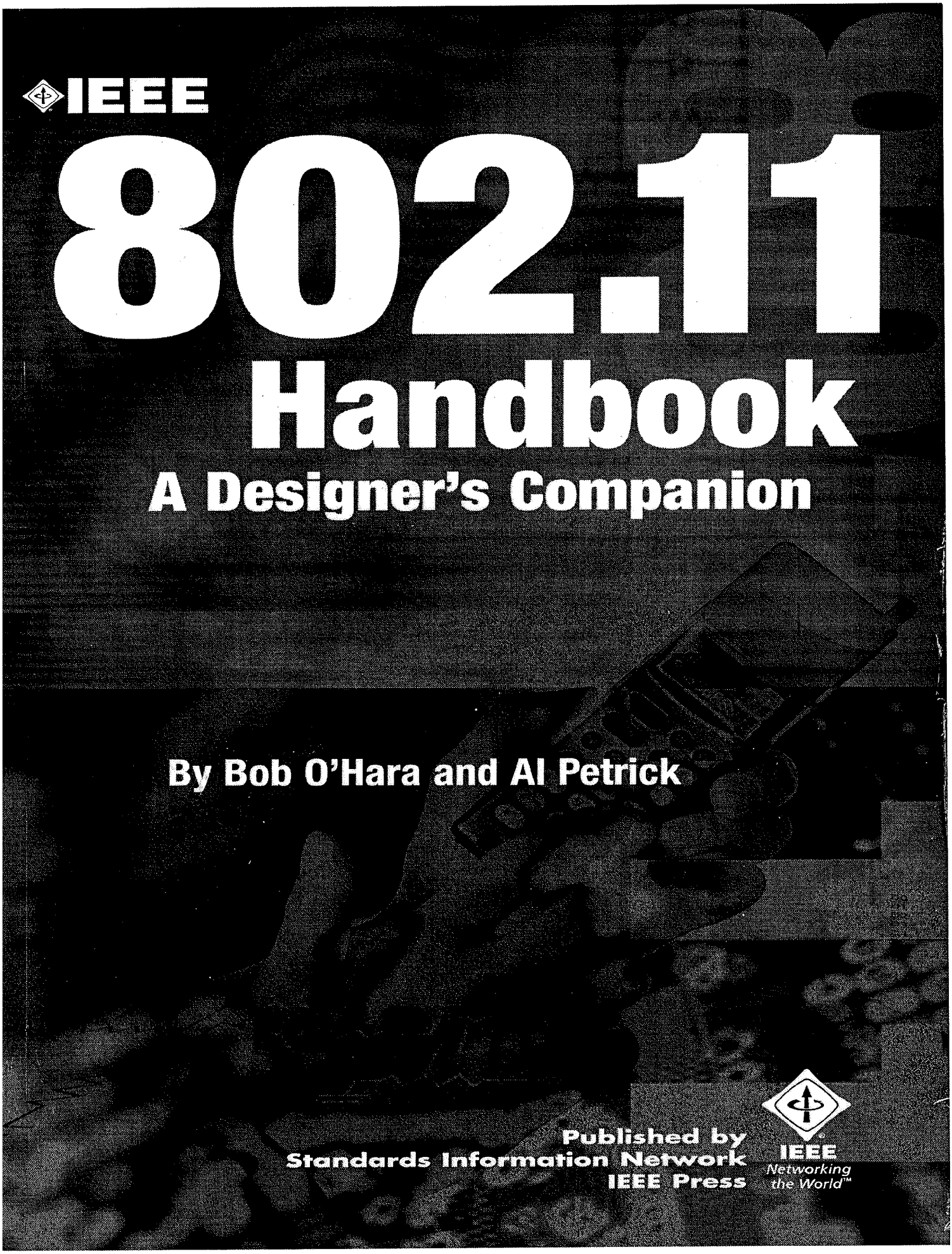
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By Bob O'Hara and Al Petrick
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The IEEE 802.11 Handbook

A Designer's Companion

Authored by

Bob O'Hara
Al Petrick

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For teaching me that a little hard work never hurt anyone and for being there every time I have needed them, I dedicate this book to my parents, Bob and Shirley.

- Bob O'Hara

To my parents, Albert and Marge, who have provided me with loving care and taught me the values of life. Also, to my wife and best friend, Patricia, for her loving support, understanding, and patience throughout the writing process, for which I'm forever grateful.

- Al Petrick

Acknowledgment

We wrote this book as a guide for those who will implement interoperable IEEE 802.11 2.4 GHz and 5 GHz wireless LAN (WLAN) products. We were fortunate enough to be part of the IEEE 802.11 Working Group for the past 7 years as chairs and active participants. We would like to thank all of our engineering colleagues who have worked so passionately in the development of the IEEE 802.11 2.4 GHz and 5 GHz WLAN standards and to those who have inspired us to undertake the writing of this book. It gives us great pleasure to have worked with some of the finest, and most creative and innovative engineering professionals in the standards-setting process.

We would like to thank the external reviewers who have commented on the material throughout the process. Their evaluation of the technical content of the handbook has helped us clarify our thinking and make sure we included topics that were core to the physical layer, MAC layer, and for practical system implementations. The reviewers' names and affiliations are listed below.

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And finally, we want to thank Yvette Ho Sang and the editorial team at IEEE Press for guiding us throughout the writing process.

Bob O'Hara

Al Petrick

About the Authors

Bob O'Hara is the president and founder of Informed Technology, Inc., a company that specializes in strategic, technology, and network consulting. He is actively involved in the development of networking, telecommunications, and computing standards and products. His areas of expertise are: network and communication protocols and their implementation, operating systems, system specification and integration, standards development, cryptography and its application, strategy development, and product definition. Mr. O'Hara has been involved with the development of the IEEE 802.11 WLAN standard since 1992. He is the technical editor of that standard and chairman of the revisions and regulatory extensions task groups.

Prior to starting Informed Technology, Mr. O'Hara worked for Advanced Micro Devices in both senior engineering and management positions for the I/O and Network Products Division and in the Advanced Development Lab, as well as engineering positions at Fairchild Space and Communications and TRW Defense and Space Systems Group. He Graduated with a BSEE from the University of Maryland in 1978.

Al Petrick is Director of Marketing and Business Development at ParkerVision for the wireless product line. Mr. Petrick's experience includes over 20 years of combined marketing and systems engineering in wireless communications with emphasis on semiconductor technology. Prior to ParkerVision, Mr. Petrick held senior management marketing and business development positions at Intersil Semiconductor. He successfully pioneered semiconductor technology for the WLAN market from inception through announcement. Mr. Petrick serves as Vice-Chair of the IEEE 802.11 WLAN standards committee. Mr. Petrick published various marketing and technical papers on wireless communications and is a distinguished writer with leading wireless trade journals and market and financial analysts. Mr. Petrick holds a BSET from Rochester Institute of Technology, Rochester, New York and an MBA from Rollins College, Winter Park, Florida. He also studied business-strategies at Northwestern University Kellogg Graduate School of Management.

Foreword

Since the publication of the IEEE 802.11 WLAN standard, many equipment manufacturers have entered the market with interoperable WLAN systems. In September 1999, the IEEE-SA Standards Board approved the 2.4 GHz, 11 Mbps 802.11b and 5 GHz, 54 Mbps 802.11a extensions. However, standards are written as specifications for interoperable products and not as handbooks for obtaining a thorough understanding of the protocol. It is impossible to include in the standards all the reasons for decisions taken to get the standard ratified.

The only people who could write a handbook with the qualities I have in mind are those that have followed the standards process from the beginning. I applaud Bob O'Hara and Al Petrick for taking on the task of writing this handbook. Bob and Al have been very instrumental throughout the development of the IEEE 802.11 standard and are recognized for their contributions and technical leadership. This book is a first-of-a-kind and provides a perfect balance of information for embracing the physical and MAC layers of the standard.

I expect *The IEEE 802.11 Handbook: A Designer's Companion* to become a standard reference for every WLAN systems engineer and anticipate the reader will find this text extremely useful.

Vic Hayes
Chairman, IEEE P802.11, Standards WG for Wireless LANs
Lucent Technologies Nederland B. V.
Zadelstede 1-10
The Netherlands

Preface

This book from Bob and Al is very timely. Wireless LANs are exploding in popularity. The WLAN industry is taking off and expanding beyond its vertical niche market roots. One of the key drivers of this new market expansion for WLANs is the IEEE 802.11 standard. Simply having a WLAN standard was not enough to spark the industry. IEEE 802.11 has been around since June of 1997. The IEEE 802.11b High-Rate Physical Layer extension enabled us to deliver 11 Mbps and products conforming to that standard have been shipping for a while. Wireless LANs have finally hit the right price and performance to appeal to a broader market. Breaking the 10 Mbps barrier makes IEEE 802.11 LANs appealing for enterprise applications. Home networking is becoming more popular, and WLANs are an attractive option. By the time you read this, you will be able to purchase an IEEE 802.11-compliant, 11 Mbps consumer WLAN adapter for $99 or less. Wireless LANs are ready for prime time and IEEE 802.11 made it happen.

The IEEE 802.11 standard represents many years of work from a global team of engineers. One of the challenges of developing the IEEE 802.11 standard was bringing together experts from two different disciplines —analog radio design and network protocol design. We had many arguments about whether this is a radio standard or a network standard. Very clearly, IEEE 802.11 is a network standard. That is the whole point. Because IEEE 802.11 fits into the IEEE 802 framework, systems conforming to the standard can be added to existing networks transparently. IEEE 802.11 WLANs will support the network protocols and applications that were developed for the other IEEE 802 LAN standards over the past 25 years. So IEEE 802.11 is a network standard that happens to have a radio physical layer. This book benefits from the fact that Bob and Al are experts in both of these disciplines. They have a deep understanding of the material gained through their many years of contribution to the standard.

The standard was over 400 pages when initially published, and recently two new physical layer extensions were added. Bob and Al help the reader navigate through the complexity of the standard and focus on the core issues. This book is a great guide to the standard for anyone developing IEEE 802.11 products or those simply wanting to gain a better understanding of the standard.

Enjoy!

Phil Belanger
Chairman of the Wireless Ethernet Compatibility Alliance, www.wi-fi.com
Co-Author of the DFWMAC protocol, the proposal that was used as the basis for the IEEE 802.11 MAC

Introduction

A number of books have been written in the last several years on the topic of WLANs. Why is it necessary to bring another one to your shelves? We believe that, with the advent of the IEEE 802.11 standard for WLANs, the consolidation of the WLAN market will commence. Therefore, it is important that WLAN designers, network planners and administrators, and users understand the operation and application of IEEE 802.11. This handbook will provide the detail required to attain that understanding.

With the advent of IEEE 802.11 WLANs, an era of multivendor product competition and innovation has begun, similar to that begun by the adoption of the IEEE 802.3 standard. This era is closing the door on proprietary WLANs that have seen limited acceptance, mostly in vertical applications such as warehousing, inventory control, and retail. The goal of the IEEE 802.11 Working Group was to define a complete WLAN system that would allow the use of WLANs in all application areas, including the typical horizontal application of corporate LANs, where wired LANs are found today. It is our belief that the working group has been successful in reaching this goal.

There are two major components of the WLAN described by IEEE 802.11, the mobile station and the access point (AP). Going well beyond what other IEEE 802 standards have done in the past, IEEE 802.11 defines a complete management protocol between the mobile station and AP. This management protocol makes it possible for a single IEEE 802.11 WLAN to comprise equipment from many vendors, marking true multivendor interoperability.

There is a huge amount of information in the IEEE 802.11 standard and its extensions. Finding the information required in a short time can be challenging. To help meet the challenge, a mapping between the information in the standards and that presented in this handbook is given here. IEEE standards are divided into clauses and annexes. Information in the standard is referred to by the clause and annex in which it is found. This book is divided into chapters. Information in this book is referred to by the chapter in which it is found.

Clauses 1 through 4 of the standard contain a brief overview of the standard, other references that are required to implement the standard, definitions of terms, and the abbreviations and acronyms used in the standard. This information corresponds to the Introduction and abbreviations in this handbook.

Clause 5 of the standard provides a description of the architecture and components of an IEEE 802.11 WLAN system. This corresponds to Chapter 2 in this handbook.

Clause 6 of the IEEE 802.11 standard describes the MAC service interface. This is an abstract interface for the exchange of data between the MAC and the protocol layer above the MAC. This is not described explicitly in this handbook.

Clause 7 of the standard describes the MAC frames and their content. Clause 8 of the standard describes the WEP functionality that may be implemented in an IEEE 802.11 station. Clause 9 describes the functionality and frame exchange protocols of the MAC. Information from these clauses is found in Chapter 3.

Clause 10 describes the layer management service interface primitives and their functionality. Clause 11 describes the MAC management functionality and protocols. This information may be found in Chapter 4.

Clause 12 describes the PHY service interface. This is an abstract interface for the exchange of data between the MAC and PHY. Clause 13 describes the PHY management service interface, which consists solely of the MIB interface. This is not described explicitly in this handbook.

Clause 14 describes the frequency hopping spread spectrum physical layer. Clause 15 describes the direct sequence spread spectrum physical layer. Clause 16 describes the infrared baseband physical layer. Clause 17 (IEEE 802.11a) describes the orthogonal frequency division multiplexed physical layer. Clause 18 (IEEE 802.11b) describes the higher rate direct sequence spread spectrum physical layer. Information on all physical layers is found in Chapter 6.

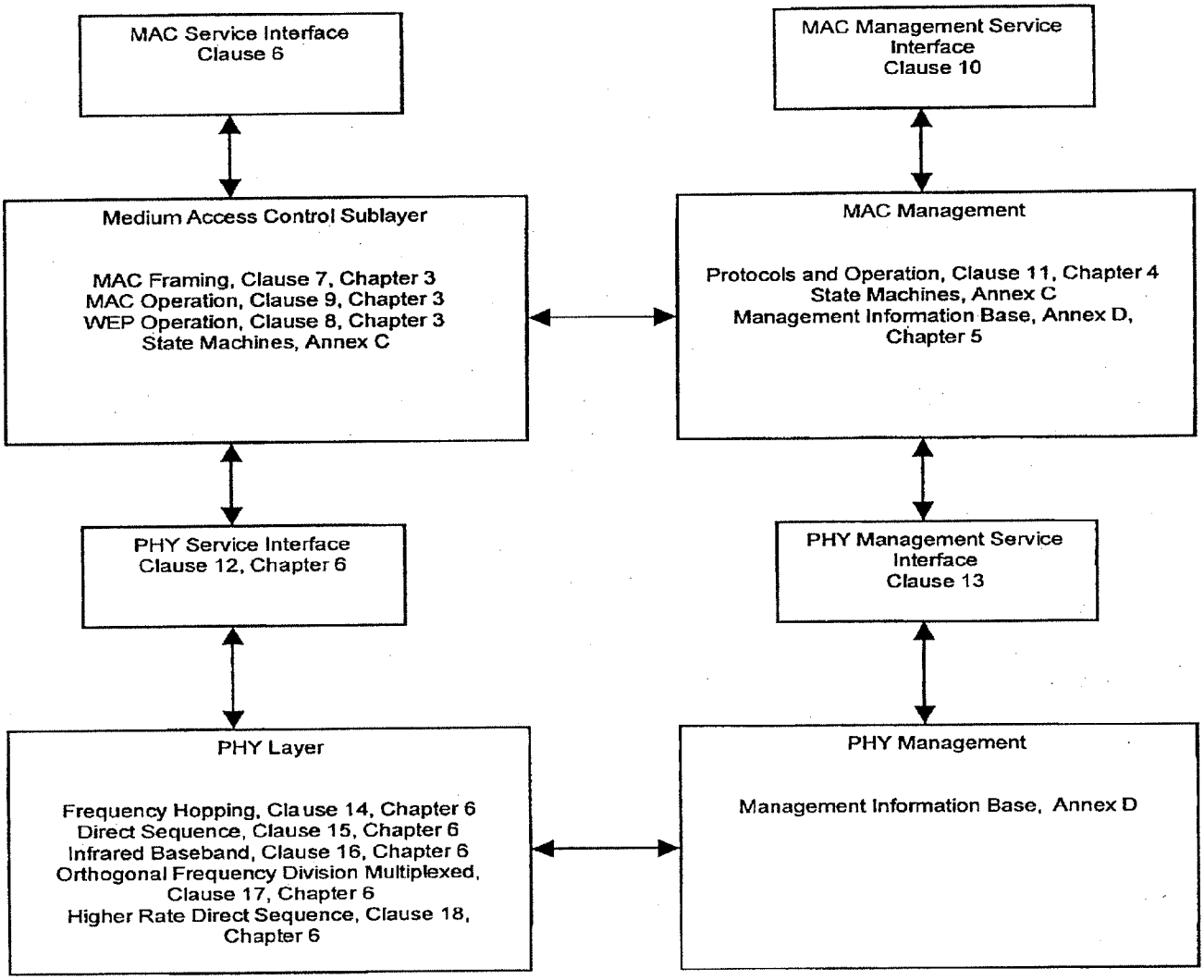
Annex A of the standard is the Protocol Implementation Conformance Statement (PICS) pro forma. This form may be used to identify the exact options implemented in a device claiming conformance to IEEE 802.11. This annex is not discussed in this handbook.

Annex B of the standard is a set of tables of the hopping patterns for the frequency hopping physical layer. This annex is not discussed in this handbook.

Annex C of the standard is the state machine description of the MAC and MAC management functionality. A discussion of the state machines is beyond the scope of this handbook.

Annex D of the standard is the Management Information Base, written in Abstract Syntax Notation 1 (ASN.1) to comply with the requirements of the Simple Network Management Protocol version 2 (SNMPv2). The MAC portion of the MIB is discussed in Chapter 5.

The figure below provides a quick, graphical map between the information in the IEEE 802.11 standard and this handbook.



Where to find information on IEEE 802.11

Updated information about IEEE 802.11 and responses to questions by users of this handbook are provided by the authors at the following Web site: **http://www.informed-technology.com/handbook_additional_material.htm**.

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The IEEE 802.11 Handbook

A Designer's Companion

Chapter 1
Similarities and Differences between Wireless and Wired LANs

There are many similarities and differences of wired LANs and the IEEE 802.11 wireless LAN (WLAN). This chapter will describe them.

Similarities between WLANs and Wired LANs

From the beginning, the IEEE 802.11 WLAN was designed to look and feel like any IEEE 802 wired LAN. This meant that it must appear to be the same as the wired networks to which a user may be accustomed. It must support all of the protocols and all of the LAN management tools that operate on a wired network.

To accomplish the task of similarity to wired LANs, IEEE 802.11 is designed to the same interface as IEEE 802.3. IEEE 802.11 operates under the IEEE 802.2 logical link control (LLC) sublayer, providing all of the services required supporting that sublayer. In this fashion,

IEEE 802.11 is indistinguishable from IEEE 802.3 by the protocols that may be running above IEEE 802.2.

Using the IEEE 802.2 interface guarantees that protocol layers above LLC need not be aware of the network that is actually transporting their data.

Differences between WLANs and Wired LANs

There are also a number of differences between wired LANs and WLANs. The two most important differences are that there are no wires (the air link) and the mobility thus conferred by the lack of a wired tether. These differences lead to both the tremendous benefits of a WLAN, as well as the perceived drawbacks to them.

The air link is the radio or infrared link between WLAN transmitters and receivers. Because WLAN transmissions are not confined to a wire, there may be concerns that the data carried by a WLAN is not private, not protected. This concern is certainly valid; the data on a WLAN is broadcast for all to hear. Many proprietary WLANs do not provide any protection for the data carried. The designers of IEEE 802.11 realized that this concern could be a significant problem for users wishing to use a WLAN and designed strong cryptographic mechanisms into the protocol to provide protection for the data that is at least as strong as sending the data over a wire. Details of this protection are described in Chapter 3.

The air link also exposes the transmissions of a WLAN to the vagaries of electromagnetic propagation. For both radio- and infrared-based WLANs, everything in the environment is either a reflector or an attenuator of the signal carrying the LAN data. This can cause significant changes in the strength of a signal received by a WLAN station, sometimes severing the station from the LAN entirely. At the wavelengths used in the IEEE 802.11 WLAN, small changes in position can

cause large changes in the received signal strength. This is due to the signal traveling many paths of differing length to arrive at the receiver. Each individual arriving signal is of a slightly different phase from all of the others. Adding these different phases together results in the composite signal that is received. Since these individual signals sometimes add up in phase and sometimes out of phase, the overall received signal strength is sometimes large and sometimes small. Objects moving in the environment, such as people, aluminized Mylar balloons, doors, and other objects, can also affect the strength of a signal at a receiver by changing the attenuation or reflection of the many individual signals.

Figure 1-1 is taken from the IEEE Std 802.11-1997 standard and shows the result of a ray tracing simulation in a closed office environment. The various shades of gray depict the different signal strengths at each location in the room. Dealing with the variability of the air link is also designed into the IEEE 802.11 WLAN. For more on this, see Chapter 4.

The second significant difference a WLAN has from a wired LAN is mobility. The user of a WLAN is not tethered to the network outlet in the wall. This is both the source of the benefits of a WLAN and the cause of much of the internal complexity.

The benefit of mobility is that the LAN goes wherever you are, instantly and without the need to search out outlets or to arrange in advance with the network administrators. In a laptop equipped with an IEEE 802.11 WLAN connection, the connection to the network is available in a coworker's office, down the hall in the conference room, downstairs in the lobby, across the parking lot in another building, even across the country on another campus. This means that all of the information available over the network, while sitting in your office, is still available in all these locations: email, file servers, the company-internal web sites, and the Internet.

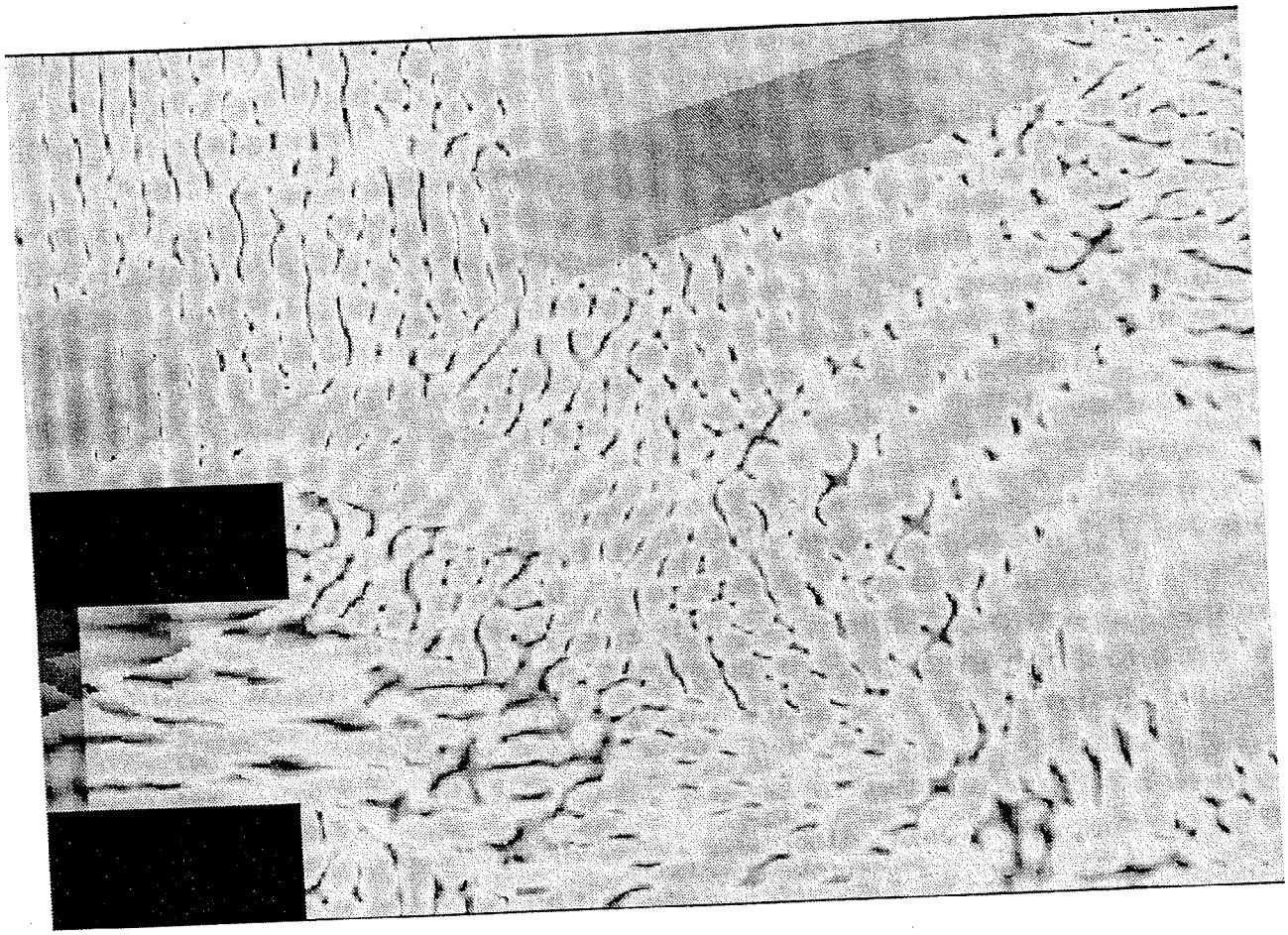

Figure 1-1—Ray Tracing Simulation Results

Of course, there is a flip side to the benefits of mobility. Most of the network protocols and equipment in use today were not designed to cope with mobility. They were designed with an assumption that the addresses assigned to a network node would remain in a fixed location on the network. For example, early WLANs required that a mobile station could only roam within an area where the WLAN was connected to the wired LAN, with only layer-2 bridges between the parts of the WLAN. This requirement existed because there was no simple way to deal with the change of a layer-3 network address should the mobile station cross from one part of the network to another that is connected by a

router. Today, there are ways to deal with this problem using new protocols, including DHCP and Mobile-IP.

Another problem introduced by mobility is that location-based services lose their "hook" to a user's location, when network addresses are not locked to a physical location. Thus, notions such as the nearest network printer must be defined in a different way, when the physical location of a network user may be constantly changing. This may increase the complexity of the service location provider, but meets the needs of the mobile user.

Chapter 2
IEEE Standard 802.11: The First International Standard for WLANs

In 1997 the IEEE adopted the first standard for WLANs, IEEE Std 802.11-1997. This standard was revised in 1999. IEEE Std 802.11-1997 defines a medium access control (MAC) sublayer, MAC management protocols and services, and three physical (PHY) layers. The three PHY layers are an infrared (IR) baseband PHY, a frequency hopping spread spectrum (FHSS) radio in the 2.4 GHz band, and a direct sequence spread spectrum (DSSS) radio in the 2.4 GHz band. All three physical layers describe both 1 and 2 Mbps operation. This chapter will introduce the standard and its concepts.

As this book is being written, the IEEE 802.11 Working Group is developing two new PHY layers. The first, IEEE Std 802.11a, is an orthogonal frequency domain multiplexing (OFDM) radio in the UNII bands, delivering up to 54 Mbps data rates. The second, IEEE Std 802.11b, is an extension to the DSSS PHY in the 2.4 GHz band, delivering up to 11 Mbps data rates.

The goals of the IEEE 802.11 standard is to describe a WLAN that delivers services previously found only in wired networks, e.g., high throughput, highly reliable data delivery, and continuous network connections. In addition, IEEE 802.11 describes a WLAN that allows transparent mobility and built-in power saving operations to the network user. The remainder of this chapter will describe the architecture of the IEEE 802.11 network and the concepts that support that architecture.

IEEE 802.11 Architecture

The architecture of the IEEE 802.11 WLAN is designed to support a network where most decision making is distributed to the mobile stations. This architecture has several advantages, including being very

tolerant of faults in all of the WLAN equipment and eliminating any possible bottlenecks a centralized architecture would introduce. The architecture is very flexible, easily supporting both small, transient networks and large semipermanent or permanent networks. In addition, deep power-saving modes of operation are built into the architecture and protocols to prolong the battery life of mobile equipment without losing network connectivity. The IEEE 802.11 architecture comprises several components: the station, the AP, the wireless medium, the basic service set, the DS, and the Extended Service Set. The architecture also includes station services and distribution services.

The IEEE 802.11 architecture may appear to be overly complex. However, this apparent complexity is what provides the IEEE 802.11 WLAN with its robustness and flexibility. The architecture also embeds a level of indirection that has not been present in previous LANs. It is this level of indirection, handled entirely with the IEEE 802.11 architecture and transparent to protocol users of the IEEE 802.11 WLAN, that provides the ability of a mobile station to roam throughout a WLAN and appear to be stationary to the protocols above the MAC that have no concept of mobility. This "sleight of hand" performed by IEEE 802.11 allows all of the existing network protocols to run over a WLAN without any special considerations.

Station

The station is the component that connects to the wireless medium. It consists of a MAC and a PHY. Generally, the station may be referred to as the network adapter or network interface card (NIC). These names may be more familiar to users of wired networks.

The station may be mobile, portable, or stationary. Every station supports station services. These services are authentication, deauthentication, privacy, and delivery of the data (MAC service data unit or MSDU in the standard). The station services will be described below.

Basic Service Set

The IEEE 802.11 WLAN architecture is built around a basic service set (BSS). A BSS is a set of stations that communicate with one another. A BSS does not generally refer to a particular area, due to the uncertainties of electromagnetic propagation. When all of the stations in the BSS are mobile stations and there is no connection to a wired network, the BSS is called an independent BSS (IBSS). The IBSS is the entire network and only those stations communicating with each other in the IBSS are part of the LAN. An IBSS is typically a short-lived network, with a small number of stations, that is created for a particular purpose, e.g., to exchange data with a vendor in the lobby of your company's building or to collaborate on a presentation at a conference.

In an IBSS, the mobile stations all communicate directly with one another. Not every mobile station may be able to communicate with every other mobile station, but they are all part of the same IBSS. There is also no relay function in an IBSS. Thus, if one mobile station must communicate with another, they must be in direct communication range. See Figure 2-1.

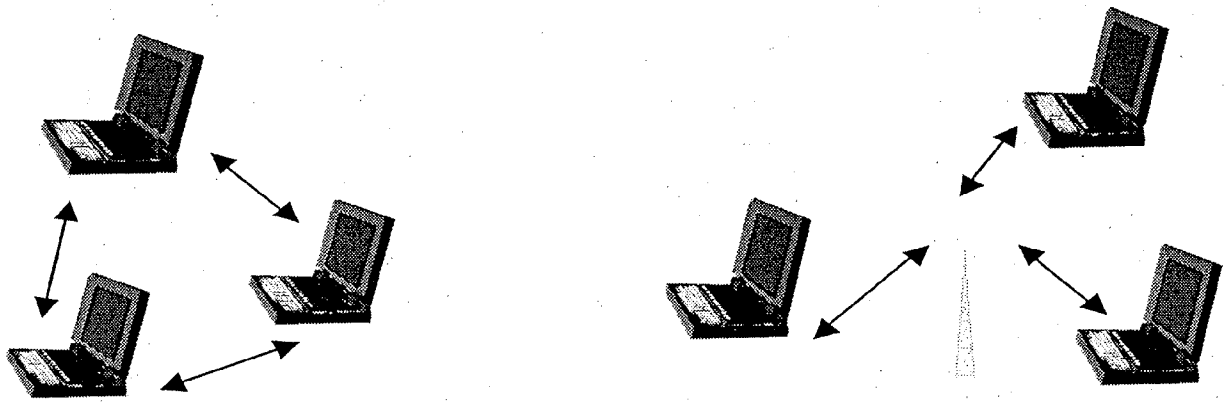

Figure 2-1—Independent Basic Service Set (IBSS)

When a BSS includes an access point (AP), the BSS is no longer independent and is called an infrastructure BSS, but referred to simply as a BSS. An AP is a station that also provides distribution services. Distribution services will be described below.

In an infrastructure BSS, all mobile stations communicate with the AP. The AP provides both the connection to the wired LAN, if any, and the local relay function for the BSS. Thus, if one mobile station in the BSS must communicate with another mobile station, the communication is sent first to the AP and then from the AP to the other mobile station. This causes communications that both originate and end in the same BSS to consume twice the bandwidth that the same communication would consume if sent directly from one mobile station to another. While this appears to be a significant cost, the benefits provided by the AP far outweigh this cost. One of the benefits provided by the AP is the buffering of traffic for a mobile station while that station is operating in a very low power state. The protocols and mechanisms for the support of power saving by mobile stations is described in Chapter 4.

Extended Service Set (ESS)

One of the most desirable benefits of a WLAN is the mobility it provides to its users. This mobility would not be of much use if it were confined to a single BSS. IEEE 802.11 extends the range of mobility it provides to any arbitrary range through the extended service set (ESS). An ESS is a set of infrastructure BSSs, where the APs communicate among themselves to forward traffic from one BSS to another and to facilitate the movement of mobile stations from one BSS to another. The APs perform this communication via an abstract medium called the distribution system (DS). The DS is the backbone of the WLAN and may be constructed of either wired or wireless networks. The DS is a thin layer in each AP that determines if communications received from the BSS are to be relayed back to a destination in the BSS, forwarded on the DS to another AP, or sent into the wired network infrastructure to a destination not in the ESS. Communications received by an AP from the DS are transmitted to the BSS to be received by the destination mobile

station. To network equipment outside of the ESS, the ESS and all of its mobile stations appears to be a single MAC-layer network where all stations are physically stationary. Thus, the ESS hides the mobility of the mobile stations from everything outside the ESS. This is the level of indirection provided by the IEEE 802.11 architecture, allowing existing network protocols that have no concept of mobility to operate correctly with a WLAN where there is lots of mobility. See Figure 2-2.

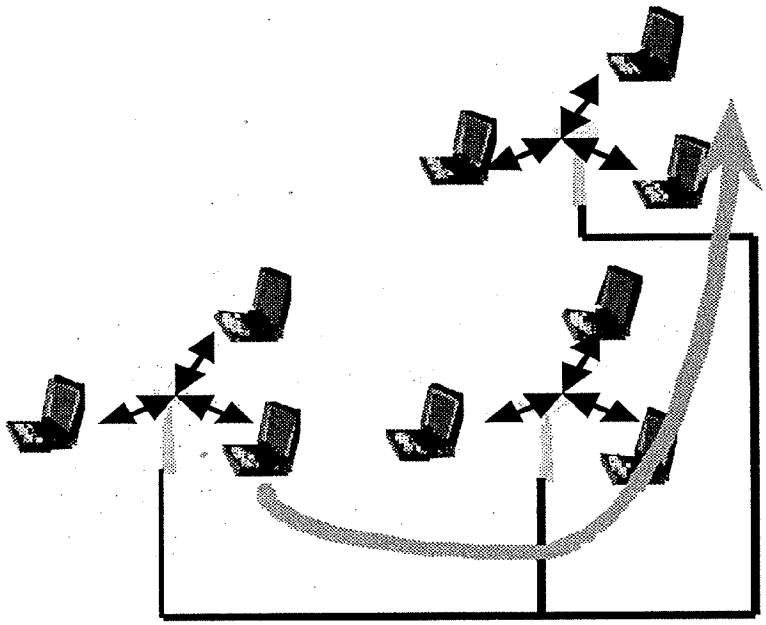

Figure 2-2—Extended Service Set

One area that is beyond the scope of the IEEE 802.11 standard is the communication between APs. There has been some industry cooperative work in this area to develop an inter-access point protocol (IAPP). Because this work has not yet been completed, it is unlikely that APs from different vendors will communicate well enough to allow a single ESS to be created from APs of different vendors.

Distribution System

The distribution system (DS) is the mechanism by which one AP communicates with another to exchange frames for stations in their BSSs, forward frames to follow mobile stations from one BSS to another, and exchange frames with wired networks, if any. As IEEE 802.11 describes it, the DS is not necessarily a network. The standard does not place any restrictions on how the DS is implemented, only on the services it must provide. Thus, the DS may be a wired network, such as IEEE 802.3, or it may be a purpose-built box that interconnects the APs and provides the required distribution services.

Services

There are nine services defined by the IEEE 802.11 architecture. These services are divided into two groups, station services and distribution services. The station services comprise authentication, deauthentication, privacy, and delivery of the data. The distribution services comprise association, disassociation, reassociation, distribution, and integration.

Station Services

The four station services—authentication, deauthentication, privacy, and data delivery—provide the IEEE 802.11 WLAN similar functions to those that are expected of a wired network. The wired network function of physically connecting to the network cable is similar to the authentication and deauthentication services, where use of the network is allowed only to authorized users. The authentication service is used to prove the identity of one station to another. Without this proof of identity, the station is not allowed to use the WLAN for data delivery. The deauthentication service is used to eliminate a previously authorized user from any further use of the network. Thus, once a station is deauthenticated, e.g., when an employee resigns, that station can no longer access the services of the IEEE 802.11 WLAN.

The privacy service of IEEE 802.11 is designed to provide an equivalent level of protection for data traversing the WLAN as that provided by a wired network that exists in an office building with restricted physical access to the network plant. This service protects the data only as it traverses the wireless medium. It is not designed to provide complete protection of data between applications running over a mixed network environment that happens to include an IEEE 802.11 WLAN.

Finally, the data delivery service of an IEEE 802.11 WLAN is similar to that provided by all other IEEE 802 LANs. The data delivery service provides reliable delivery of data frames from the MAC in one station to the MAC in one or more other stations, with minimal duplication and minimal reordering.

Distribution Services

The five distribution services—association, reassociation, disassociation, distribution, and integration—provide the services necessary to allow mobile stations to roam freely within an ESS and allow an IEEE 802.11 WLAN to connect with the wired LAN infrastructure. The distribution services comprise a thin layer above the MAC and below the LLC sublayer that are invoked to determine how to forward frames within the IEEE 802.11 WLAN and also how to deliver frames from the IEEE 802.11 WLAN to network destinations outside of the WLAN.

The association service is used to make a logical connection between a mobile station and an AP. This logical connection is necessary in order for the DS to know where and how to deliver data to the mobile station. The logical connection is also necessary for the AP to accept data frames from the mobile station and to allocate resources to support the mobile station. Typically, the association service is invoked once, when the mobile station enters the WLAN for the first time, after the application of power or when rediscovering the WLAN after being out of touch for a time.

The reassociation service is similar to the association service, with the exception that it includes information about the AP with which a mobile station has been previously associated. A mobile station will use the reassociation service repeatedly as it moves throughout the ESS, loses contact with the AP with which it is associated, and needs to become associated with a new AP. By using the reassociation service, a mobile station provides information to the AP to which it will be associated that allows that AP to contact the AP with which the mobile station was previously associated, to obtain frames that may be waiting there for delivery to the mobile station, as well as other information that may be relevant.

The disassociation service is used either to force a mobile station to associate or for a mobile station to inform an AP that it no longer requires the services of the WLAN. An AP to inform one or more mobile stations that the AP can no longer provide the logical connection to the WLAN may use the disassociation service. This may be due to demand exceeding available resources in the AP, the AP shutting down, or for any number of other reasons. When the mobile station becomes disassociated, it must begin a new association by invoking the association service.

A mobile station may also use the disassociation service. When a mobile station is aware that it will no longer require the services of the AP, it may invoke the disassociation service to notify the AP that the logical connection to the WLAN from this mobile station is no longer required. For example, this may be done when the mobile station is being shut down or when the IEEE 802.11 adapter card is being ejected. At that point, an AP may free any resources dedicated to the mobile station and recover them for other uses.

An AP to determine how to deliver the frames it receives uses the distribution service. When a mobile station sends a frame to the AP for delivery to another station, the AP invokes the distribution service to determine if the frame should be sent back into its own BSS, for delivery to a mobile station that is associated with the AP, or if the frame

should be sent into the DS for delivery to another mobile station associated with a different AP or to a network destination outside the IEEE 802.11 WLAN. The distribution service determines if the frame is sent to another AP or to a portal.

The integration service connects the IEEE 802.11 WLAN to other LANs, including one or more wired LANs, or other IEEE 802.11 WLANs. A portal performs the integration service. The portal is an abstract architectural concept and may physically reside as a thin layer in some or all APs, or may be a separate network component entirely. The integration service translates IEEE 802.11 frames to frames that may traverse another network, and vice versa, translates frames from other networks to frames that may be delivered by an IEEE 802.11 WLAN.

Interaction between Some Services

The IEEE 802.11 standard states that each station must maintain two variables that are dependent on the authentication/deauthentication services and the association/reassociation/disassociation services. The two variables are authentication state and association state. While the standard describes these variables as being enumerated types, they are available only internal to an implementation and can be implemented as Boolean truth-values. The variables are used in a simple state machine that determines the order in which certain services must be invoked and when a station may begin using the data delivery service. The variables must exist in enough instances to allow the station to maintain a unique copy for each station with which it communicates. A station may be authenticated with many different stations simultaneously. However, a station may be associated with only one other station at a time.

A station begins operation in state 1, where both authentication state and association state are false, indicating that the station is neither authenticated nor associated. In state 1, a station may use a very limited number of frame types. (The details of the frame types will be described in Chapter 3.) The allowable frame types provide the capability for a station in state 1 to find an IEEE 802.11 WLAN, an ESS, and its APs, to complete

the required frame handshake protocols, and to implement the authentication service. If a station is not successful in becoming authenticated, it will remain in state 1. If a station becomes authenticated, setting authentication state to true, it will make a transition to state 2. See Figure 2-3.

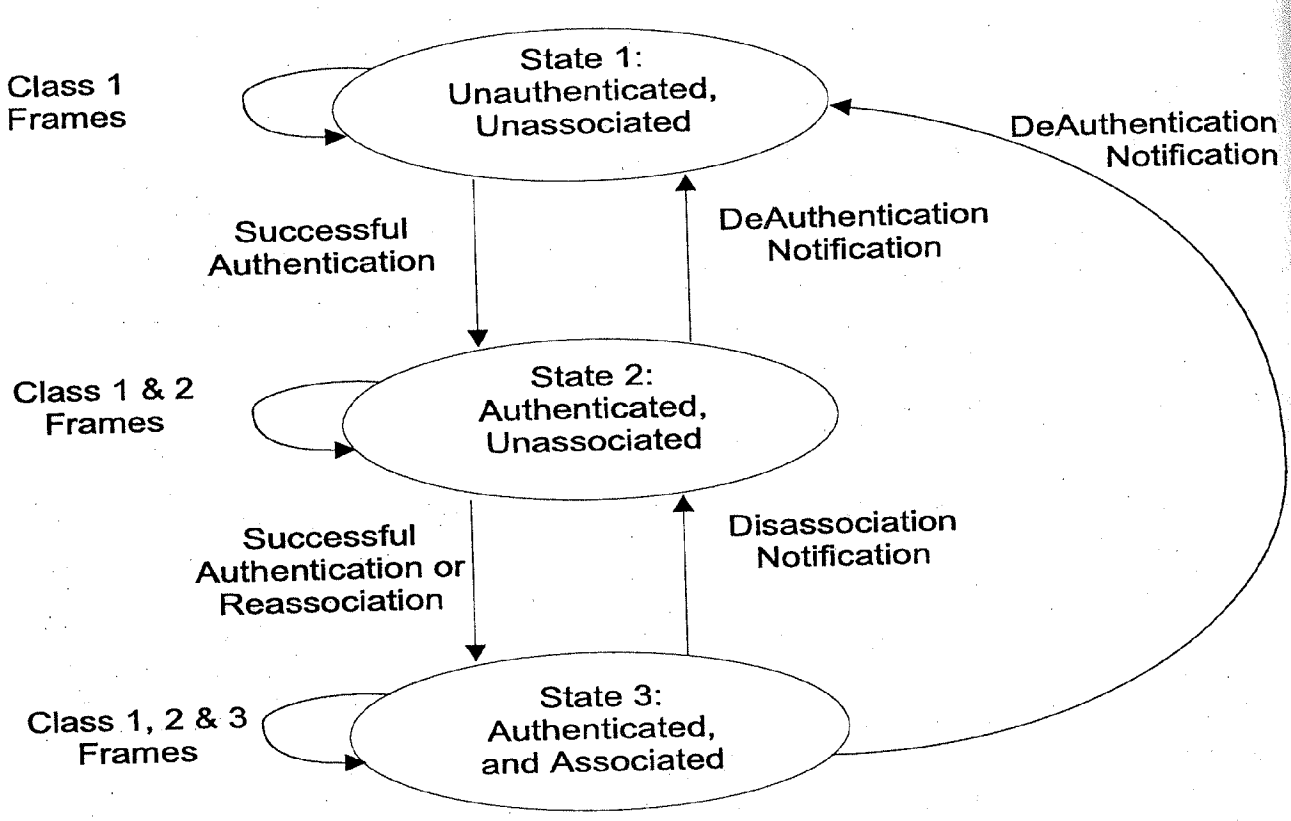

Figure 2-3—Relationship between State Variables and Services

If a station is part of an IBSS, it is allowed to implement the data service in state 1. This is because neither authentication nor association is used in an IBSS, leaving no mechanism for a station in an IBSS to leave state 1.

In state 2, the station has been authenticated, indicated by authentication state being true, but not yet associated. In this state, additional frame types are allowed, beyond those allowed in state 1. The additional frame

types provide the capability for a station in state 2 to implement the association, reassociation, and disassociation services. If a station is not successful in becoming associated, it will remain in state 2, unless it receives a deauthentication notification, in which case it will return to state 1 and authentication state will be made false. If a station becomes associated, setting association state to true, it will make a transition to state 3.

In state 3, the station has been both authenticated and associated, indicated by both authentication state and association state being true. In this state, all frame types are allowed and the station may use the data delivery service. A station will remain in this state until receiving either a disassociation notification or a deauthentication notification, or until it reassociates with another station. If a station receives a disassociation notification, it will make a transition to state 2 and set association state to false. If a station receives a deauthentication notification, it will make a transition to state 1 and set both authentication state and association states to false.

A station must react to frames it receives in each of the states, even those that are disallowed for a particular state. A station will send a deauthentication notification to any station with which it is not authenticated if it receives frames that are not allowed in state 1. A station will send a disassociation notification to any station with which it is authenticated, but not associated, if it receives frames not allowed in state 2. These notifications will force the station that sent the disallowed frames to make a transition to the proper state in the state diagram and allow it to proceed properly toward state 3.

It can now be seen that a station will make transitions between the states of this state machine many times as it roams through an ESS. Because a station may be authenticated with many stations at once, it may be in state 2 with relation to those stations. However, a station may only be in state 3 with relation to a single other station. When a station reassociates with another station, the station with which it was previously associated must be moved back to state 2, by setting the value of associated state for that station to false.

As a graphical example of how the services are used, Figure 2-4 shows a station moving between APs. As the station finds AP1, it will authenticate and associate (a). As the station moves, it may pre-authenticate with AP2 (b). When the station determines that its association with AP1 is no longer desirable, it may reassociate with AP2 (c). The reassociation causes AP2 to notify AP1 of the new location of the station, terminating the station's previous association with AP1 (d). At some point, AP2 may be taken out of service. Should this occur, AP2 would disassociate the stations that were associated with it (e). At this point the station would need to find another access point and authenticate and associate, in order to continue using the wireless LAN (f).

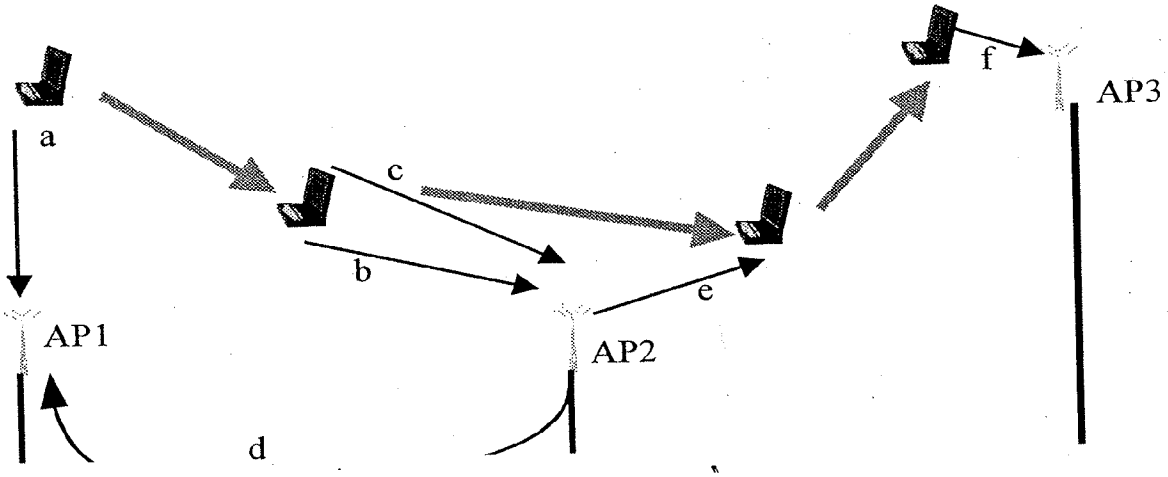

Figure 2-4—Example Usage of the Services

Summary

The architecture and services of IEEE 802.11 are designed to allow the WLAN to appear identical to wired LANs. The architecture clearly divides the functionality of the WLAN into nonoverlapping functional blocks. The services described by IEEE 802.11 provide the user of IEEE 802.11 with the functionality of a wired LAN and the additional benefits of nearly ubiquitous mobility.

Chapter 7
Physical Layer Extensions to IEEE 802.11

In October 1997 the IEEE 802 Executive Committee approved two projects to for higher rate physical layer (PHY) extensions to IEEE 802.11. The first extension, IEEE 802.11a, defines requirements for a PHY operating in the 5.0 GHz U-NII frequency and data rates ranging from 6 Mbps to 54 Mbps. The second extension, IEEE 802.11b, defines a set of PHY specifications operating in the 2.4 GHz ISM frequency band up to 11Mbps. Both PHY are defined to operate with the existing MAC. At the time this handbook was written, the draft specifications for IEEE 802.11a and IEEE 802.11b were in the final stages of approval, and vendors' products were starting to emerge in the market. This chapter gives the reader a general overview of some of the requirements specified for each.

IEEE 802.11a — The OFDM Physical Layer

The IEEE 802.11a PHY is one of the physical layer (PHY) extensions of IEEE 802.11 and is referred to as the orthogonal frequency division multiplexing (OFDM) PHY. The OFDM PHY provides the capability to transmit PSDU frames at multiple data rates up to 54 Mbps for WLAN networks where transmission of multimedia content is a consideration. The OFDM PHY defined for IEEE 802.11a is similar to the OFDM PHY specification of ETSI-HIPERLAN II. At the time this book was written, both organizations were in the final stages of agreeing to a common set of specifications.

In the OSI structure, the PHY's PLCP sublayer and PMD sublayer are unique to the OFDM PHY. The following sections give an overview of the PLCP header, data rates, and modulations defined in IEEE 802.11a.

OFDM PLCP Sublayer

The PPDU is unique to the OFDM PHY. The PPDU frame consists of a PLCP preamble and signal and data fields as shown in Figure 7-1. The receiver uses the PLCP preamble to acquire the incoming OFDM signal and synchronize the demodulator. The PLCP header contains information about the PSDU from the sending OFDM PHY. The PLCP preamble and the signal field are always transmitted at 6 Mbps, binary phase shift keying (BPSK)-OFDM modulated using convolutional encoding rate R = 1/2.

PLCP preamble: This field is used to acquire the incoming signal and train and synchronize the receiver. The PLCP preamble consists of 12 symbols, ten of which are short symbols, and two long symbols. The short symbols are used to train the receiver's AGC and obtain a coarse estimate of the carrier frequency and the channel. The long symbols are used to fine-tune the frequency and channel estimates. Twelve subcarriers are used for the short symbols and 53 for the long. The training of an OFDM is accomplished in 16 μs. PLCP preamble is BPSK–OFDM modulated at 6 Mbps.

Signal: The signal is a 24-bit field, which contains information about the rate and length of the PSDU. The Signal field is convolutional encoded rate 1/2, BPSK–OFDM modulated. Four bits (R1-R4) are used to encode the rate, eleven bits are defined for the length, one reserved bit, a parity bit, and six "0" tail bits. The rate bits (R1-R4) are defined in Table 7-1. The mandatory data rates for IEEE 802.11a-compliant systems are 6 Mbps, 12 Mbps, and 24 Mbps.

Length: The length field is an unsigned 12-bit integer that indicates the number of octets in the PSDU.

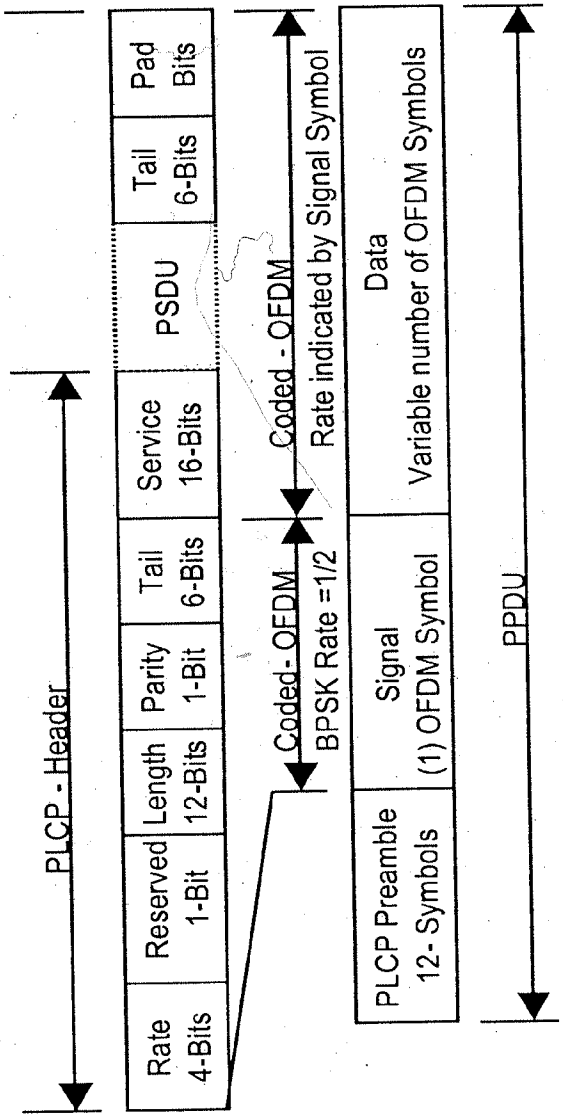

Figure 7-1—OFDM PLCP Preamble, Header, and PSDU

Table 7-1—PSDU Date Rate Selection

Rate	Modulation	Coding Rate	Signal bits (R1-R4)
6 Mbps	BPSK	R = 1/2	1101
9 Mbps	BPSK	R = 3/4	1111
12 Mbps	QPSK	R = 1/2	0101
18 Mbps	QPSK	R = 3/4	0111
24 Mbps	16QAM	R = 1/2	1001
36 Mbps (optional)	16QAM	R = 3/4	1011
48 Mbps (optional)	64QAM	R = 2/3	0001
54 Mbps (optional)	64QAM	R = 3/4	0011

Data: The data field contains the service field, PSDU, tails bits, and pad bits. A total of six tail bits containing 0s are appended to the PPDU to ensure that the convolutional encoder is brought back to zero state. The equation for determining the number of bits in the data field, the number of tail bits, the number of OFDM symbols, and the number pad bits is defined in IEEE 802.11a. The data portion of the packet is transmitted at the data rate indicated in the signal field.

Data Scrambler

All the bits transmitted by the OFDM PMD in the data portion are scrambled using a frame-synchronous 127-bit sequence generator. Scrambling is used to randomize the service, PSDU, pad bit, and data patterns, which may contain long strings of binary 1s or 0s. The tail bits are not scrambled. The scrambling polynomial for the OFDM PHY is: $S(x) = x^{-7} + x^{-4} + 1$. The initial state of the scrambler is randomly

chosen. Prior to scrambling the PPDU frame, the seven least significant bits of the service field are reset to 0 in order to estimate the initial state of the scrambler in the receiver.

Convolutional Encoding

All information contained in the service, PSDU, tail, and pad are encoded using convolutional encoding rate R = 1/2, 2/3, or 3/4 corresponding to the desired data rate. Convolutional encoding is generated using the following polynomials; $g_0 = 133_8$ and $g_1 = 171_8$ of rate R = 1/2. Puncture codes are used for the higher data rates. Industry standard algorithms, such as the Viterbi algorithm, are recommended for decoding.

OFDM Modulation

In July of 1998 the IEEE 802.11 Working Group adopted OFDM modulation as the basis for IEEE 802.11a. This OFDM method chosen is similar to the modulation technique adopted in Europe by ETSI-HIPERLAN II 5 GHz radio PHY specification. The basic principal of operation first divides a high-speed binary signal to be transmitted into a number of lower data rate subcarriers. There are 48 data subcarriers and 4 carrier pilot subcarriers for a total of 52 nonzero subcarriers defined in IEEE 802.11a. Each lower data rate bit stream is used to modulate a separate subcarrier from one of the channels in the 5 GHz band. Intersymbol interference is generally not a concern for lower speed carrier, however the subchannels may be subjected to frequency selective fading. Therefore, bit interleaving and convolutional encoding is used to improve the bit error rate performance. The scheme uses integer multiples of the first subcarrier, which are orthogonal to each other. This technique is known as orthogonal frequency division multiplexing (OFDM). Prior to transmission the PPPU is encoded using a convolutional coded rate R = 1/2, and the bits are reordered and bit interleaved for the desired data rate. Each bit is then mapped into a complex number according the modulation type and subdivided in 48 data subcarriers and 4 pilot subcarriers. The subcarriers are combined

using an inverse fast fourier transform and transmitted. At the receiver, the carrier is converted back to a multicarrier lower data rate form using an FFT. The lower data subcarriers are combined to form the high rate PPDU. An example of an IEEE 802.11a OFDM PMD is illustrated in Figure 7-2.

OFDM Operating Channels and Transmit Power Requirements

The 5 GHz U-NII frequency band is segmented into three 100 MHz bands for operation in the US. The lower band ranges from 5.15–5.25 GHz, the middle band ranges from 5.25–5.35 GHz and the upper band ranges from 5.725–5.825 GHz. The lower and middle bands accommodate 8 channels in a total bandwidth of 200 MHz and the upper band accommodates 4 channels in a 100 MHz bandwidth. The frequency channels center frequencies are spaced 20 MHz apart. The outermost channels of the lower and middle bands are centered 30 MHz from the outer edges. In the upper band the outermost channel centers are 20 MHz from the outer edges. The channel frequencies and numbering defined in IEEE 802.11a start at 5 GHz and each channel is spaced 5 GHz apart. A set of channel frequencies for each of the U-NII bands is defined in Table 7-2.

In addition to frequency and channel allocations, transmit power is a key parameter regulated in the 5 GHz U-NII frequency band. Three transmit RF power levels are specified; 40 mW, 200 mW and 800 mW as illustrated in Table 7-3. The upper band defines RF transmit power levels suitable for bridging applications while the lower band specifies a transmit power level suitable for short-range indoor home and small office environments.

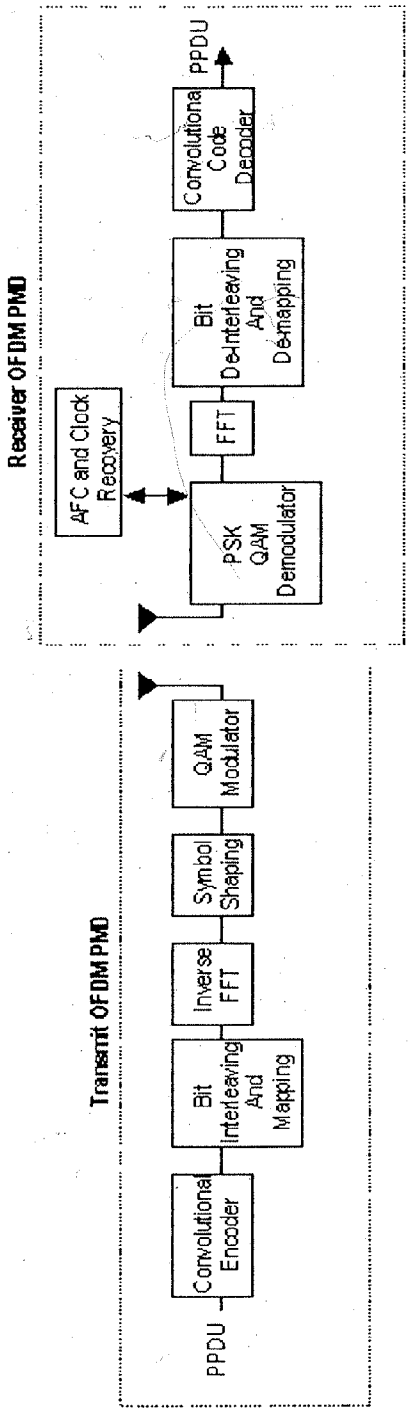

Figure 7-2—IEEE 802.11a Transmit and Receive OFDM PMD

Table 7-2—Channel Frequencies and Channel Numbers for Operating in the US

Regulatory Domain	Frequency Band	Channel Number	Center Frequencies
USA	U-NII lower band 5.15–5.25 GHz	36 40 44 48	5.180 GHz 5.220 GHz 5.220 GHz 5.240 GHz
USA	U-NII middle band 5.25–5.35 GHz	52 56 60 64	5.260 GHz 5.280 GHz 5.300 GHz 5.320 GHz
USA	U-NII upper band 5.725–5.825 GHz	149 153 157 161	5.745 GHz 5.765 GHz 5.785 GHz 5.805 GHz

Table 7-3—Transmit Power Levels for North America Operation

Frequency Band	Maximum Transmit Power with 6 dBi Antenna Gain
5.150 – 5.250 GHz	40 mW (2.5 mW/MHz)
5.250– 5.350 GHz	200 mW (12.5 mW/MHz)
5.725– 5.825 GHz	800 mW (50 mW/MHz)

Geographic Regulatory Bodies

WLAN IEEE 802.11a-compliant OFDM radios operating in the 5 GHz UNII frequency band must comply with the local geographical regulatory domains before operating in this spectrum. These products are subject to certification. At the time IEEE 802.11a was being developed, the technical requirements were specified to comply with the regulatory requirements in North America. The regulatory agencies set emission requirements for WLANs to minimize the amount of interference a radio can generate or receive from another in the same proximity. The regulatory requirements do not affect the interoperability of IEEE 802.11a-compliant products. It is the responsibility of the product developers to check with the regulatory agencies for the necessary certifications. In the US the FCC is responsible for the allocation of 5 GHz U-UNII bands.

North America

Geographic Area: USA
Approval Standards: Federal Communications Commission (FCC)
Documents: CFR47, Part 15; Sections 15.205,15.209, and subpart E; Sections 15.401–15.407
Approval Authorities: Federal Communications Commission (FCC)

Globalization of Spectrum at 5 GHz

At the time, we were writing this book, IEEE 802.11, ETSI's HIPERLAN II and Japan's Mobile Multimedia Access Communication Promotion Council (MMAC-PC) were pursuing available spectrum allocations in the 5 GHz band. In Europe the 5.15–5.35 GHz frequency band is reserved for HIPERLAN II devices. Discussions were underway between ETSI-HIPERLAN II and IEEE 802.11 to share the lower 5 GHz band as a possibility, drawing on the extreme similarity of the PHY layers of both projects. In Japan the Wireless Ethernet Working Group of the MMAC-PC recommends using the 802.11a standard whenever the 5.15–5.25 GHz band becomes available in Japan.

IEEE 802.11b–2.4 High Rate DSSS PHY

The IEEE 802.11b PHY is one of the PHY layer extensions of IEEE 802.11 and is referred to as high rate direct sequence spread spectrum (HR/DSSS). The HR/DSSS PHY provides two functions. First, the HR/DSSS extends the PSDU data rates to 5.5 Mbps and 11 Mbps using an enhanced modulation technique. Secondly, the HR/DSSS PHY provides a rate shift mechanism, which allows 11 Mbps networks to fall back to 1 and 2 Mbps and interoperate with the legacy IEEE 802.11 2.4 GHz RF PHY layers. The OSI structure and operation of the PHY's PLCP sublayer and PMD sublayer for HR/DSSS is similar to the existing IEEE 802.11 DSSS PHY described in Chapter 6. The following sections give an overview of the PLCP header, data rates, and modulations defined in IEEE 802.11b.

HR/DSSS PHY PLCP Sublayer

A PPDU frame consists of the PLCP preamble, PLCP header, and the PSDU. As with IEEE 802.11 DSSS, the PMD uses the PLCP preamble to acquire the incoming signal and synchronize the receiver's demodulator. The HR/DSSS PHY defines two PLCP preambles, long and short (see Figure 7-3). The long preamble uses the same PLCP preamble and header as the IEEE 802.11 DSSS PHY and sends the information at 1 Mbps using DBPSK and Barker word direct sequence spreading. The PSDU is transmitted at 1, 2, 5.5, and 11 Mbps as determined by the content in the signal field. The long preamble is backwards compatible with existing IEEE 802.11 DSSS PHY and defined to interoperate with existing IEEE 802.11 wireless networks operating at 1 and 2 Mbps.

The short preamble uses a 56-bit SYNC field to acquire the incoming signal, and transmits the preamble at 1 Mbps using DBPSK modulation and Barker word spreading. The PLCP header transmits at 2 Mbps using DQPSK and Barker word spreading (see Figure 7-3) In this case, the PSDU is transmitted at 2, 5.5, or 11 Mbps as determined by the content in the signal field. The short preamble is an option in IEEE 802.11b and is useful for those networks where throughput efficiency and interoperability with existing IEEE 802.11 DSSS radios in not necessary. There is one caveat: the short preamble radio can only interoperate with itself; therefore, for a short preamble radio to be IEEE 802.11b compliant must support the long preamble.

SYNC: The receiver uses this field to acquire the incoming signal and synchronize the receiver's carrier tracking and timing prior to receiving the SFD. The long preamble SYNC field is 128 bits in length containing a string of scrambled 1s. The scrambler seed bit patterned used to initialize the scrambler for the long preamble is 01101100. The short preamble SYNC field is 56 bits in length and contains a string of scrambled 0s. The scrambler seed bit patterned used to initialize the scrambler for short preamble operation is 00011010. The short preamble SYNC field is used for networks where minimizing overhead and maximizing PSDU throughput is a consideration.

SFD: This field contains information marking the start of a PPDU frame. The SFD specified is common for all IEEE 802.11 DSSS and IEEE 802.11b long preamble radios. The following hexadecimal word is used: F3A0hex transmitted LSB first. For short preamble radios, the following hexadecimal word is used: 05CFhex transmitted LSB first.

Signal: The signal field defines which type of modulation must be used to receive the incoming PSDU. The binary value in this field is equal to the data rate multiplied by 100 kbit/s. The 1 Mbps data rate is used for long and short preamble implementations.

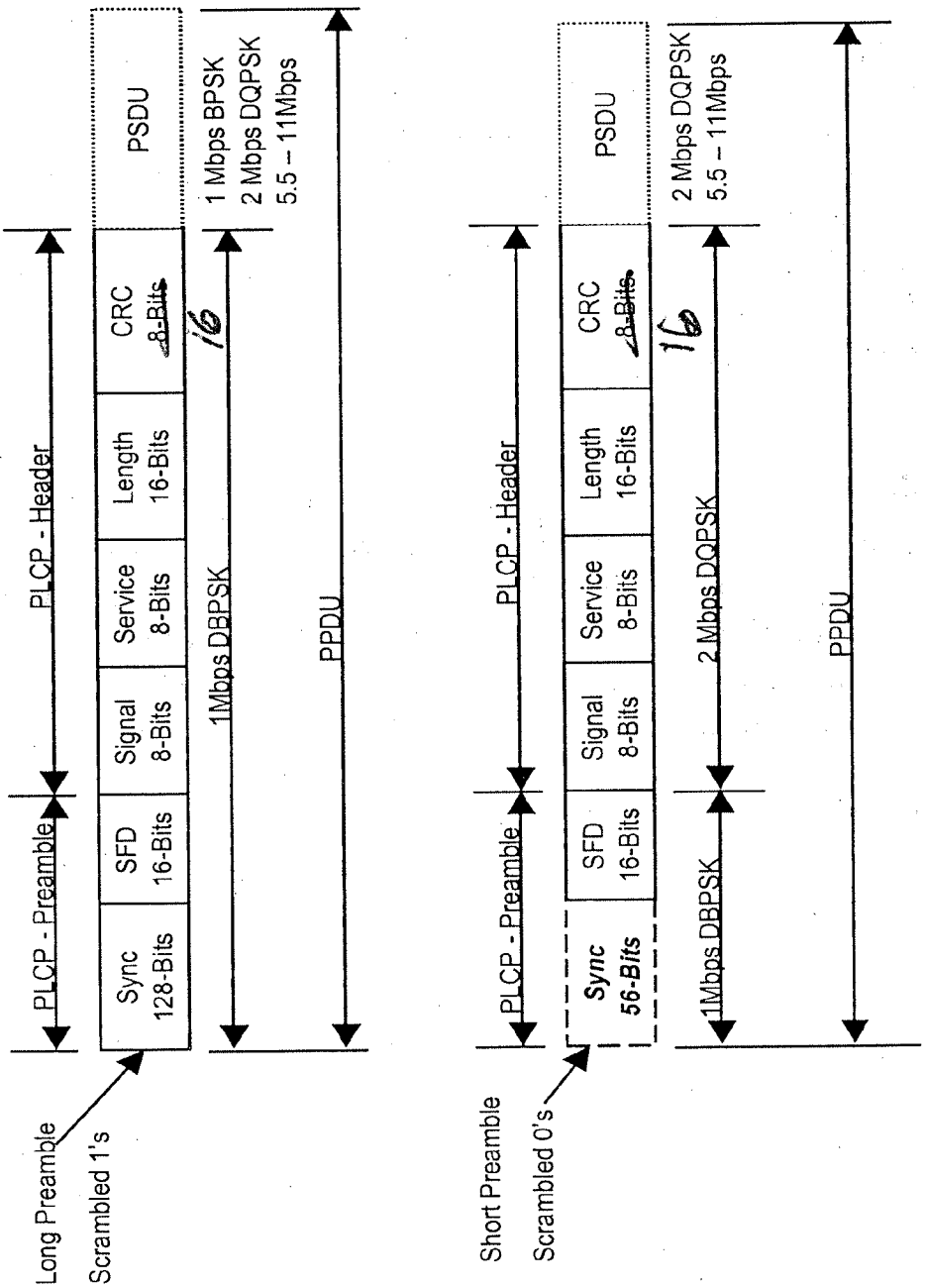

Figure 7-3 – HR/DSSS PHY Long and Short Preamble PLCP, Header, and PSDU

The bit patterns in this field always represent the following data rates:

Signal Field	Data Rate
00001010	1 Mbps (long preamble only)
00010100	2 Mbps
~~00111110~~ 0011 0111 = 37h	5.5 Mbps
01101110	11 Mbps

Service: The service field uses 3 bits of the reserved 8 bits for IEEE 802.11b. Data bit (b2) determines whether the transmit frequency and symbol clocks use the same local oscillator. Data bit (b3) indicates whether complimentary code keying (CCK) or packet binary convolutional coding (PBCC) is used and data bit (b7) is a bit extension used in conjunction with the length field to calculate the duration of the PSDU in microseconds. This field is used for the long and short preamble frames.

Length: The length field is an unsigned 16-bit integer that indicates the number of microseconds necessary to transmit the PSDU. For any data rate over 8 Mbps, bit-7 of the service field is used with the length field to determine the time in microseconds from the number of octets contained in the length field. A calculation is defined in IEEE 802.11b for determining the length in microseconds for CCK and PBCC as applied to both preambles. The MAC layer uses this field to determine the end of a PPDU frame.

CRC: The CRC field contains the results of a calculated frame check sequence from the sending station. The calculation is performed prior to data scrambling for the long and short preamble. The CCITT CRC-16 error detection algorithm is used to protect the signal, service, and length fields. The CRC-16 algorithm is represent by the following polynomial: $G(x) = x^{16} + x^{12} + x^5 + 1$. The receiver performs the calculation on the incoming Signal, Service and Length field and compares the results against the transmitted value. If an error is detected, the receiver's MAC makes the decision if incoming PSDU should be terminated.

High Rate Data Scrambling

All information bits transmitted by the DSSS PMD are scrambled using a self-synchronizing 7-bit polynomial. The scrambling polynomial for the DSSS PHY is: $G(z) = z^{-7} + z^{-4} + 1$. Scrambling is used to randomize the long and short preamble data in the SYNC field of the PLCP and for data patterns which contain long strings of binary 1s or 0s. The receiver can descramble the information bits without prior knowledge from the sending station. The scrambler initialization bit patterns are represented as (00011010) for the short preamble and (01101100) for the long preamble.

IEEE 802.11 High Rate Operating Channels

The HR/DSSS PHY uses the same frequency channels as defined in Chapter 6 for the IEEE 802.11 direct sequence PHY. The channel center frequencies are spaced 25 MHz apart to allow multiple WLAN systems to operate simultaneously in the same area without interfering with each other. An example of a typical channel arrangement for noninterfering channels for North America is illustrated in Figure 7-4. In Europe the channels 1 (2.412 GHz), 7 (2.442 GHz) and 13 (2.472 GHz) are used to form three non-interfering networks.

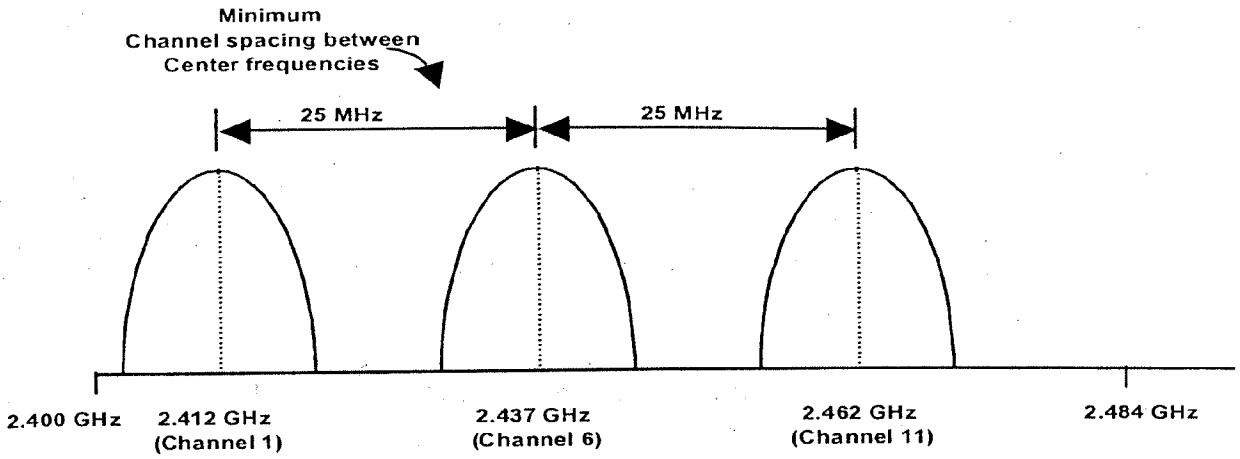

Figure 7-4—Minimum Channel Spacing for IEEE 802.11 High Rate Networks

IEEE 802.11 DSSS High Rate Modulation and Data Rates

There are four modulation formats and data rates defined in IEEE 802.11b. The data rates include the basic rate, the extended rate, and enhanced rate. The basic rate is defined, as 1 Mbps modulated with DBPSK, and the extended rate is 2 Mbps DQPSK modulated. The 11-bit Barker word is used as the spreading format for the basic and extended rate as described for the DSSS PHY in Chapter 6. The enhanced rate is defined to operate at 5.5 Mbps and 11 Mbps using CCK modulation and packet binary convolutional coding (PBCC). PBCC is an option in the standard for those networks requiring enhanced performance. Frequency agility is another option defined in IEEE 802.11b. As with the 1 and 2 Mbps DSSS PHY, this option enables existing IEEE 802.11 FHSS 1 Mbps networks to be interoperable with 11 Mbps CCK high rate networks. The PBCC and frequency agility option are described later in the section.

Complementary Code Keying (CCK) Modulation

In July of 1998, the IEEE 802.11 Working Group adopted CCK as the basis for the high rate extension to deliver PSDU frames at speeds of 5.5 Mbp and 11 Mbps. CCK was adopted because it easily provides a path for interoperability with existing IEEE 802.11 1 and 2 Mbps systems by maintaining the same bandwidth and incorporating the existing DSSS PHY PLCP preamble and header.

CCK is a variation on M-ary orthogonal keying modulation and is based on an in-phase (I) and quadrature (Q) architecture using complex symbols. CCK allows for multichannel operation in the 2.4 GHz band by using the existing 1 and 2 Mbps DSSS channelization scheme. CCK uses 8 complex chips in each spreading code word. Each chip can assume one of four phases (QPSK). CCK uses 64 base spreading code words out of a possible set of 65536 (i.e., $65536=4^8$). Base spreading codes were chosen with good autocorrelation and cross-correlation properties. The CCK modulator chooses one of M unique for transmission of the scrambled PSDU. CCK uses one vector from a set of 64 complex quadrature phase shift keying (QPSK) vectors for the symbol and thereby modulates 6 bits (one of 64) on each spreading code symbol, as shown in Figure 7-5. Each spreading code is 8 complex chips in length. CCK uses a complex set of Walsh/Hadamard functions know as complementary codes. Refer to IEEE 802.11b for the equation used to derive the set of code words. There are four phase terms in the CCK equation. One of the terms modulates all of the chips, and this is used for the QPSK rotation of entire code vector. The others modulate every odd chip, every odd pair of chips and every odd quad of chips. To minimize DC offsets, the 4th and 7th terms in the equation are rotated by 180 degrees with a cover sequence. As with the IEEE 802.11 DSSS PHY, the phase rotation for CCK is counterclockwise. To insure that the modulation has the same bandwidth as the legacy IEEE 802.11 DSSS PHY, the chipping rate is kept at 11 Mbps while the symbol rate is increased to 1.375 Mbps. The spreading rate remains constant and only the data rate changes, and the CCK spectrum is the same as the legacy IEEE 802.11 waveform.

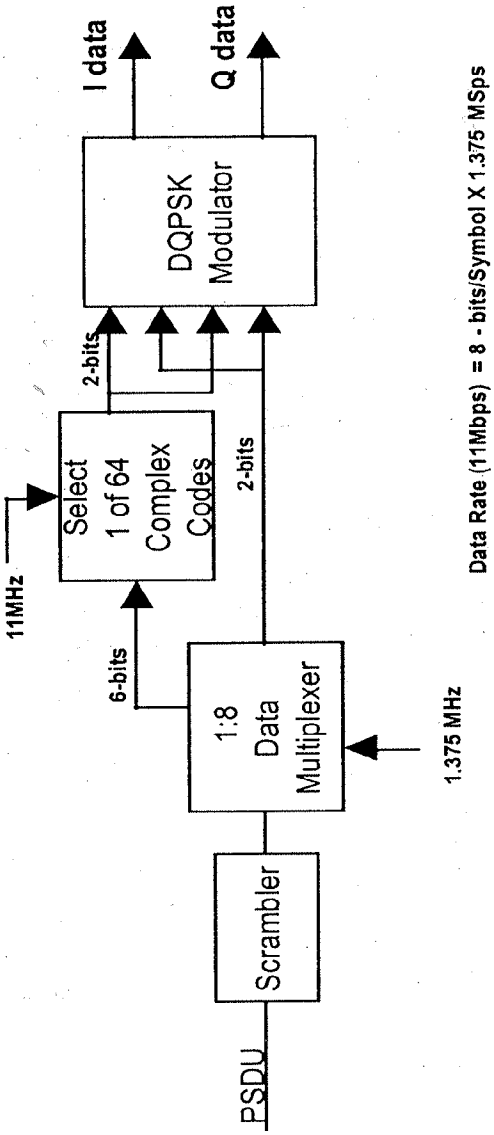

Figure 7-5 – Generation of CCK Modulation

For 5.5 Mbps transmission, the scrambled binary bits of the PSDU are grouped into 4-bit nibbles, where two of the bits select the spreading function while the remaining two bits QPSK modulate the symbol, as illustrated in Figure 7-6. The spreading sequence then DQPSK modulates the carrier by driving the I and Q modulators. For 11 Mbps operation, the incoming scrambled PSDU binary bits are grouped into 2 and 6 bits. The 6 bits are used to select (one of 64) complex vectors of 8 chips in length for the symbol and the other 2 bits DQPSK modulate the entire symbol. The transmit waveform is the same, and the chipping rate is maintained at 11 Mbps.

DSSS Packet Binary Convolutional Coding

Packet binary convolutional coding (PBCC) is an optional coding scheme defined in IEEE 802.11b. The coding option uses a 64-state binary convolutional code (BCC), rate R = 1/2 code, and a cover sequence. The PBCC modulator is illustrated in Figure 7-7. The HR/DSSS PMD uses PBCC to transmit the PPDU. To ensure that the PPDU frame is properly decoded at the receiver, the BCC encoder's memory is cleared at the beginning and at the end of a frame. A cover sequence is used to map the QPSK symbols. The cover sequence is initialized with a 16-bit pattern (0011001110001011) to produce a 256-bit cover sequence, which selects the QPSK symbols. Binary phase shift keying (BPSK) is used for 5.5 Mbps, and QPSK for 11 Mbps. For QPSK each pair of output bits from the BCC is used to generate one symbol, conversely each pair of bits for BPSK produce two symbols. The result is one bit per symbol for QPSK and 1/2 bit for BPSK. Refer to IEEE 802.11b for the equation used for the cover sequence generator.

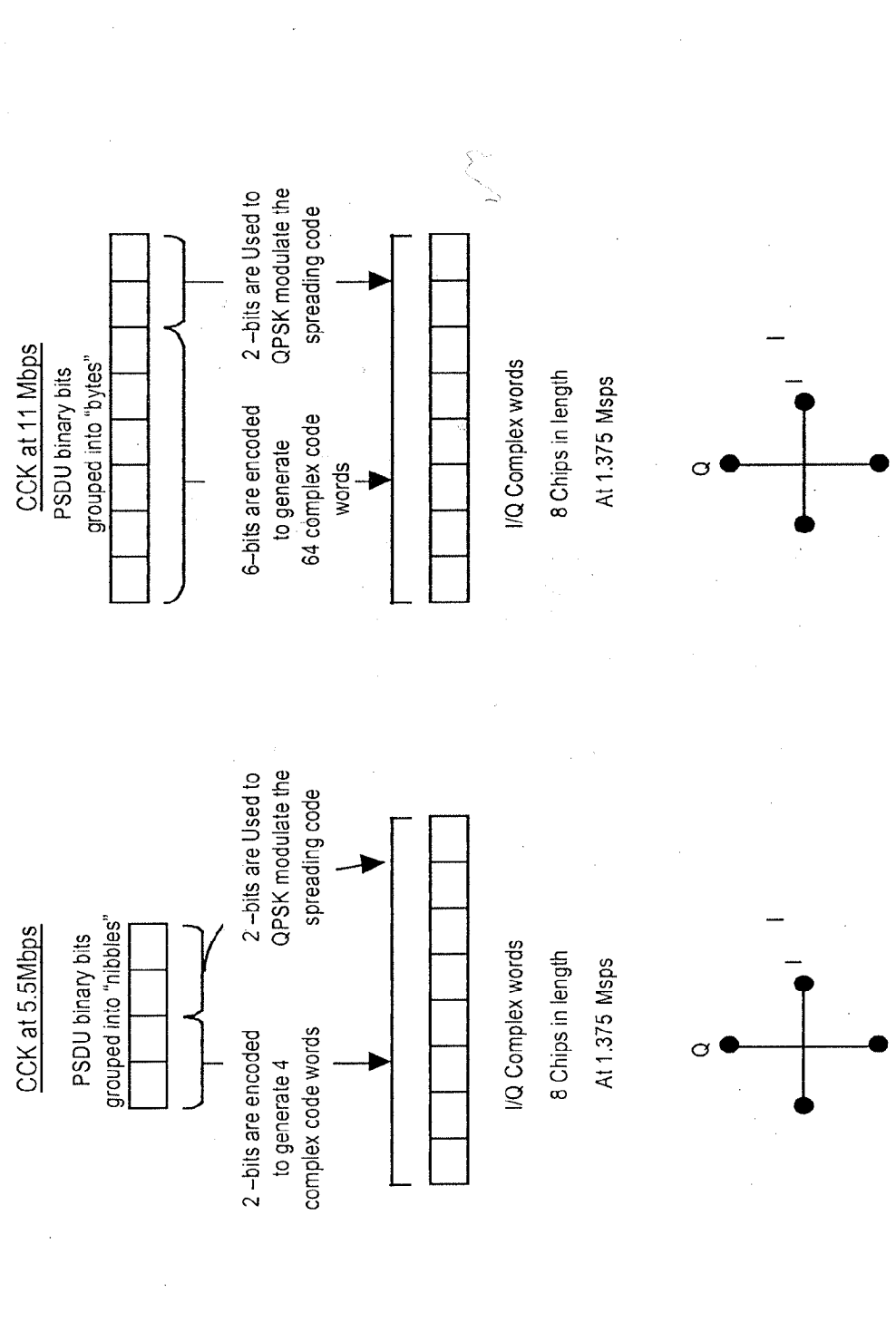

Figure 7-6—The PSDU bit assignments and for CCK at 5.5 Mbps and 11 Mbps

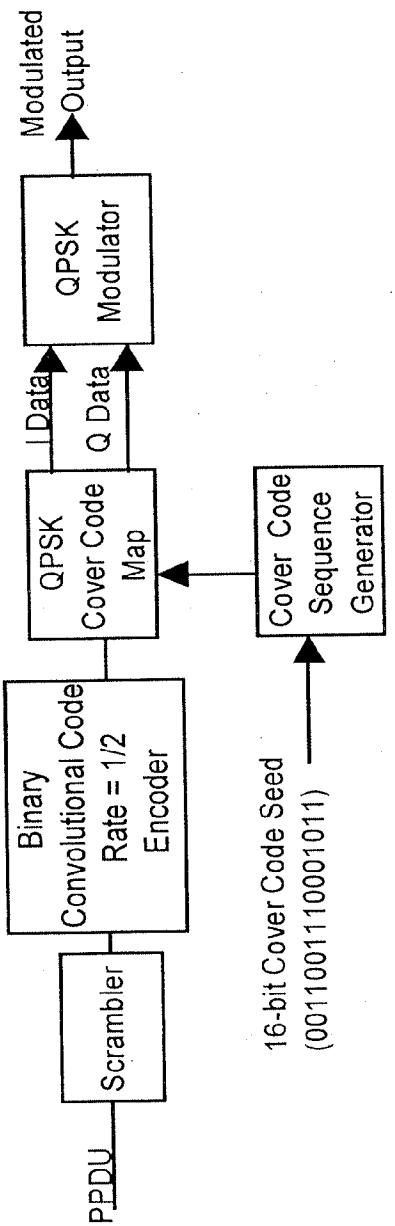

Figure 7-7 – PBCC Modulator

Frequency Hopped Spread Spectrum (FHSS) Interoperability

A channel agility option is defined in IEEE 802.11b which allows IEEE 802.11 FHSS 1 and 2 Mbps networks to interoperate with HR/DSSS 11 Mbps WLANs. Both nonoverlapping and overlapping high rate channels are supported. The nonoverlapping allows WLAN systems to operate simultaneously in the same area without interfering with each other. In North America channels 1, 6, and 11 are specified for nonoverlapping networks, and in Europe (excluding France and Spain) channels 1, 7, and 13 are specified. Two sets of hopping sequences are defined for worldwide operation. For more details on the hop patterns, refer to IEEE 802.11b.

Chapter 8
System Design Considerations for IEEE 802.11 WLANs

The IEEE 802.11 WLAN standard provides a number of physical layer options in terms of data rates, modulation types, and spreading spectrum techniques. Selecting the right physical layer and MAC technologies for your application requires careful planning and detailed systems analysis for developing the optimal WLAN implementation. It is impossible to include every possible system consideration in this handbook. However, we have focused on a few key issues we believe are important for consideration when implementing a compliant IEEE 802.11 interoperable WLAN system. The issues covered in this chapter are some of which the IEEE 802.11 Working Group focused on during the development of the standard.

The Medium

The difference between "wired" and RF WLANs is the radio communications link. While the radio communications link provides the freedom to move without constraints of wires, the wired media has the luxury of a controlled propagation media. Wireless RF medias are very difficult to control because the dynamics of the propagated signals over the media are constantly changing. This is the case for IEEE 802.11 WLANs because the 2.4 GHz bands are shared with unlicensed users. Radio system designers need to have a thorough understanding of the RF medium to properly design 2.4 GHz and 5 GHz IEEE 802.11 WLAN systems, especially for networks operating at data rates greater than 2 Mbps. The RF communication media for Home, Enterprise, and Manufacturing environments are very different and no two environments are the same. Multipath and Path loss are issues to consider when designing an IEEE 802.11 WLAN system.

Multipath

Multipath is one of the performance concerns for indoor IEEE 802.11 WLAN systems. Multipath occurs when the direct path of the transmitted signal is combined with paths of the reflected signal paths, resulting in a corrupted signal at the receiver, as show in Figure 8-1. The delay of the reflected signals is measured in nanoseconds (nsec), and is commonly known as delay spread. Delay spread is the parameter used to signify multipath. The amount of delay spread varies for indoors home, office, and manufacturing environments, as shown in Table 8-1. Surfaces of furniture, elevator shafts, walls, factory machinery, and metal constructed buildings all contribute to the amount of delay spread in a given environment.

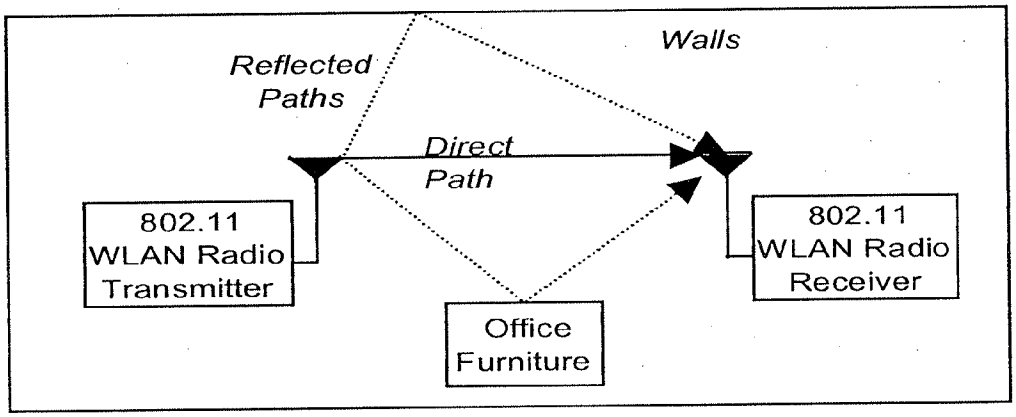

Figure 8-1—How Multipath is Generated

The channel impulse response is a way to illustrate the amount of multipath dispersion. For example, the amount of delay spread in an office environment is approximately 100 nsec, as shown in Figure 8-2. Typically, energy reflected off the surface of walls causes the impulse response to have energy on the leading edge before the peak. The leading energy is called the precursor energy. The amount of precursor energy differs from one environment to the next. The processing required to correct the precursor energy is more complex than required

for the trailing edge energy. The symbol period on the x-axis of the graph in Figure 8-2 is equal to the length of the 8 chip CCK code word. The 11 chip barker code is only 3 chips longer.

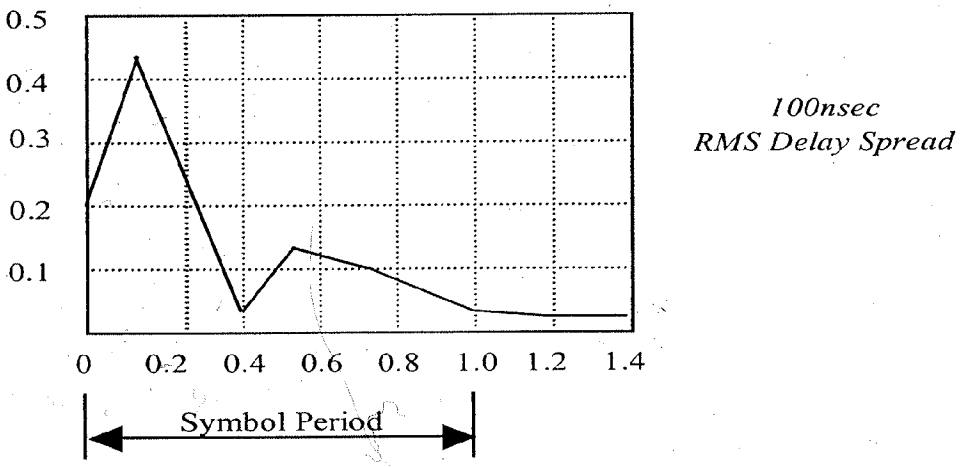

Figure 8-2—Impulse Channel Response Multipath (Delay Spread) for Office Environment

Table 8-1—Typical Multipath Delay Spread for Indoor Environments

Environment	Delay Spread
Home	< 50 nsec
Office	~100 nsec
Manufacturing floor	200–300 nsec

RAKE processing and equalization are two methods used to process and resolve delay spread. A RAKE receiver is well-known architecture used to remove delay spreads on the order of 100 nsec. The RAKE is structured as a bank of correlators (fingers) with weighed delays and a

combiner. Equalization is an alternative used to correct delay spreads greater than 100 nsec. Multipath causes the signals from the previous symbol to interfere with the signals of the next. This is known as intersymbol interference (ISI). As with ISI, interchip interference (ICI) results when the signals of the previous chip interfere with the signals of the next chip. ISI and ICI are issues for higher data rate systems because the symbol and chip periods are shorter. This is the case for IEEE 802.11a and IEEE 802.11b. Equalization corrects for ISI and ICI. An equalizer is a multitapped delay line, which takes the delayed and attenuated signal subtracted from the actual received signal. However, for environments where delay spreads are greater than 200 nsec, more complex signal processing is necessary. RAKE processing combined with ISI and ICI equalization is commonly implemented to resolve multipath dispersions of this magnitude.

Multipath Channel Model

In an environment where performance measurements of the same radio are used, in the same location, the results may not agree. This is due to the changing position of people in the room and slight changes in the environment, can produce significant changes in the signal power at the radio receiver. A consistent channel model is required to allow comparison of different WLAN systems and to provide consistent results. In doing so, the IEEE 802.11 Working Group adopted the following channel model as the baseline for predicting multipath for modulations used in IEEE 802.11a (5 GHz) and IEEE 802.11b (2.4 GHz). This model is ideal for software simulations predicting performance results of a given implementation. The channel impulse response illustrated in Figure 8-3 is composed of complex samples with random uniformly distributed phase and Rayleigh distributed magnitude with average power decaying exponentially.

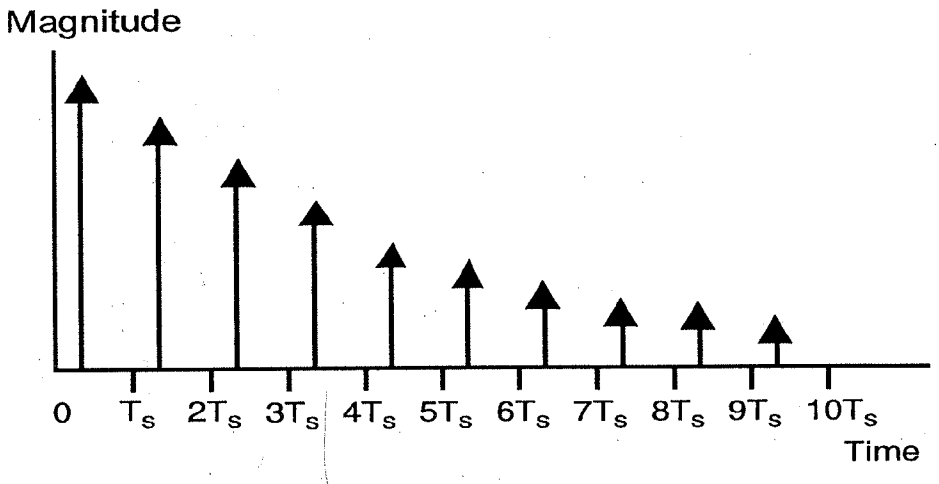

Figure 8-3—Channel Impulse Response for IEEE 802.11a and IEEE 802.11b

The mathematical model for the channel is as follows

$$h_k = N\left(0, \frac{1}{2}\sigma_k^2\right) + jN\left(0, \frac{1}{2}\sigma_k^2\right)$$

$$\sigma_k^2 = \sigma_0^2 e^{-kT_s/T_{RMS}}$$

$$\sigma_0^2 = 1 - e^{-T_S/T_{RMS}}$$

Where $N\left(0, \frac{1}{2}\sigma_k^2\right)$ is a zero mean Gaussian random variable with variance $\frac{1}{2}\sigma_k^2$ produced by generating an N(0, 1) and multiplying it by $\sigma_k/\sqrt{2}$), and $\sigma_0^2 = 1 - e^{-T_S/T_{RMS}}$ is chosen so that the condition $\sigma_k^2 = 1$ is satisfied to ensure same average received power.

Let T_s be the sampling period and T_{RMS} be the delay spread of the channel. The performance assessment shall be no longer than the smaller of 1/(signal bandwidth) or $T_{RMS}/2$. The number of samples to be taken in the impulse response should ensure sufficient decay of the impulse response tail, e.g. $k_{\max} = 10 \times T_{RMS}/T_s$.

Path Loss in a WLAN System

Another key consideration is the issue of operating range relative to path loss. This plays an important role in determining the size of overlapping WLAN cells and distribution of APs. Path loss calculations are equally important for determining the radio's receiver sensitivity and transmitting power level and signal to noise ratio (SNR) requirements. As radios transmit signals to other receivers in a given area, the signal attenuates as a square of the distance (D). The distance is the radius of a WLAN cell, as shown in Figure 8-4. The wavelength (lambda) is the ratio between the speed of light and the signal frequency. As the receiver moves away from the transmitter, the receiver's signal power decays until it reaches the receiver's noise floor, at which time the bit error rate becomes unacceptable. For indoor applications beyond 20 feet, propagation losses increase at about 30 dB per 100 feet. This occurs because of a combination of attenuation by walls, ceilings, and furniture. Each wall constructed with sheet rock and wood typically attenuates the signal by 6 dB and walls constructed with cement block walls attenuate the signal by 4 dB. However, additional losses may occur depending on the fading characteristics of the operating environment, which we describe in the next section. The same path loss principles apply for all frequency bands. However, as the operating frequency increases from 2.4 GHz to 5 GHz, for example, an additional path loss of 5–10 dB occurs. This results in a smaller cell radius and may require additional overlapping cells and APs to guarantee the same area as a system operating at 2.4 GHz.

Path Loss (dB) = 20 Log_{10}(4 x PI x D/Lambda)

Where:

r = D is the radius of the WLAN cell

Lambda = c/f

where : c = speed of light (3 x $10^8 ms^{-1}$)

f = signal frequency in Hz

Figure 8-4 – Free Space Path Loss Model

Multipath Fading

Another key consideration is the path loss due to multipath fading. Multipath fading occurs when the reflected signal paths refract off people, furniture, windows, and walls, and scatter the transmitted signal. For example, moving the receiver from the transmitter a small distance even only a few inches, can produce an additional loss of signal power on the order of 20 dB or more. Multipath fading is viewed as two separate factors and described as probability distribution functions. The first factor is a characteristic known as log normal fading. These are coefficient products which result as the signal reflects off surfaces and propagates to the receiver. As the signal coefficients product propagate to the receiver, they are summed together with the direct path where they cancel each other, causing significant attention of the transmitted signal. This is the second factor, known as Rayleigh fading. As previously, mentioned RAKE architectures and equalization are techniques used to correct for these effects.

Es/No vs BER Performance

System performance tradeoffs are often made in the decision process when selecting a modulation type and data rate. System tradeoffs in terms of receiver sensitivity, range, and transmit power become very important for developing low cost implementations, especially for higher rate 2.4 GHz IEEE 802.11b systems. Figure 8-5 illustrates a comparison of the theoretical Es/No vs BER curves for uncoded QPSK, PBCC 5.5–11 Mbps, CCK 5.5–11 Mbps, and Barker 1 and 2 Mbps. The theoretical curves include additive white gaussian (AWG) noise in the channel. These curves are provided as a guide to assess the performance for a complete system implementing CCK and PBCC. However to get better understanding of the overall systems performance, other factors such as multipath, signal fading, carrier phase noise, noise figure, and other implementation losses should be considered in the link budget as part of the systems analysis.

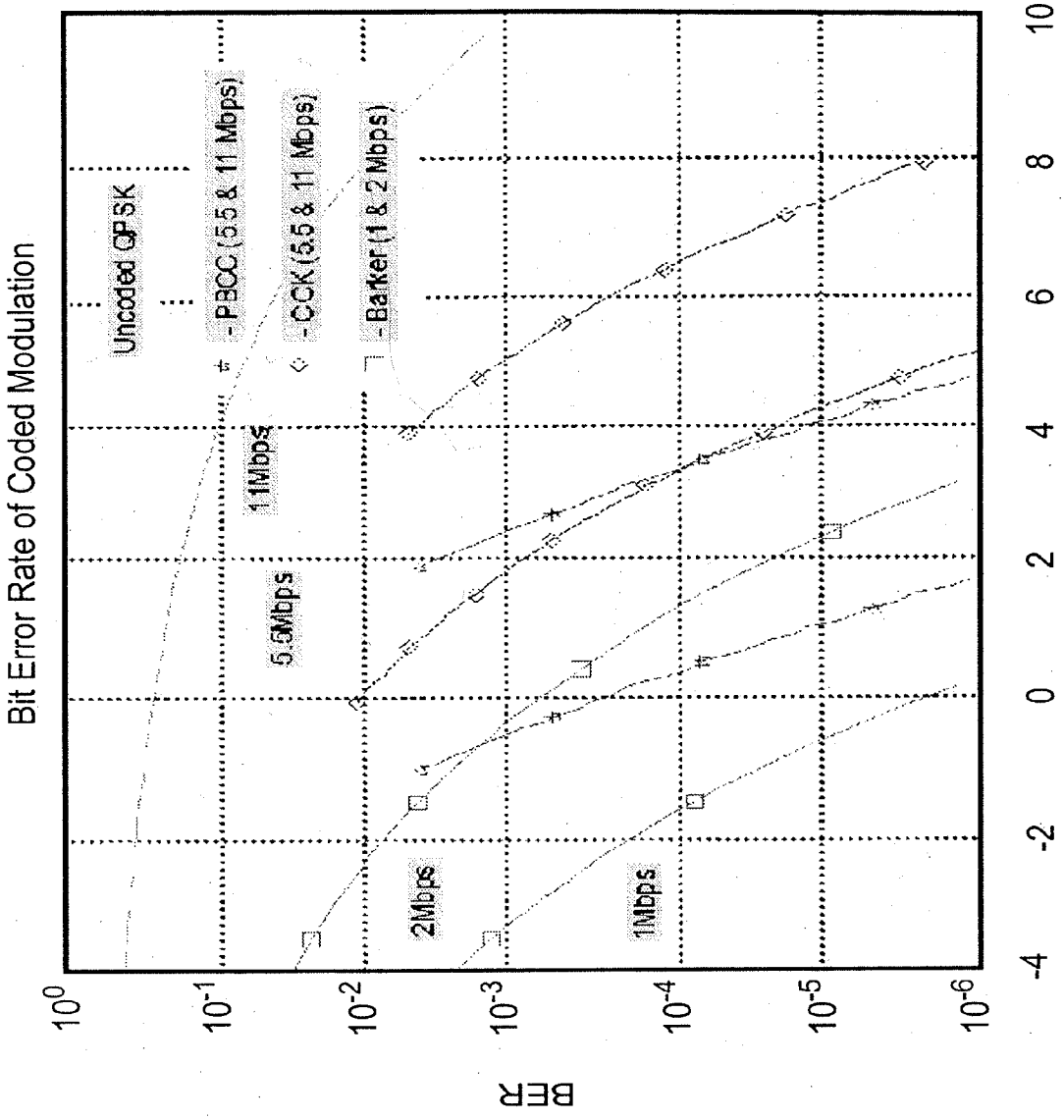

Figure 8-5 – Theoretical Eb/No vs BER with AGW for 2.4 GHz IEEE 802.11b

Data Rate vs Aggregate Throughput

The IEEE 802.11 standard defines data rate in terms of symbol rate, or available bit rate. The PPDU data is modulated and transmitted over the RF or IR medium at this rate. This rate is often confused with the aggregate data throughput. The aggregate data rate, takes into account the overhead associated with protocol frame structure, collisions, and implementation processing delays associated with frames processed by mobile stations and APs. Simulations may be run in software to estimate the aggregate throughput of the protocol and benchmarked against compliant IEEE 802.11 WLAN systems. However, calculating the aggregate throughput can be complex because there are a number of detailed variables to consider. The protocol overhead includes parameters such as RTS, CTS, ACK frames, (SIF, DIFs, PIFs) interframe space timing, beacon periods and random back-off periods, estimated collisions, PPDU frame size, and RF propagation delays. A good rule of thumb for estimating the average aggregate throughput of an IEEE 802.11 wireless network is 75% of the data rate for DCF operation, and 85% of the data rate for PCF.

WLAN Installation and Site Survey

Many installations begin with a site survey. A site survey serves a number of purposes. First, the survey is used to determine the maximum operating range between an AP (fixed location) and mobile stations for a specified transmit RF power level. Second, the survey helps identify holes of coverage due to multipath, interference sources, and neighboring existing WLAN installations. Lastly, it is used in cell planning of overlapping BSAs and for layout of APs giving them hardwired access to existing wired Ethernet LAN infrastructures.

Today, many equipment manufactures have tests built in to their products to conduct such surveys. PC laptops with IEEE 802.11 WLAN adaptor cards, with embedded software tools, are commonly used. In

some cases, a spectrum analyzer with special directional antennas is used to measure path loss through walls and other obstructions and to pinpoint and identify interference sources. Some of the tests include BER and PER, and link quality measurements as a function of range. Typically, the tests are recorded using a pair of WLAN adaptors; one is set up in a fixed location and the other as a mobile station. Every environment is different and the number of APs required for a given installation depends upon the number of holes in the coverage area due to multipath, and signal attenuation through walls, ceilings, and floors. However, on average, for indoor operation, the maximum operating distance between a mobile station and an AP operating in the 2.4 GHz frequency, transmitting at an RF transmit power of +20 dBm (100 mW) at data rates of 1 and 2 Mbps, yields approximately 400 feet and 100 feet at 11 Mbps.

Interference in the 2.4 GHz Frequency Band

The microwave oven used in household and commercial kitchens is the main interference source in the 2.4 GHz unlicensed frequency band. The magnetron tubes used in the microwave ovens radiate a continuous-wave-like (CW-like) interference that sweeps over tens of megahertz (MHz) of the 2.4–2.483 GHz band during the positive half cycle of ac line voltage. The microwave oven's EIRP has a maximum ranging between 16 and 33 dBm. The power cycle frequency is 50 Hz 20 msec or 60 Hz 16 msec depending upon the geographical location. In North America, the ac line frequency is 60 Hz and the microwave oven's magnetron pulses on for 8 msec and off for 8 msec. The maximum packet length defined in the IEEE 802.11 protocol was designed to operate between the 8 msec pulses of the microwave energy.

Other sources of interference include neighboring in-band radios. Two types of interference are considered here. First is cochannel interference, which is induced from radios from adjacent cells that are on the same

channel frequency. Proper cell planning of the channel frequency and hopping patterns and careful layout of the APs can minimize this interference. The second type of interference is from other systems such as neighboring DSSS and FHSS WLAN networks. Built into the standard are three mechanisms used to help minimize the amount of interference. The first is the clear channel assessment, where the MAC layer protocol provides a method of collision avoidance. The second is processing gain, which provides some protection from FHSS radios, whose spectrum appears as narrowband interferers. The third are the hop patterns; there is sufficient frequency spacing between pseudorandom hops to minimize the interference due to neighboring DSSS channels. To some degree, legacy 2.4 GHz IEEE 802.11-compliant FHSS and DSSS systems and IEEE 802.11b high-rate WLAN systems do coexist. However, careful cell planning will help minimize the amount of interference a system will experience especially at the outer fringe of the cell.

Antenna Diversity

Historically antenna diversity has been an effective low-cost alternative solution used to combat and mitigate the effects of multipath and delay spread in WLAN radio receivers. It is relatively easy to implement in the mobile stations and APs and does not require the signal processing hardware used in other diversity techniques. The object behind antenna diversity is to space the antennas apart from each other to minimize the effects of the uncorrelated multipath at the receiver. Spacing the antennas far apart allows the receiver to pick and demodulate the larger signal of the two signals. For 2.4 GHz IEEE 802.11 implementations, the bit length of the preamble sync fields was selected based on these criteria. The antennas are typically spaced anywhere from 0.251 to several lambdas (wavelengths) apart. The amount of separation depends upon the amount of delay-spread tolerance required for the system to operate in a given operating environment. Adding antenna diversity will improve the packet error rate (PER) performance of a wireless link by 2 to 1, as well as improve the availability of the link. There are a number of 2.4 GHz antennas on the market today with different configurations. Patch

antennas are commonly used at the mobile client PCMCIA implements, because of cost and size constraints. On the other hand, omni-directional antennas are used at the AP because they provide the optimal antenna coverage. Although antenna diversity is an option in the standard, as a minimum, antenna diversity should always be consider at the AP, as shown in Figure 8-6. This form of diversity will minimize the risk of packet loss due to multipath and interference, and ensure optimal throughput performance in a system.

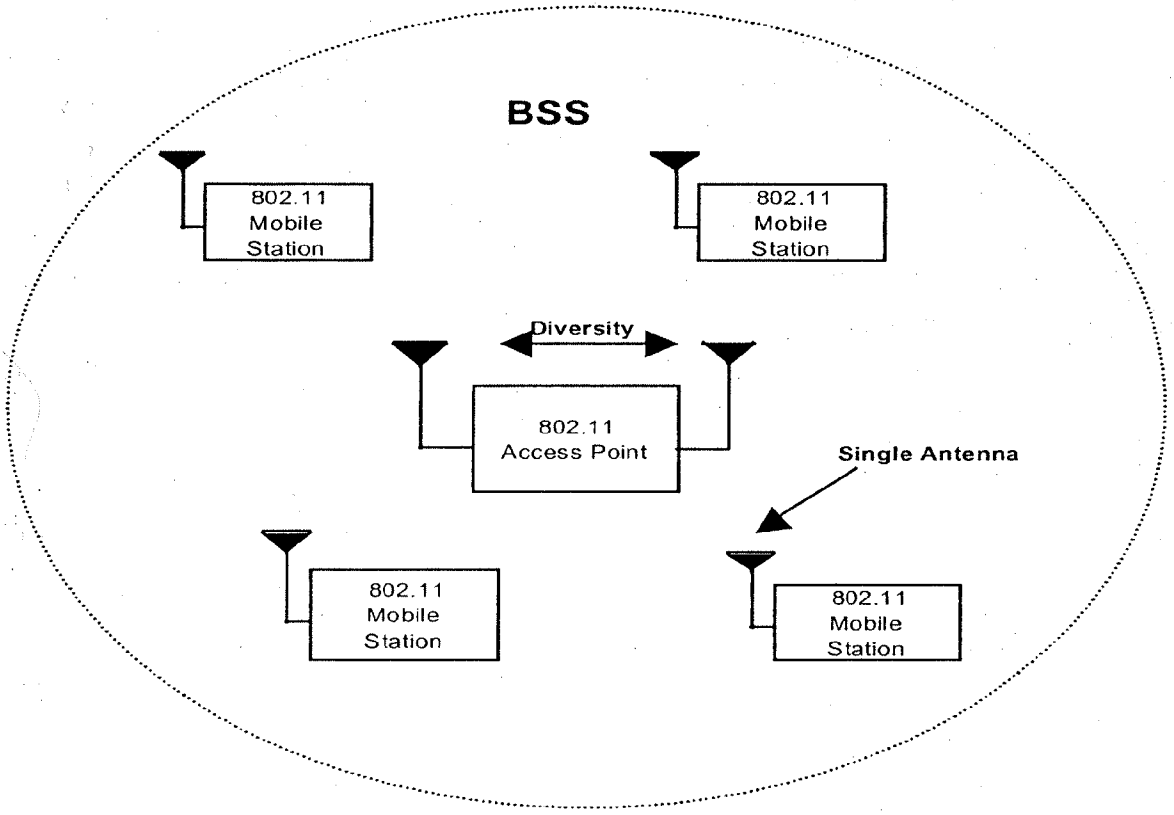

Figure 8-6— Antenna Diversity at the AP as a Minimum

Acronyms and Abbreviations

ACK	acknowledgment frame
AGC	automatic gain control
AID	association identifier
AP	access point
ATIM	announcement traffic indication message
BCC	binary convolutional code
BPSK	binary phase shift keying
BSS	basic service set
BSSID	basic service set identifier
CDMA	code division multiple access
CF-End	contention-free end
CFP	contention-free period
CF-Poll	contention-free poll
CSMA/CA	carrier sense multiple access with collision avoidance
CTS	clear to send
DA	destination address
dB	decibels
DBPSK	differential binary phase shift keying
DCF	distributed coordination function
DIFS	distributed interframe space
DPSK	differential phase shift keying
DQPSK	differential quadrature phase shift keying
DS	distribution system
DSSS	direct sequence spread spectrum
EIFS	extended interframe space
ESS	extended service set
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FCS	frame check sequence
FFT	fast fourier transform
FHSS	frequency hopping spread spectrum
GFSK	Gaussian frequency shift key
GPS	global positioning system
HR/DSSS	high rate direct sequence spread spectrum
I/Q	interphase/quadrature
IAPP	inter-access point protocol
IBSS	independent basic service set
ICI	interchip interference
ICV	integrity check value
IEEE	Institute of Electrical and Electronics Engineers
IR	infrared
ISI	intersymbol interference
ISM	industrial, scientific, and medical
LBT	"listen before talk"
LLC	logical link control
MAC	medium access control
MIB	management information base
MKK	Ministery of Telecommunications
MMACS	Multimedia Mobile Access Communication System
MPDU	MAC protocol data unit
MSDU	MAC service data unit
NAV	network allocation vector
NIC	network interface card
OFDM	orthogonal frequency domain multiplexing
OFDM PHY	OFDM physical layer
PBCC	packet binary convolutional coding
PC	point coordinator
PCF	point coordination function
PHY	physical, physical layer
PIFS	priority interframe space
PLCP	physical layer convergence procedure
PMD	physical medium dependent
PPDU	PLCP protocol data unit
PPM	pulse position modulation
PSDU	PLCP service data unit
PSF	PLCP signaling field
PS-Poll	power save poll
QAM	Quadrature Amplitude Modulation
QPSK	quadrature phase shift keying
RA	receiver address
RF	radio frequency
RFID	radio frequency ID
RSADSI	RSA Data Security, Inc.
RTS	request to send
SA	source address
SFD	start of frame delimiter
SIFS	short interframe space
SNR	signal to noise ratio
SSID	service set identity
STA	station
TA	transmitter address
TBTT	target beacon transmission time
TIM	traffic indication map
TSF	timer synchronization factor
TU	time units
WLAN	wireless LAN

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