of fifteen 0s and one binary 1. For the 2-Mbps data rate, each group of 2 data bits is mapped into one of four 4-pulse-position sequences. Each sequence consists of three 0s and one binary 1. The actual transmission uses an intensity modulation scheme, in which the presence of a signal corresponds to a binary 1 and the absence of a signal corresponds to binary 0.

IEEE 802.11a

Channel Structure IEEE 802.11a makes use of the frequency band called the Universal Networking Information Infrastructure (UNNI), which is divided into three parts. The UNNI-1 band (5.15 to 5.25 GHz) is intended for indoor use; the UNNI-2 band (5.25 to 5.35 GHz) can be used either indoor or outdoor, and the UNNI-3 band (5.725 to 5.825 GHz) is for outdoor use.

IEEE 80211.a has several advantages over IEEE 802.11b/g:

- IEEE 802.11a utilizes more available bandwidth than 802.11b/g. Each UNNI band provides four nonoverlapping channels for a total of 12 across the allocated spectrum.
- IEEE 802.11a provides much higher data rates than 802.11b and the same maximum data rate as 802.11g.
- IEEE 802.11a uses a different, relatively uncluttered frequency spectrum (5 GHz).

Coding and Modulation Unlike the 2.4-GHz specifications, IEEE 802.11 does not use a spread spectrum scheme but rather uses orthogonal frequency division multiplexing (OFDM). Recall from Section 11.2 that OFDM, also called multicarrier modulation, uses multiple carrier signals at different frequencies, sending some of the bits on each channel. This is similar to FDM. However, in the case of OFDM, all of the subchannels are dedicated to a single data source.

To complement OFDM, the specification supports the use of a variety of modulation and coding alternatives. The system uses up to 48 subcarriers that are modulated using BPSK, QPSK, 16-QAM, or 64-QAM. Subcarrier frequency

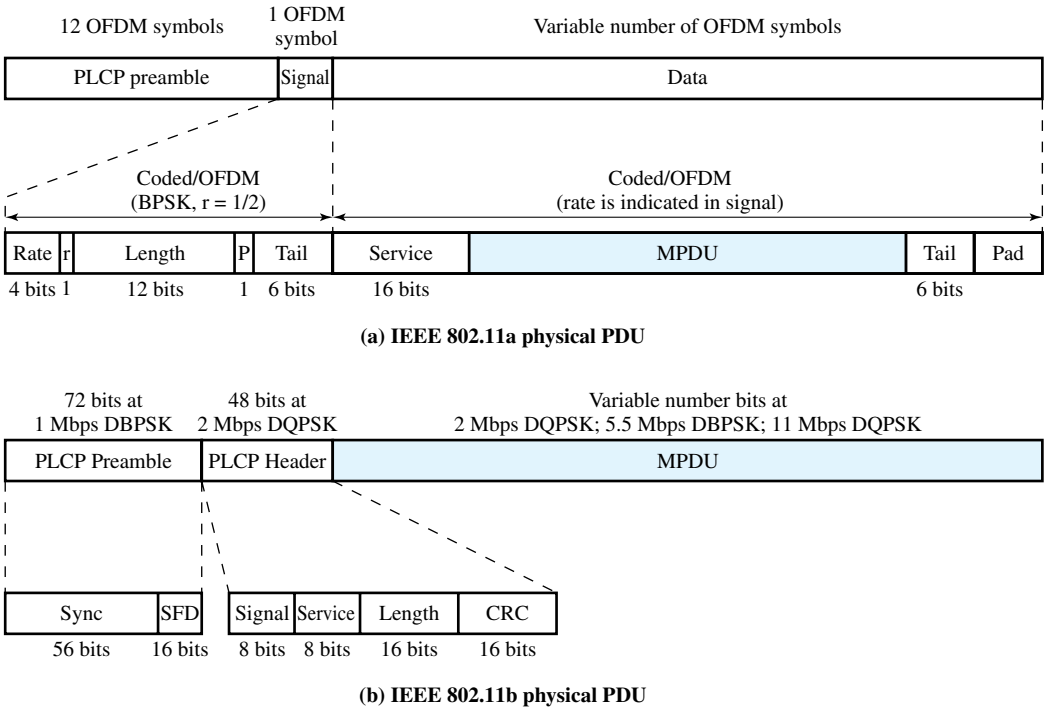


Figure 17.9 IEEE 802 Physical-Level Protocol Data Units

spacing is 0.3125 MHz., and each subcarrier transmits at a rate of 250 kbaud. A convolutional code at a rate of 1/2, 2/3, or 3/4 provides forward error correction. The combination of modulation technique and coding rate determines the data rate.

Physical-Layer Frame Structure The primary purpose of the physical layer is to transmit medium access control (MAC) protocol data units (MPDUs) as directed by the 802.11 MAC layer. The PLCP sublayer provides the framing and signaling bits needed for the OFDM transmission and the PDM sublayer performs the actual encoding and transmission operation.

Figure 17.9a illustrates the physical layer frame format. The **PLCP Preamble** field enables the receiver to acquire an incoming OFDM signal and synchronize the demodulator. Next is the **Signal** field, which consists of 24 bits encoded as a single OFDM symbol. The Preamble and Signal fields are transmitted at 6 Mbps using BPSK. The signal field consists of the following subfields:

- **Rate:** Specifies the data rate at which the data field portion of the frame is transmitted
- **r:** reserved for future use
- **Length:** Number of octets in the MAC PDU

- **P:** An even parity bit for the 17 bits in the Rate, r, and Length subfields
- **Tail:** Consists of 6 zero bits appended to the symbol to bring the convolutional encoder to zero state

The **Data** field consists of a variable number of OFDM symbols transmitted at the data rate specified in the Rate subfield. Prior to transmission, all of the bits of the Data field are scrambled (see Appendix 16C for a discussion of scrambling). The Data field consists of four subfields:

- **Service:** Consists of 16 bits, with the first 7 bits set to zeros to synchronize the descrambler in the receiver, and the remaining 9 bits (all zeros) reserved for future use.
- **MAC PDU:** Handed down from the MAC layer. The format is shown in Figure 17.8.
- **Tail:** Produced by replacing the six scrambled bits following the MPDU end with 6 bits of all zeros; used to reinitialize the convolutional encoder.
- **Pad:** The number of bits required to make the Data field a multiple of the number of bits in an OFDM symbol (48, 96, 192, or 288).

IEEE 802.11b

IEEE 802.11b is an extension of the IEEE 802.11 DSSS scheme, providing data rates of 5.5 and 11 Mbps in the ISM band. The chipping rate is 11 MHz, which is the same as the original DSSS scheme, thus providing the same occupied bandwidth. To achieve a higher data rate in the same bandwidth at the same chipping rate, a modulation scheme known as complementary code keying (CCK) is used.

The CCK modulation scheme is quite complex and is not examined in detail here. Figure 17.10 provides an overview of the scheme for the 11-Mbps rate. Input data are treated in blocks of 8 bits at a rate of 1.375 MHz (8 bits/symbol $\times$ 1.375 MHz = 11 Mbps). Six of these bits are mapped into one of 64 codes sequences derived from a 64 $\times$ 64 matrix known as the Walsh matrix

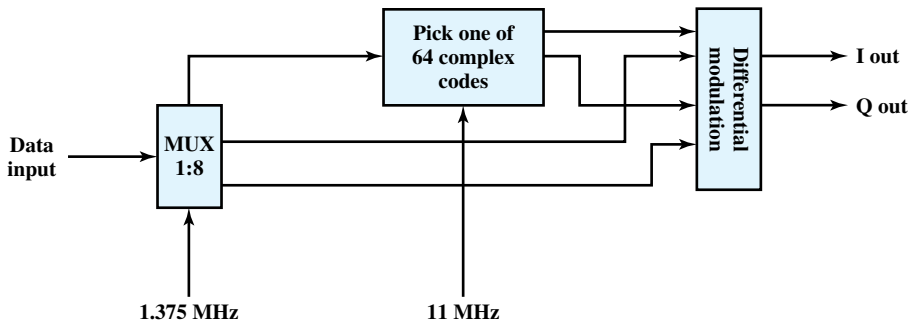


Figure 17.10 11-Mbps CCK Modulation Scheme

(discussed in [STAL05]). The output of the mapping, plus the two additional bits, forms the input to a QPSK modulator.

An optional alternative to CCK is known as packet binary convolutional coding (PBCC). PBCC provides for potentially more efficient transmission at the cost of increased computation at the receiver. PBCC was incorporated into 802.11b in anticipation of its need for higher data rates for future enhancements to the standard.

Physical-Layer Frame Structure IEEE 802.11b defines two physical-layer frame formats, which differ only in the length of the preamble. The long preamble of 144 bits is the same as used in the original 802.11 DSSS scheme and allows interoperability with other legacy systems. The short preamble of 72 bits provides improved throughput efficiency. Figure 17.9b illustrates the physical layer frame format with the short preamble. The **PLCP Preamble** field enables the receiver to acquire an incoming signal and synchronize the demodulator. It consists of two subfields: a 56-bit **Sync** field for synchronization, and a 16-bit start-of-frame delimiter (**SFD**). The preamble is transmitted at 1 Mbps using differential BPSK and Barker code spreading.

Following the preamble is the **PLCP Header**, which is transmitted at 2 Mbps using DQPSK. It consists of the following subfields:

- **Signal:** Specifies the data rate at which the MPDU portion of the frame is transmitted.
- **Service:** Only 3 bits of this 8-bit field are used in 802.11b. One bit indicates whether the transmit frequency and symbol clocks use the same local oscillator. Another bit indicates whether CCK or PBCC encoding is used. A third bit acts as an extension to the Length subfield.
- **Length:** Indicates the length of the MPDU field by specifying the number of microseconds necessary to transmit the MPDU. Given the data rate, the length of the MPDU in octets can be calculated. For any data rate over 8 Mbps, the length extension bit from the Service field is needed to resolve a rounding ambiguity.
- **CRC:** A 16-bit error detection code used to protect the Signal, Service, and Length fields.

The **MPDU** field consists of a variable number of bits transmitted at the data rate specified in the Signal subfield. Prior to transmission, all of the bits of the physical layer PDU are scrambled (see Appendix 16C for a discussion of scrambling).

IEEE 802.11g

IEEE 802.11g extends 802.11b to data rates above 20 Mbps, up to 54 Mbps. Like 802.11b, 802.11g operates in the 2.4-GHz range and thus the two are compatible. The standard is designed so that 802.11b devices will work when connected to an 802.11g AP, and 802.11g devices will work when connected to an 802.11b AP, in both cases using the lower 802.11b data rate.

Table 17.5 Estimated Distance (m) Versus Data Rate

Data Rate (Mbps)	802.11b	802.11a	802.11g
1	90+	—	90+
2	75	—	75
5.5(b)/6(a/g)	60	60+	65
9	—	50	55
11(b)/12(a/g)	50	45	50
18	—	40	50
24	—	30	45
36	—	25	35
48	—	15	25
54	—	10	20

IEEE 802.11g offers a wider array of data rate and modulation scheme options. IEEE 802.11g provides compatibility with 802.11 and 802.11b by specifying the same modulation and framing schemes as these standards for 1, 2, 5.5, and 11 Mbps. At data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps, 802.11g adopts the 802.11a OFDM scheme, adapted for the 2.4 GHz rate; this is referred to as ERP-OFDM, with ERP standing for extended rate physical layer. In addition, and ERP-PBCC scheme is used to provide data rates of 22 and 33 Mbps.

The IEEE 802.11 standards do not include a specification of speed versus distance objectives. Different vendors will give different values, depending on environment. Table 17.5, based on [LAYL04] gives estimated values for a typical office environment.

17.6 IEEE 802.11 SECURITY CONSIDERATIONS

There are two characteristics of a wired LAN that are not inherent in a wireless LAN.

1. In order to transmit over a wired LAN, a station must be physically connected to the LAN. On the other hand, with a wireless LAN, any station within radio range of the other devices on the LAN can transmit. In a sense, there is a form of authentication with a wired LAN, in that it requires some positive and presumably observable action to connect a station to a wired LAN.
2. Similarly, in order to receive a transmission from a station that is part of a wired LAN, the receiving station must also be attached to the wired LAN. On the other hand, with a wireless LAN, any station within radio range can receive. Thus, a wired LAN provides a degree of privacy, limiting reception of data to stations connected to the LAN.

Access and Privacy Services

IEEE 802.11 defines three services that provide a wireless LAN with these two features:

- **Authentication:** Used to establish the identity of stations to each other. In a wired LAN, it is generally assumed that access to a physical connection conveys authority to connect to the LAN. This is not a valid assumption for a wireless LAN, in which connectivity is achieved simply by having an attached antenna that is properly tuned. The authentication service is used by stations to establish their identity with stations they wish to communicate with. IEEE 802.11 supports several authentication schemes and allows for expansion of the functionality of these schemes. The standard does not mandate any particular authentication scheme, which could range from relatively unsecure handshaking to public-key encryption schemes. However, IEEE 802.11 requires mutually acceptable, successful authentication before a station can establish an association with an AP.
- **Deauthentication:** This service is invoked whenever an existing authentication is to be terminated.
- **Privacy:** Used to prevent the contents of messages from being read by other than the intended recipient. The standard provides for the optional use of encryption to assure privacy.

Wireless LAN Security Standards

The original 802.11 specification included a set of security features for privacy and authentication that, unfortunately, were quite weak. For **privacy**, 802.11 defined the Wired Equivalent Privacy (WEP) algorithm. The privacy portion of the 802.11 standard contained major weaknesses. Subsequent to the development of WEP, the 802.11i task group has developed a set of capabilities to address the WLAN security issues. In order to accelerate the introduction of strong security into WLANs, the Wi-Fi Alliance promulgated **Wi-Fi Protected Access (WPA)** as a Wi-Fi standard. WPA is a set of security mechanisms that eliminates most 802.11 security issues and was based on the current state of the 802.11i standard. As 802.11i evolves, WPA will evolve to maintain compatibility.

WPA is examined in Chapter 21.

17.7 RECOMMENDED READING AND WEB SITES

[PAHL95] and [BANT94] are detailed survey articles on wireless LANs. [KAHN97] provides good coverage of infrared LANs.

[ROSH04] provides a good up-to-date technical treatment of IEEE 802.11. Another useful book is [BING02]. [OHAR99] is an excellent technical treatment of IEEE 802.11. Another good treatment is [LARO02]. [CROW97] is a good survey article on the 802.11 standards but does not cover IEEE 802.11a and IEEE 802.11b. A brief but useful survey of 802.11 is [MCFA03]. [GEIE01] has a good discussion of IEEE 802.11a. [PETR00] summarizes IEEE 802.11b. [SHOE02] provides an overview of IEEE 802.11g. [XIAO04] discusses 802.11e.

BANT94 Bantz, D., and Bauchot, F. "Wireless LAN Design Alternatives." *IEEE Network*, March/April 1994.

BING02 Bing, B. *Wireless Local Area Networks.* New York: Wiley, 2002.

CROW97 Crow, B., et al. "IEEE 802.11 Wireless Local Area Networks." *IEEE Communications Magazine*, September 1997.

GEIE01 Geier, J. "Enabling Fast Wireless Networks with OFDM." *Communications System Design*, February 2001. (www.csdmag.com)

KAHN97 Kahn, J., and Barry, J. "Wireless Infrared Communications." *Proceedings of the IEEE*, February 1997.

LARO02 LaRocca, J., and LaRocca, R. *802.11 Demystified.* New York: McGraw-Hill, 2002.

MCFA03 McFarland, B., and Wong, M. 'The Family Dynamics of 802.11" *ACM Queue*, May 2003.

OHAR99 Ohara, B., and Petrick, A. *IEEE 802.11 Handbook: A Designer's Companion.* New York: IEEE Press, 1999.

PAHL95 Pahlavan, K.; Probert, T.; and Chase, M. "Trends in Local Wireless Networks." IEEE Communications Magazine, March 1995.

PETR00 Petrick, A. "IEEE 802.11b—Wireless Ethernet." *Communications System Design*, June 2000. www.commsdesign.com

ROSH04 Roshan, P., and Leary, J. *802.11 Wireless LAN Fundamentals.* Indianapolis: Cisco Press, 2004.

SHOE02 Shoemake, M. "IEEE 802.11g Jells as Applications Mount." *Communications System Design*, April 2002. www.commsdesign.com.

XIAO04 Xiao, Y. "IEEE 802.11e: QoS Provisioning at the MAC Layer." *IEEE Communications Magazine*, June 2004.

Recommended Web sites:

- **Wireless LAN Association:** Gives an introduction to the technology, including a discussion of implementation considerations and case studies from users. Links to related sites.
- **The IEEE 802.11 Wireless LAN Working Group:** Contains working group documents plus discussion archives.
- **Wi-Fi Alliance:** An industry group promoting the interoperability of 802.11 products with each other and with Ethernet.

17.8 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

access point (AP)	basic service set (BSS)	coordination function
ad hoc networking	complementary code keying (CCK)	distributed coordination function (DCF)
Barker sequence		

distribution system (DS) extended service set (ESS) infrared LAN LAN extension	narrowband microwave LAN nomadic access point coordination function (PCF)	spread spectrum LAN wireless LAN

Review Questions

17.1. List and briefly define four application areas for wireless LANs.
17.2. List and briefly define key requirements for wireless LANs.
17.3. What is the difference between a single-cell and a multiple-cell wireless LAN?
17.4. What are some key advantages of infrared LANs?
17.5. What are some key disadvantages of infrared LANs?
17.6. List and briefly define three transmission techniques for infrared LANs.
17.7. What is the difference between an access point and a portal?
17.8. Is a distribution system a wireless network?
17.9. List and briefly define IEEE 802.11 services.
17.10. How is the concept of an association related to that of mobility?

Problems

17.1 Consider the sequence of actions within a BSS depicted in Figure 17.11. Draw a time-line, beginning with a period during which the medium is busy and ending with a

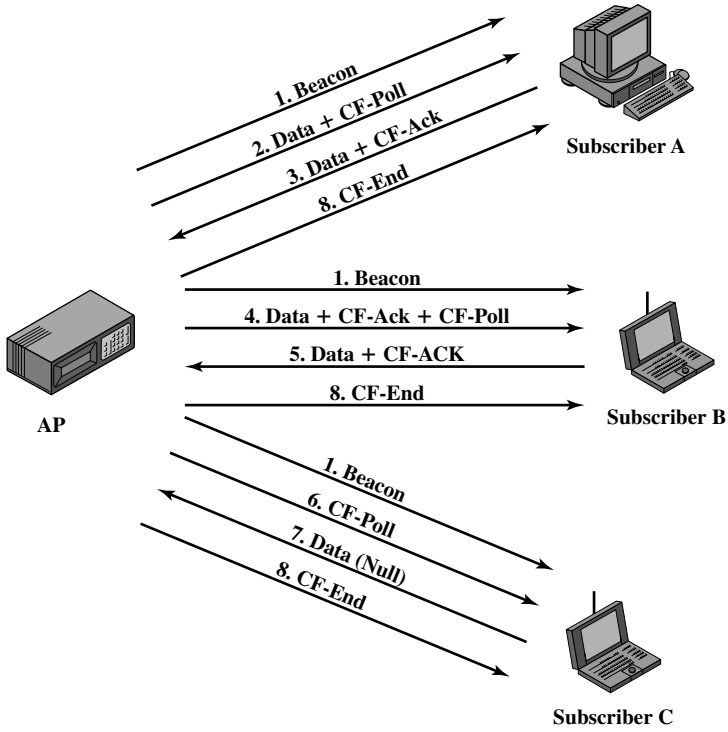


Figure 17.11 Configuration for Problem 17.1

period in which the CF-End is broadcast from the AP. Show the transmission periods and the gaps.

17.2 Find the autocorrelation for the 11-bit Barker sequence as a function of τ.

17.3 **a.** For the 16-PPM scheme used for the 1-Mbps IEEE 802.11 infrared standard,

a1. What is the period of transmission (time between bits)?

For the corresponding infrared pulse transmission,

a2. What is the average time between pulses (1 values) and the corresponding average rate of pulse transmission?

a3. What is the minimum time between adjacent pulses?

a4. What is the maximum time between pulses?

b. Repeat (a) for the 4-PPM scheme used for the 2-Mbps infrared standard.

17.4 For IEEE 802.11a, show how the modulation technique and coding rate determine the data rate.

17.5 The 802.11a and 802.11b physical layers make use of data scrambling (see Appendix 16C). For 802.11, the scrambling equation is

$$P(X) = 1 + X^4 + X^7$$

In this case the shift register consists of seven elements, used in the same manner as the five-element register in Figure 16.17. For the 802.11 scrambler and descrambler,

a. Show the expression with exclusive-or operators that corresponds to the polynomial definition.

b. Draw a figure similar to Figure 16.17.