CHAPTER 13

Wireless LANs

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Present an overview of wireless LAN (WLAN) configurations and requirements.
- Understand the elements of the 802.11 architecture.
- Describe the 802.11 MAC protocol.
- Provide an explanation of the individual fields in the 802.11 MAC frame.
- Present an overview of the alternative 802.11 physical layer specifications.

In recent years, wireless LANs (WLANs) have come to occupy a significant niche in the local area network market. Increasingly, organizations are finding that WLANs 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 WLANs. We begin with an overview that looks at the motivations for using WLANs and summarize the various approaches in current use. The next section examines the three principal types of wireless WLANs, classified according to transmission technology: infrared, spread spectrum, and narrowband microwave.

The most prominent specification for WLANs was developed by the IEEE 802.11 working group. This chapter focuses on this standard, and is based on the 2012 version.

13.1 OVERVIEW

Wireless LAN Configurations

Figure 13.1 indicates a simple WLAN 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 WLAN. The control module includes either bridge or router functionality to link the WLAN 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 stand-alone devices, such as a workstation or a server. Hubs

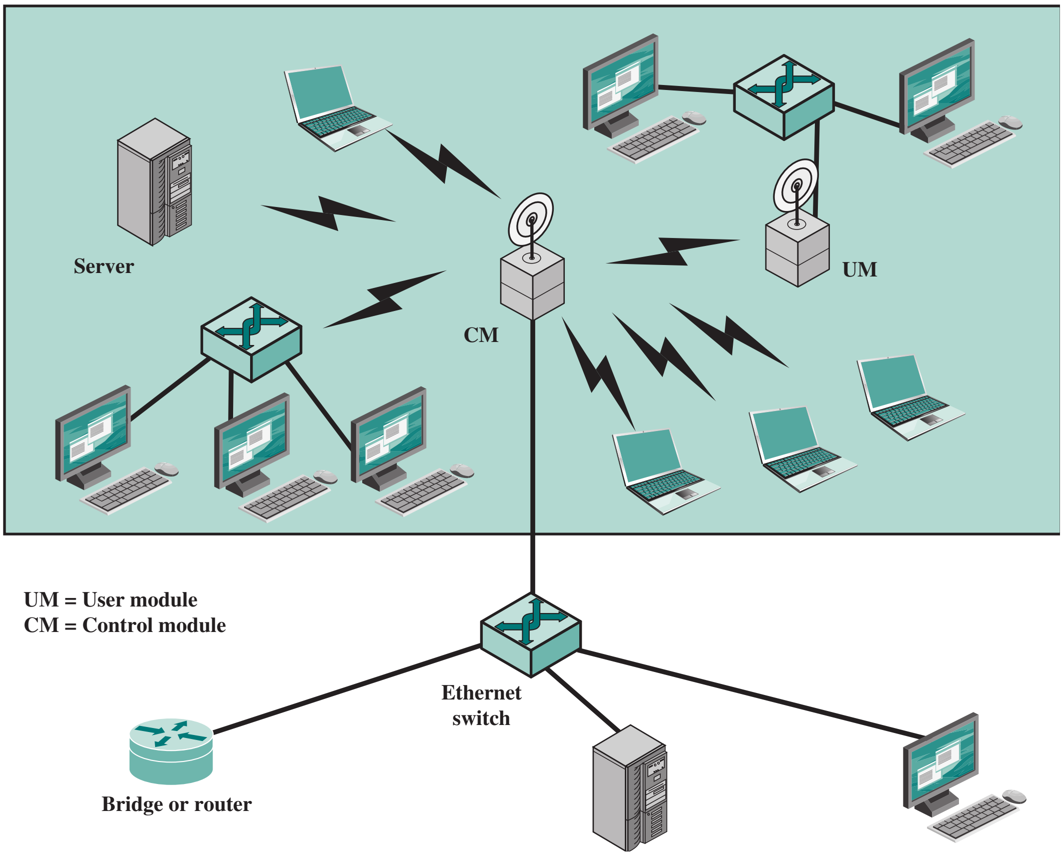


Figure 13.1 Example of Single-Cell Wireless LAN Configuration

or other user modules (UMs) that control a number of stations off a wired LAN may also be part of the WLAN configuration.

The configuration of Figure 13.1 can be referred to as a single-cell WLAN; all of the wireless end systems are within range of a single control module. Another common configuration, suggested by Figure 13.2, is a multiple-cell WLAN. 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.

Figure 13.3 illustrates a different type of configuration, referred to as an **ad hoc network**, from that shown in Figures 13.1 and 13.2. Typically, the WLAN forms a stationary infrastructure consisting of one or more cells with a control

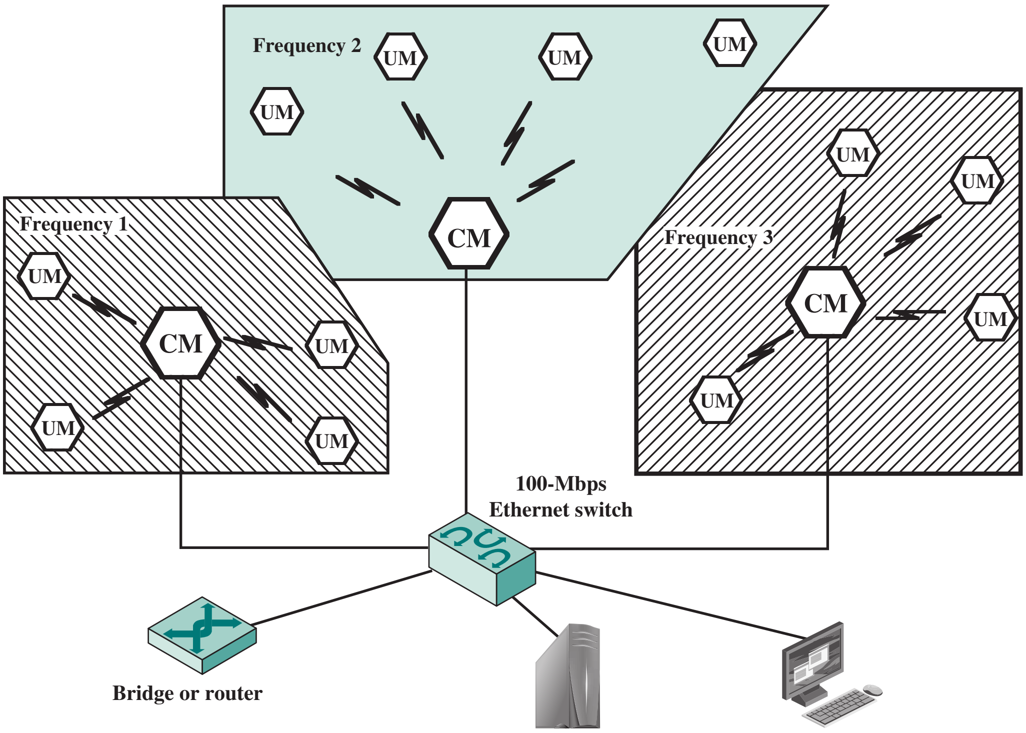


Figure 13.2 Example of Multiple-Cell Wireless LAN Configuration

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. By contrast, there is no infrastructure for an ad hoc network. Rather, a peer collection of stations within a range of each other may dynamically configure themselves into a temporary network.

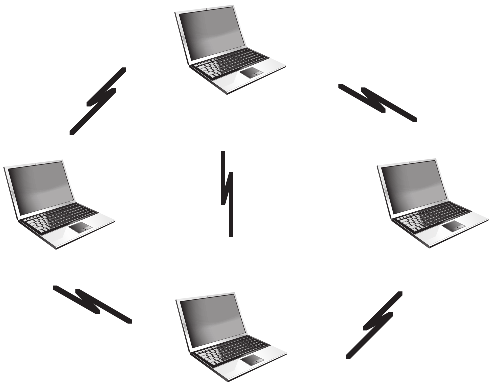


Figure 13.3 Ad Hoc Wireless LAN Configuration

Wireless LAN Requirements

A WLAN 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 requirements specific to the WLAN environment. The following are among the most important requirements for WLANs:

- **Throughput:** The medium access control (MAC) protocol should make as efficient use as possible of the wireless medium to maximize capacity.
- **Number of nodes:** WLANs 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 WLANs, 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 WLAN 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 WLAN 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 WLAN may be especially vulnerable to interference and network eavesdropping. The design of a WLAN must permit reliable transmission even in a noisy environment and should provide some level of security from eavesdropping.
- **Collocated network operation:** As WLANs become more popular, it is quite likely for two or more WLANs 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 WLAN products without having to secure a license for the frequency band used by the LAN.
- **Handoff/roaming:** The MAC protocol used in the WLAN should enable mobile stations to move from one cell to another.
- **Dynamic configuration:** The MAC addressing and network management aspects of the WLAN should permit dynamic and automated addition, deletion, and relocation of end systems without disruption to other users.

13.2 IEEE 802.11 ARCHITECTURE AND SERVICES

In 1990, the IEEE 802 committee formed a new working group, IEEE 802.11, specifically devoted to WLANs, with a charter to develop a MAC protocol and physical medium specification. 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 13.1). Table 13.2 briefly defines key terms used in the IEEE 802.11 standard.

Table 13.1 Key IEEE 802.11 Standards

Standard	Scope
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 security mechanisms
IEEE 802.11g	Physical layer: Extend 802.11b to data rates >20 Mbps
IEEE 802.11i	MAC: Enhance security and authentication mechanisms
IEEE 802.11n	Physical/MAC: Enhancements to enable higher throughput
IEEE 802.11T	Recommended practice for the evaluation of 802.11 wireless performance
IEEE 802.11ac	Physical/MAC: Enhancements to support 0.5–1 Gbps in 5-GHz band
IEEE 802.11ad	Physical/MAC: Enhancements to support ≥ 1 Gbps in the 60-GHz band

Table 13.2 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
Frame	Synonym for MAC protocol data unit
MAC protocol data unit (MPDU)	The unit of data exchanged between two peer MAC entities 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 layers

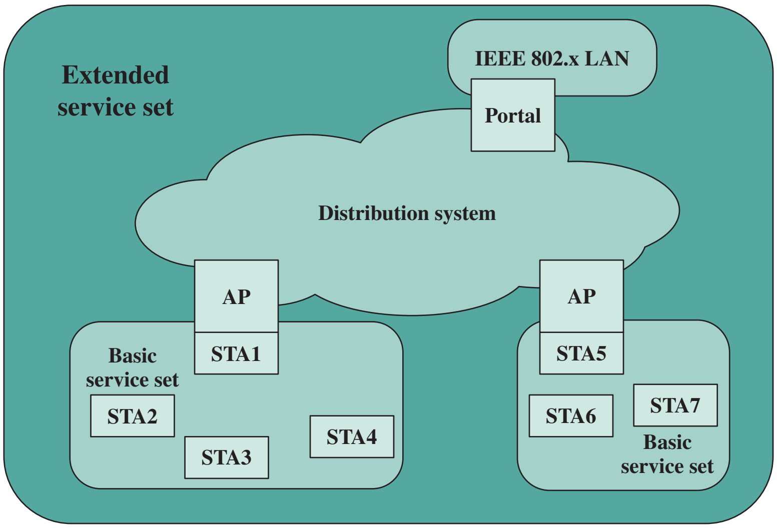
The Wi-Fi Alliance

Although 802.11 products are all based on the same standards, 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 802.11 products.

IEEE 802.11 Architecture

Figure 13.4 illustrates the model developed by the 802.11 working group. The smallest building block of a WLAN 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.

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



STA = station
AP = access point

Figure 13.4 IEEE 802.11 Architecture

ad hoc network. In an IBSS, the stations all communicate directly, and no AP is involved.

A simple configuration is shown in Figure 13.4, 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 BSSs interconnected by a distribution system. Typically, the distribution system is a wired backbone LAN but can be any communications network. The ESS appears as a single logical LAN to the logical link control (LLC) level.

Figure 13.4 indicates that an 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 a number of services that need to be provided by the WLAN to provide functionality equivalent to that which is inherent to wired LANs. Table 13.3 lists key services and indicates two ways of categorizing them.

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

Table 13.3 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
Disassociation	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
Reassociation	Distribution system	MSDU delivery

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.

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 Section 13.6.

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 (STA2) to STA7 in Figure 13.4. The frame is sent from STA2 to STA1, 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 STA5 in the target BSS. STA5 receives the frame and forwards it to STA7. 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 WLAN, 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.

13.3 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 WLAN 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 WLAN 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 13.5 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.

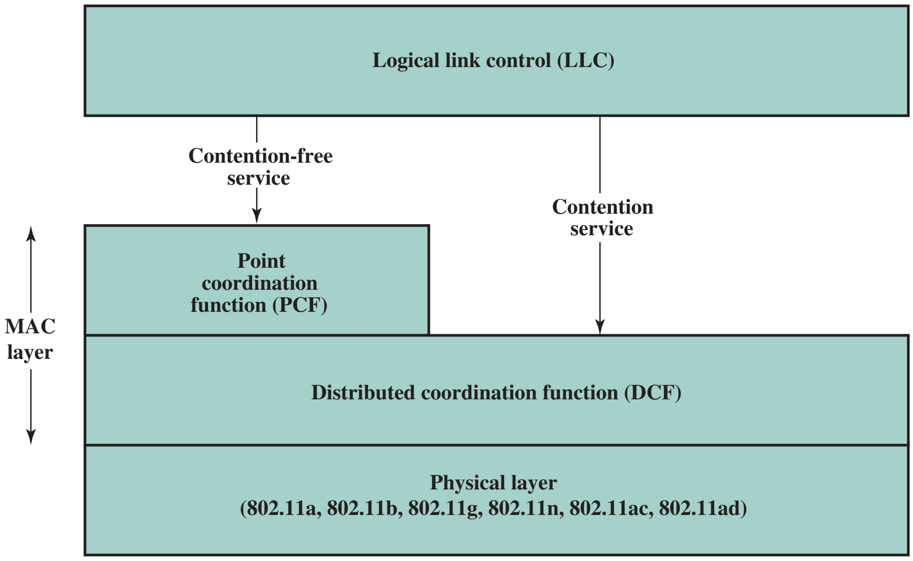

Logical link control (LLC)
Contention-free service
Contention service
Point coordination function (PCF)
MAC layer
Distributed coordination function (DCF)
Physical layer
(802.11a, 802.11b, 802.11g, 802.11n, 802.11ac, 802.11ad)

Figure 13.5 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 13.6):

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.
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 12, 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 help 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

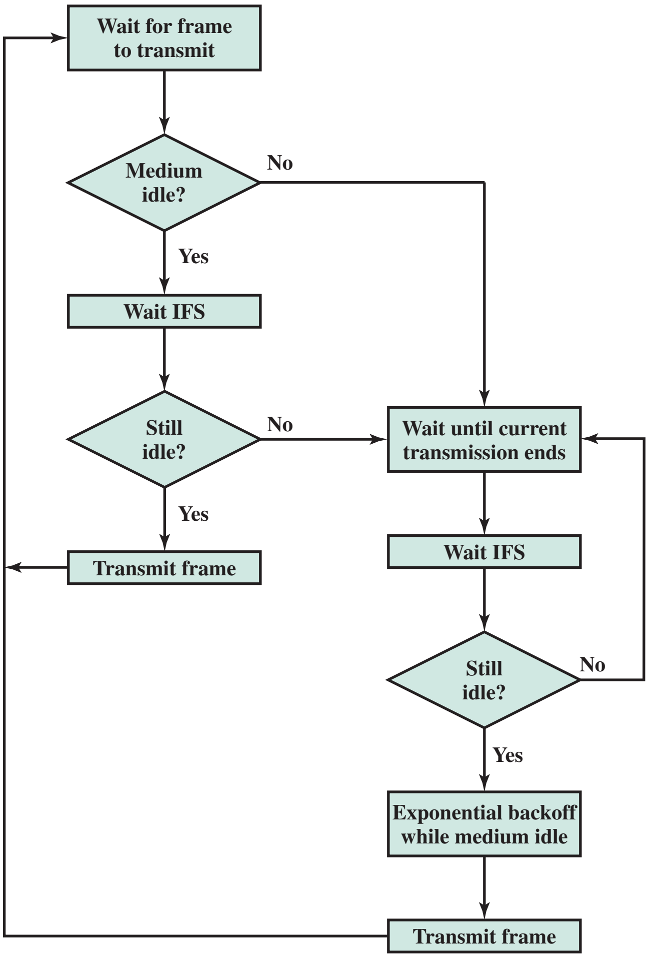
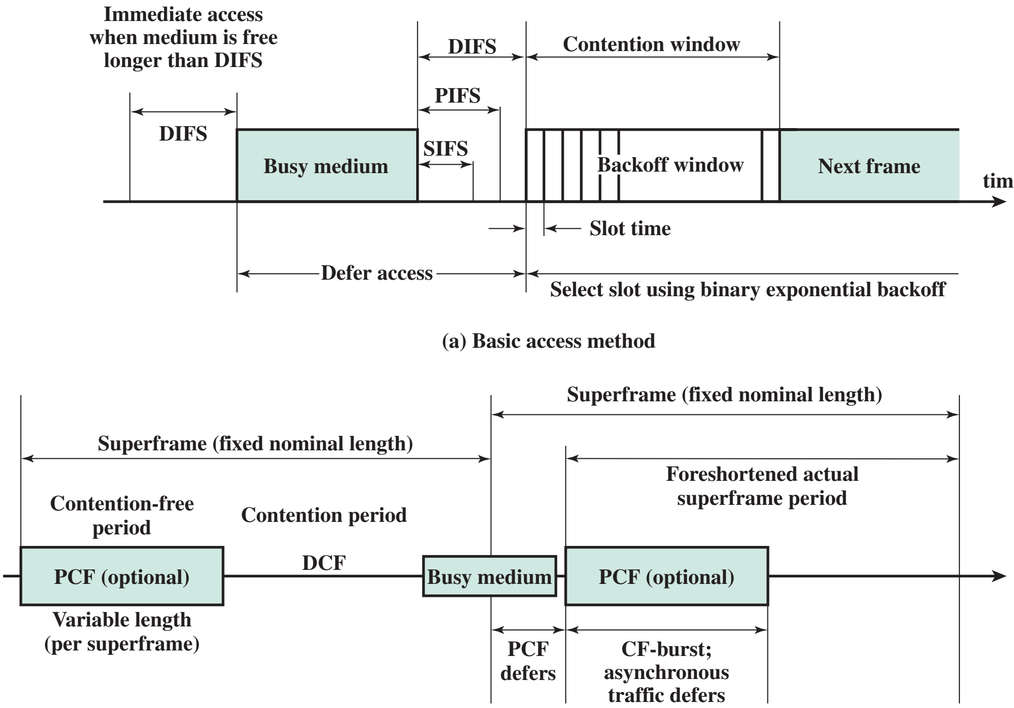

Wait for frame to transmit
Medium idle?
No
Yes
Wait IFS
Still idle?
No
Yes
Transmit frame
Wait until current transmission ends
Wait IFS
Still idle?
No
Yes
Exponential backoff while medium idle
Transmit frame

Figure 13.6 IEEE 802.11 Medium Access Control Logic

Figure 13.7a 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:

- **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



(a) Basic access method

(b) PCF superframe construction

Figure 13.7 IEEE 802.11 MAC Timing

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 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 13.7b 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 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 13.8 shows the format of IEEE 802.11 frame, also known as the MAC protocol data unit (MPDU). 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 WLAN. The **service set ID (SSID)** identifies the WLAN 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 WLAN 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 13.4). Finally the **source address** and **destination address** are the MAC addresses of

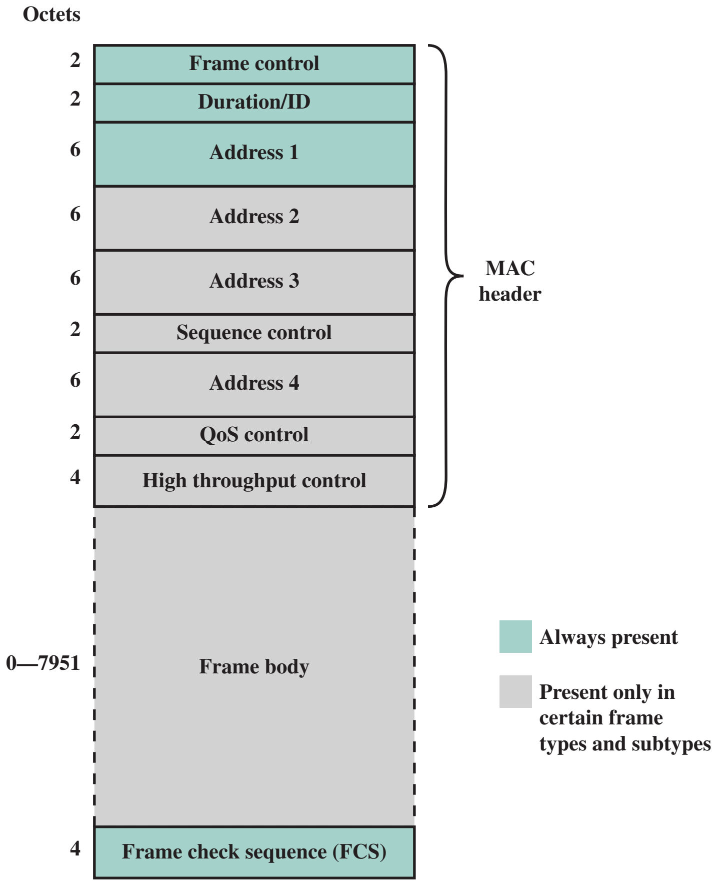


Figure 13.8 IEEE 802.11 MAC Frame Format

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.
- **QoS Control:** Contains information relating to the IEEE 802.11 quality of service (QoS) facility. A discussion of this facility is beyond our scope.
- **High Throughput Control:** This field contains control bits related to the operation of 802.11n, 802.11ac, and 802.11ad. A discussion of this field is beyond our scope.
- **Frame Body:** Contains an MSDU or a fragment of an MSDU. The MSDU is a LLC PDU 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 this section. 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).

13.4 IEEE 802.11 PHYSICAL LAYER

Since its introduction, the IEEE 802.11 standard has been expanded and revised a number of times. The first version of the standard, 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. This version is now obsolete and no longer in use. Table 13.4 summarizes key characteristics of the subsequent revisions. In this section, we survey 802.11b, 802.11a, 802.11g, and 802.11n. The following section deals with 802.11ac and 802.11ad, both of which provide for data rates greater than 1 Gbps.

IEEE 802.11b

One of the original 802.11 standards, now obsolete, used direct sequence spread spectrum (DSSS). It operates 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.

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.

Table 13.4 IEEE 802.11 Physical Layer Standards

Standard	802.11a	802.11b	802.11g	802.11n	802.11ac	802.11ad
Year introduced	1999	1999	2003	2000	2012	2014
Maximum data transfer speed	54 Mbps	11 Mbps	54 Mbps	65 to 600 Mbps	78 Mbps to 3.2 Gbps	6.76 Gbps
Frequency band	5 GHz	2.4 GHz	2.4 GHz	2.4 or 5 GHz	5 GHz	60 GHz
Channel bandwidth	20 MHz	20 MHz	20 MHz	20, 40 MHz	40, 80, 160 MHz	2160 MHz
Highest order modulation	64 QAM	11 CCK	64 QAM	64 QAM	256 QAM	64 QAM
Spectrum usage	DSSS	OFDM	DSSS, OFDM	OFDM	SC-OFDM	SC, OFDM
Antenna configuration	1×1 SISO	1×1 SISO	1×1 SISO	Up to 4×4 MIMO	Up to 8×8 MIMO, MU-MIMO	1×1 SISO

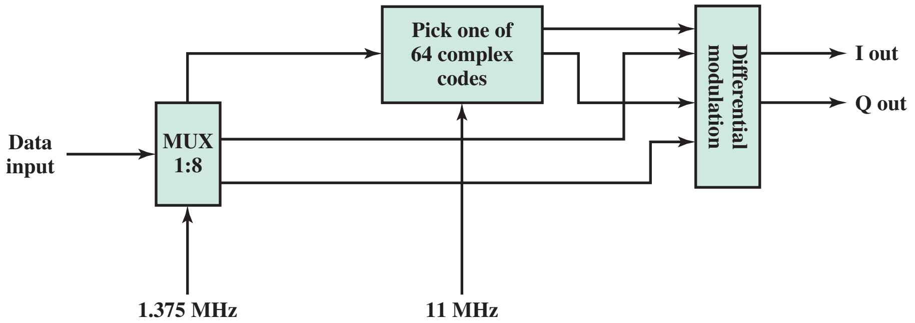


Figure 13.9 11-Mbps CCK Modulation Scheme

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 13.9 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 (8bits/symbol × 1.375MHz = 11Mbps). Six of these bits are mapped into one of 64 code sequences derived from a 64 × 64 matrix known as the Walsh matrix (discussed in Chapter 17). The output of the mapping, plus the two additional bits, forms the input to a QPSK (quadrature phase shift keying) 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 13.10b illustrates the physical-layer frame format with the short preamble. The **PLCP (physical layer conversion protocol) 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 (MAC protocol data unit) 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.

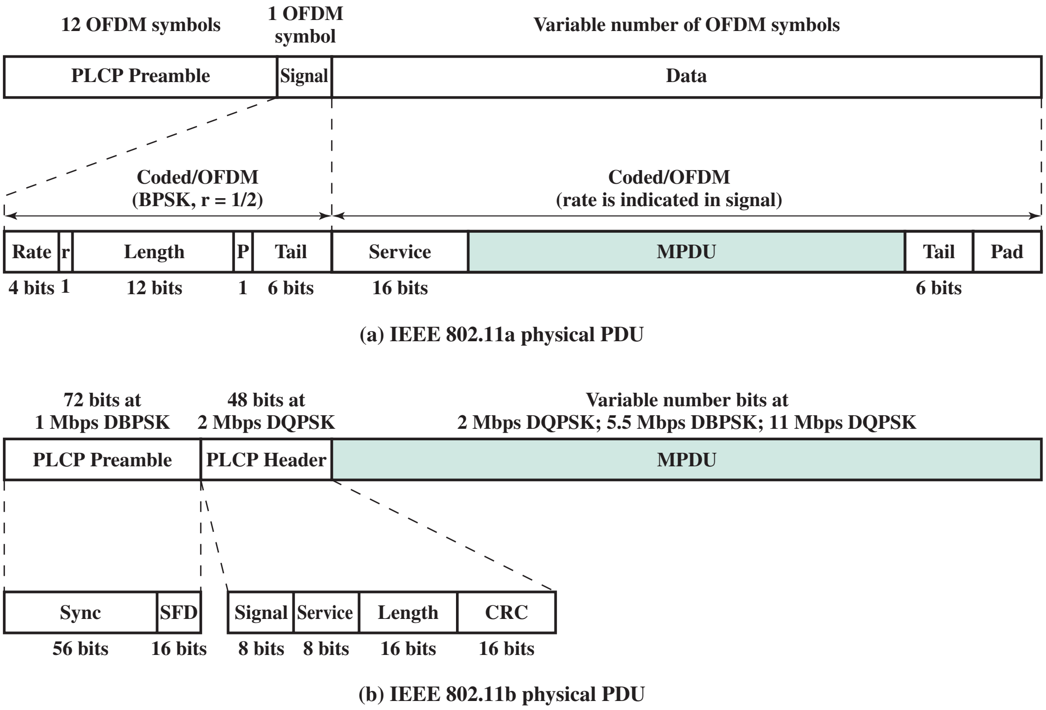


Figure 13.10 IEEE 802.11 Physical-Level Protocol Data Units

- **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 12B for a discussion of scrambling).

IEEE 802.11a

Although 802.11b achieved a certain level of success, its limited data rate results in limited appeal. To meet the needs for a truly high-speed WLAN, **IEEE 802.11a** was developed.

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 (5.15–5.25 GHz) is intended for indoor use; the UNNI-2 band (5.25–5.35 GHz) can be used either indoor or outdoor; and the UNNI-3 band (5.725–5.825 GHz) is for outdoor use.

IEEE 802.11a 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 802.11a does not use a spread spectrum scheme but rather uses OFDM (orthogonal frequency-division multiplexing). 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 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 MAC protocol data units as directed by the 802.11 MAC layer. The PLCP sublayer provides the framing and signaling bits needed for the OFDM transmission and the PMD sublayer performs the actual encoding and transmission operation.

Figure 13.10a 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 12B 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 13.8.
- **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 802.11g

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.

IEEE 802.11g offers a wide 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, an 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 13.5, based on [LAYL04], gives estimated values for a typical office environment.

IEEE 802.11n

With increasing demands being placed on WLANs, the 802.11 committee looked for ways to increase the data throughput and overall capacity of 802.11 networks. The goal of this effort is to not just increase the bit rate of the transmitting antennas but

Table 13.5 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

to increase the effective throughput of the network. Increasing effective throughput involves looking not only at the signal encoding scheme, but also at the antenna architecture and the MAC frame structure. The result of these efforts is a package of improvements and enhancements embodied in IEEE 802.11n. This standard is defined to operate in both the 2.4-GHz and the 5-GHz bands and can therefore be made upwardly compatible with either 802.11a or 802.11b/g.

IEEE 802.11n embodies changes in three general areas: use of MIMO, enhancements in radio transmission, and MAC enhancements. We briefly examine each of these.

Multiple-input-multiple-output (MIMO) antenna architecture is the most important of the enhancements provided by 802.11n. A discussion of MIMO is provided in Chapter 17, so we content ourselves with a brief overview. In a MIMO scheme, the transmitter employs multiple antennas. The source data stream is divided into *n* substreams, one for each of the *n* transmitting antennas. The individual substreams are the input to the transmitting antennas (multiple input). At the receiving end, *m* antennas receive the transmissions from the *n* source antennas via a combination of line-of-sight transmission and multipath. The outputs from the *m* receiving antennas (multiple output) are combined. With a lot of complex math, the result is a much better receive signal than can be achieved with either a single antenna or multiple frequency channels. 802.11n defines a number of different combinations for the number of transmitters and the number of receivers, from 2 × 1 to 4 × 4. Each additional transmitter or receiver in the system increases the SNR (signal-to-noise ratio).

In addition to MIMO, 802.11n makes a number of changes in the **radio transmission scheme** to increase capacity. The most significant of these techniques, known as channel bonding, combines two 20-MHz channels to create a 40-MHz channel. Using OFDM, this allows for twice as many subchannels, doubling the transmission rate.

Finally, 802.11n provides some **MAC enhancements**. The most significant change is to aggregate multiple MAC frames into a single block for transmission. Once a station acquires the medium for transmission, it can transmit long packets without significant delays between transmissions. The receiver sends a single block acknowledgement. The physical header associated with transmission is sent only at the beginning of the aggregated frame, rather than one physical header per individual frame. Frame aggregation can result in significantly improved efficiency in the use of the transmission capacity.

The 802.11n specification includes three forms of aggregation, illustrated in Figure 13.11 [CISC12b]. For simplicity, the 4-octet MAC trailer field is not shown. A-MSDU aggregation combines multiple MSDUs into a single MPDU. Thus there is a single MAC header and single FCS for all of the MSDUs rather than for each of the MSDUs. This provides a certain amount of efficiency because the 802.11 MAC header is potentially quite lengthy. However, if a bit error occurs in one of the MSDU, all of the aggregated MSDUs must be retransmitted. A-MPDU aggregation combines multiple MPDUs in a single physical transmission. Thus, as with A-MSDU, only a single physical-layer header is needed. This approach is less efficient because each MPDU includes the MAC header and FCS. However, if a bit error occurs in one of the MPDUs, only that MPDU

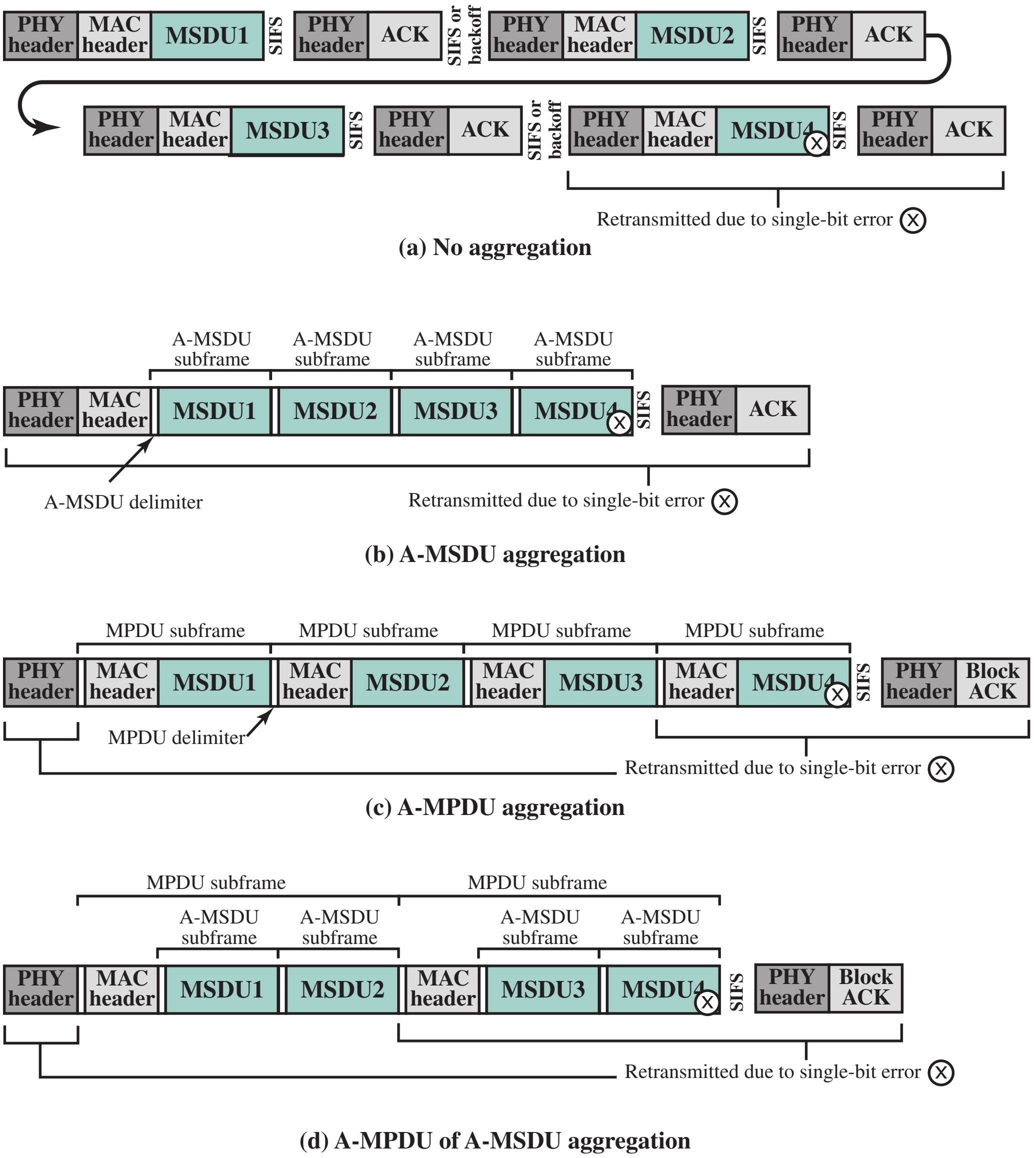


Figure 13.11 Forms of Aggregation

needs to be retransmitted. Finally, the two forms of aggregation can be combined (A-MPDU of A-MSDU).

Figure 13.12 gives an indication of the effectiveness of 802.11n compared to 802.11g [DEBE07]. The chart shows the average throughput per user on a shared system. As expected, the more active users competing for the wireless capacity, the smaller the average throughput per user. IEEE 802.11n provides a significant improvement, especially for networks in which a small number of users are actively competing for transmission time.

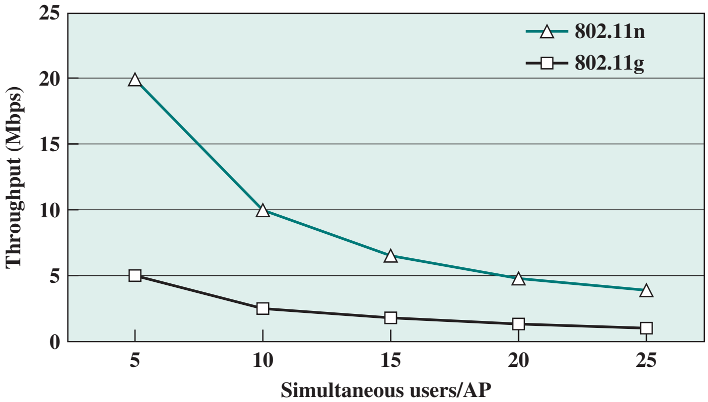


Figure 13.12 Average Throughput per User

13.5 GIGABIT WI-FI

Just as there has been a need to extend the Ethernet standard to speeds in the gigabit per second range, the same requirement exists for Wi-Fi. Accordingly, IEEE 802.11 has recently introduced two new standards, 802.11ac and 802.11ad, which provide for Wi-Fi networks that operate at well in excess of 1 Gbps. We look at these two standards in turn.

IEEE 802.11ac

IEEE 802.11ac operates in the 5-GHz band, as does 802.11a and 802.11n. It is designed to provide a smooth evolution from 802.11n. The new standard achieves much higher data rates than 802.11n by means of enhancements in three areas (Figure 13.13):

- **Bandwidth:** The maximum bandwidth of 802.11n is 40 MHz; the maximum bandwidth of 802.11ac is 160 MHz.
- **Signal encoding:** 802.11n uses 64 QAM with OFDM, and 802.11ac uses 256 QAM with OFDM. Thus, more bits are encoded per symbol. Both schemes use forward error correction with a code rate of 5/6 (ratio of data bits to total bits).
- **MIMO:** With 802.11n, there can be a maximum of 4 channel input and 4 channel output antennas. 802.11ac increases this to 8 × 8.

We can quantify these enhancements using the following formula, which yields the physical layer data rate in bps:

$$\text{Data rate} = \frac{(\text{number of data subcarriers}) \times (\text{number of spatial streams}) \times (\text{data bits per subcarrier})}{(\text{time per OFDM symbol, in seconds})}$$

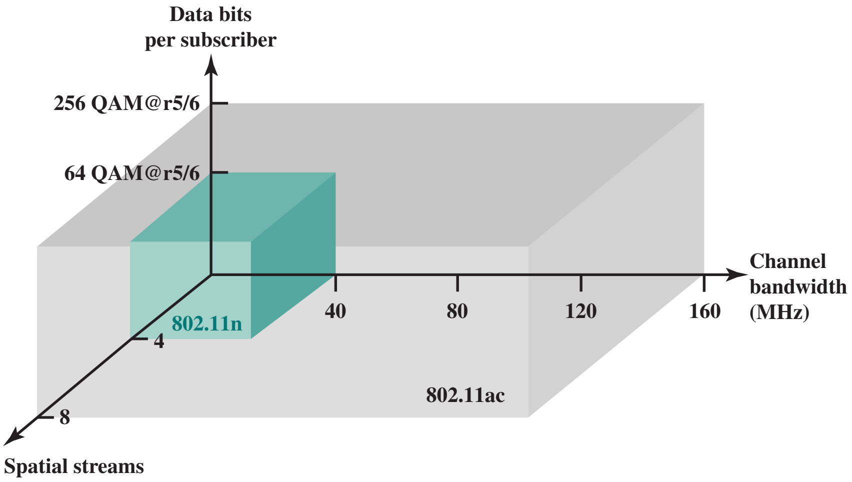


Figure 13.13 IEEE 802.11 Performance Factors

Using this equation, we have the following maximum data rates:

$$\text{802.11n: } \frac{108 \times 4 \times (5/6 \times \log_2 64)}{3.6 \times 10^{-6}} = 600 \times 10^6 \text{ bps} = 600\,\text{Mbps}$$

$$\text{802.11ac: } \frac{468 \times 8 \times (5/6 \times \log_2 256)}{3.6 \times 10^{-6}} = 6937 \times 10^6 \text{ bps} = 6.937\,\text{Gbps}$$

Increasing the channel bandwidth by a factor of 4 approximately quadruples the data rate. The transmit power must now be spread over 4 times as many subcarriers, resulting in a slight reduction in range. Going from 64 QAM to 256 QAM increases the data rate by a factor of 1.33. However, 256 QAM is more sensitive to noise and thus is most effective at shorter ranges. Finally, the speed is directly proportional to the number of spatial streams. Of course, more spatial streams require more antennas, increasing the cost of the subscriber device.

Two other changes going from 802.11n to 802.11ac are noteworthy. 802.11ac includes the option of multiuser MIMO (MU-MIMO). This means that on the downlink, the transmitter is able to use its antenna resources to transmit multiple frames to different stations, all at the same time and over the same frequency spectrum. Thus, each antenna of a MU-MIMO AP can simultaneously communicate with a different single-antenna device, such as a smartphone or tablet. This enables the AP to deliver significantly more data in many environments.

Another difference is that 802.11ac requires that every 802.11ac transmission to be sent as an A-MPDU aggregate. Briefly, this requirement is imposed to guarantee efficient use of the channel. For a more extended explanation, see [CISC12b].

IEEE 802.11ad

IEEE 802.11ad is a version of 802.11 operating in the 60-GHz frequency band. This band offers the potential for much wider channel bandwidth than the 5-GHz band, enabling high data rates with relatively simple signal encoding and antenna characteristics. Few devices operate in the 60-GHz band, which means communications would experience less interference than in the other bands used by 802.11.

However, at 60 GHz, 802.11ad is operating in the millimeter range, which has some undesirable propagation characteristics:

1. Free space loss increases with the square of the frequency [Equation (4.3)]; thus losses are much higher in this range than in the ranges used for traditional microwave systems.
2. Multipath losses can be quite high. Reflection occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal; scattering occurs if the size of an obstacle is on the order of the wavelength of the signal or less; diffraction occurs when the wavefront encounters the edge of an obstacle that is large compared to the wavelength.
3. Millimeter-wave signals generally don't penetrate solid objects.

For these reasons, 802.11ad is likely to be useful only within a single room. Because it can support high data rates and, for example, could easily transmit uncompressed high-definition video, it is suitable for applications such as replacing wires in a home entertainment system, or streaming high-definition movies from your cell phone to your television.

There are two striking differences between 802.11ac and 802.11ad. Whereas 802.11ac supports a MIMO antenna configuration, 802.11ad is designed for single-antenna operation. And 802.11ad has a huge channel bandwidth of 2160 MHz.

IEEE 802.11ad defines four physical layer modulation and coding schemes (Table 13.6). Each type has a distinct purpose and supports a different range of data rates.

Control PHY (CPHY) is by far the most robustly coded (and consequently, lowest throughput) mode, with a code rate of only 1/2. Its purpose is exclusively to transmit control channel messages. The CPHY robustness is evident from its use of differential encoding, code spreading, and BPSK modulation. Differential encoding eliminates the need for carrier tracking, 32× spreading contributes a theoretical 15 dB gain to the link budget, and BPSK is very noise tolerant.

As with CPHY, **single-carrier PHY (SCPHY)** uses the powerful low-density parity-check (LDPC) code for robust forward error correction and provides three options for modulation. The set of options for code rate and modulation density allow for a trade-off between throughput and robustness to be determined operationally.

OFDM PHY (OFDMPHY) employs multicarrier modulation, which can provide higher modulation densities and hence higher data throughput than the single-carrier options. As with SCPHY, OFDMPHY provides a choice of error protection ratio and the depth of modulation applied to the OFDM data carriers, again to provide operational control over the robustness/throughput trade-off. The choice between SCPHY and OFDMPHY depends on several factors. OFDM modulation will generally impose greater power requirements than SCPHY, but is more robust in the presence of multipath distortion.

Table 13.6 IEEE 802.11ad Modulation and Coding Schemes

Physical Layer	Coding	Modulation	Raw Bit Rate
Control (CPHY)	1/2 LDPC, 32 × spreading	π/2-DBPSK	27.5 Mbps
Single carrier (SCPHY)	1/2 LDPC 1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC	π/2-BPSK π/2-QPSK π/2-16 QAM	385 Mbps to 4.62 Gbps
OFDM (OFDMPHY)	1/2 LDPC 5/8 LDPC 3/4 LDPC 13/16 LDPC	OFDM-OQPSK OFDM-QPSK OFDM-16 QAM OFDM-64 QAM	693 Mbps to 6.76 Gbps
Low-power single carrier (LPSCPHY)	RS(224,208) + Block Code(16/12/9/8,8)	π/2-BPSK π/2-QPSK	636 Mbps to 2.5 Gbps

BPSK = binary phase shift keying
DBPSK = differential binary phase shift keying
LDPC = low-density parity-check code
OFDM = orthogonal frequency-division multiplexing
OQPSK = offset quadrature phase shift keying
QAM = quadrature amplitude modulation
QPSK = quadrature phase shift keying
RS = Reed–Solomon

The LDPC error-correcting coding technique that is common to the CPHY, SCPHY, and OFDMPHY is based on a common codeword length of 672 bits carrying 336, 504, 420, or 546 payload bits to achieve a code rate of 1/2, 3/4, 5/8, or 13/16 as required.

Low-power single carrier (LPSCPHY) employs single-carrier modulation to minimize power consumption. It also uses either Reed–Solomon or Hamming block codes, which require less IC area and hence less power than LDPC, at the expense of less robust error correction. Small battery-powered devices could benefit from the extra power savings.

13.6 IEEE 802.11 SECURITY CONSIDERATIONS

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

1. In order to transmit over a wired LAN, a station must be physically connected to the LAN. On the other hand, with a WLAN, 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 WLAN, 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 WLAN 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 WLAN, 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 27.

13.7 RECOMMENDED READING

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. [CISC07] is a detailed treatment of IEEE 802.11n. [SKOR08] is a thorough examination of the 802.11n MAC frame aggregation scheme. [HALP10] examines the 802.11n MIMO scheme. [ALSA13] is a good technical introduction to 802.11ac. [CORD10] and [PERA10] provide good technical overviews of 802.11ad.

ALSA13 Alsabbagh, E.; Yu, H.; and Gallagher, K. "802.11ac Design Consideration for Mobile Devices." *Microwave Journal,* February 2013.

CISC07 Cisco Systems, Inc. "802.11n: The Next Generation of Wireless Performance." Cisco White Paper, 2007, cisco.com

CORD10 Cordeiro, C.; Akhmetov, D.; and Park, M. "IEEE 802.11ad: Introduction and Performance Evaluation of the First Multi-Gbps WiFi Technology." Proceedings of the 2010 ACM international workshop on mmWave communications: From circuits to networks, 2010.

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

HALP10 Halperin, D., et al. "802.11 with Multiple Antennas for Dummies." *Computer Communication Review*, January 2010.

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

PERA10 Perahia, E., et al. "IEEE 802.11ad: Defining the Next Generation Multi-Gbps Wi-Fi." Proceedings, 7th IEEE Consumer Communications and Networking Conference, 2010.

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

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

SKOR08 Skordoulis, D., et al. "IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs." *IEEE Wireless Communications*, February 2008.

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

13.8 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

access point (AP)
ad hoc networking
basic service set (BSS)
complementary code keying (CCK)
coordination function
distributed coordination function (DCF)
distribution system (DS)
extended service set (ESS)
narrowband microwave LAN
point coordination function (PCF)
wireless LAN (WLAN)

Review Questions

13.1 List and briefly define key requirements for WLANs.

13.2 What is the difference between a single-cell and a multiple-cell WLAN?

13.3 What is the difference between an access point and a portal?

13.4 Is a distribution system a wireless network?

13.5 List and briefly define IEEE 802.11 services.

13.6 How is the concept of an association related to that of mobility?

Problems

13.1 Consider the sequence of actions within a BSS depicted in Figure 13.14. Draw a timeline, beginning with a period during which the medium is busy and ending with a period in which the CF-End is broadcast from the AP. Show the transmission periods and the gaps.

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

13.3 The 802.11a and 802.11b physical layers make use of data scrambling (see Appendix 12B). 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 12.17. For the 802.11 scrambler and descrambler,

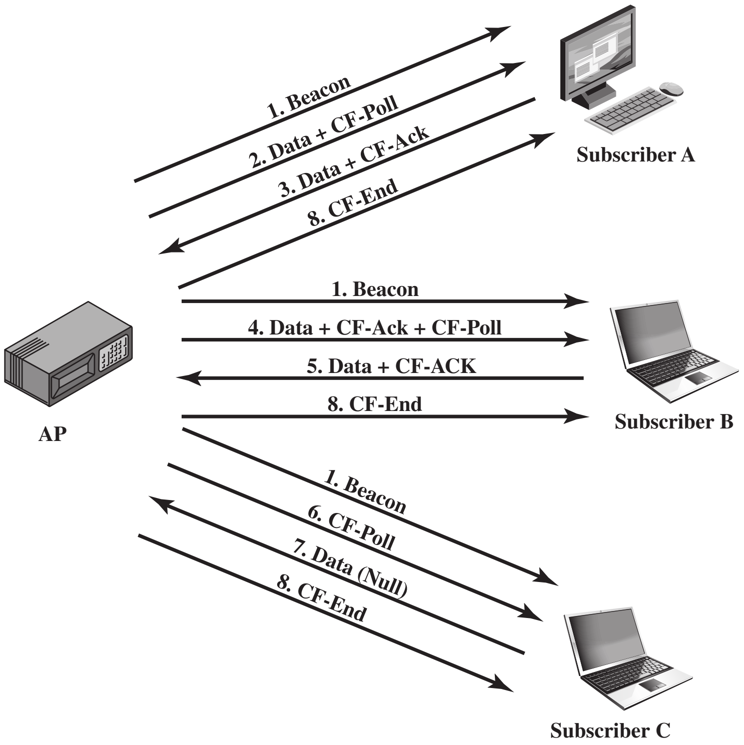


Figure 13.14 Configuration for Problem 13.1