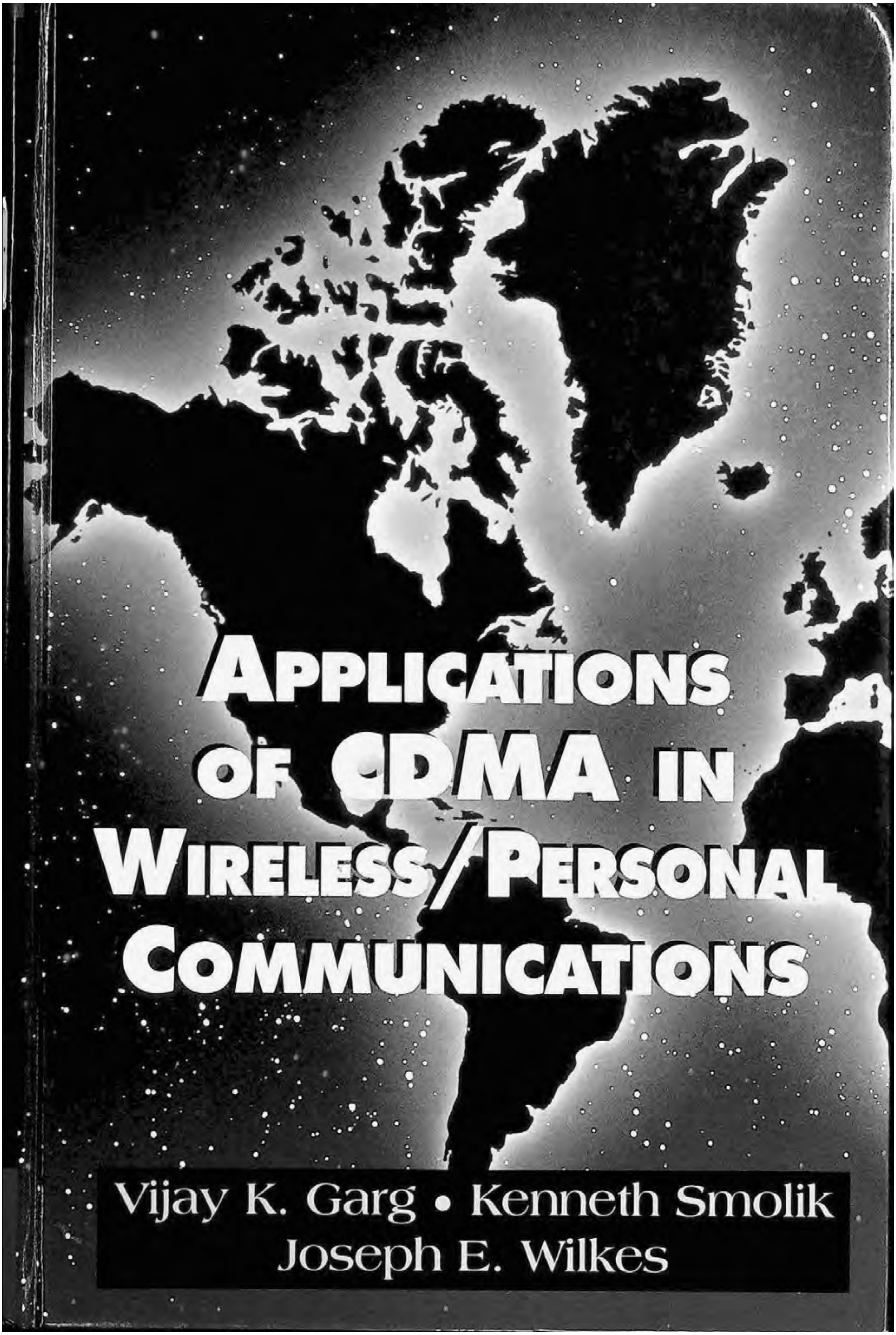

APPLICATIONS OF CDMA IN WIRELESS/PERSONAL COMMUNICATIONS

Vijay K. Garg • Kenneth Smolik
Joseph E. Wilkes

Applications of CDMA in Wireless/Personal Communications

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Library of Congress Cataloging-in-Publication Data

Garg, Vijay Kumar, 1938-
Applications of CDMA in wireless/personal communications /
Vijay K. Garg, Kenneth F. Smolick, Joseph E. Wilkes.
p. cm. — (Feher/Prentice Hall digital and wireless
communications series)
Includes bibliographical references and index.
ISBN 0-13-572157-1 (case)
1. Code division multiple access. 2. Personal communication
service systems. I. Smolick, Kenneth. II. Wilkes, Joseph E.
III. Title. IV. Series.
TK5103.45.G37 1997
621.3845—dc20 96-42194
CIP

Editorial/production supervision: *BooksCraft, Inc., Indianapolis, IN*
Cover design director: *Jerry Votta*
Cover design: *Design Source*
Acquisitions editor: *Karen Gettman*
Manufacturing manager: *Alexis R. Heydt*

Published by Prentice Hall PTR
Prentice-Hall, Inc.
A Simon & Schuster Company
Upper Saddle River, NJ 07458

The publisher offers discounts on this book when ordered in bulk quantities.
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Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN: 0-13-572157-1

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Simon & Schuster Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

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Preface

Over the last decade, deployment of wireless communications has been significant. In the 1980s, many analog cellular networks were implemented. These networks are already reaching capacity limits in several service areas. The wireless industry anticipated these limitations at the beginning of the 1990s. Several digital technologies were introduced to increase spectral efficiency and enhance wireless communications by adding attractive and innovative features and services such as facsimile and data transmission and various call handling features. Thus, wireless communication technology has evolved from simple first-generation analog systems for business applications to second-generation digital systems with rich features and services for residential and business environments. As the end of century approaches, a new vision of ubiquitous telecommunications for individuals is beginning to emerge. This vision, known as personal communications systems (PCS), will enable the network to deliver telecommunication services (voice, data, video, and so on) without restrictions on the user's terminal, location in the world, point of access to the network, access technology, or transport method. PCS is the challenge for the future. PCS also has a second vision, the use of the 1.8-GHz band in North America. In this book, by PCS, we mean the second vision of PCS (cellular concept at a new frequency band).

There are several reasons for the transition from wireless analog to digital technology: increased traffic, which requires greater call capacity (an explosive growth of the number of wireless telephone subscribers demands that the frequency bandwidth per call should be reduced from 30 kHz, which is currently used for analog systems); speech privacy (digital technology facilitates speech to be encrypted); new services (digital technology allows voice services to be combined with other services); and greater radio link robustness (with digital technology, improved coding techniques can be used to enhance the robustness of transmission).

Europe and Japan have developed their digital mobile communications systems by using new dedicated frequency bands. In Europe, dedicated bands were necessary since each country used a different, incompatible analog standard, and the growth of the Common Market concept required common standards throughout. In North America, however, digital technologies allow coexistence with the first-generation analog technology, since there was a common nationwide standard. Thus, the North American digital technologies enhance rather than replace the existing analog technology. Several competing digital technologies are vying for predominance in the wireless market. These include the U.S. digital cellular time-division multiple access (TDMA) system, the global system of mobile communications (GSM) that also uses TDMA with a different standard, code-division multiple access (CDMA), wideband CDMA, and several other TDMA and mixed CDMA/TDMA systems. Currently, it is projected that CDMA will be the most widely deployed digital technology in the United States; however, it may be several years before the marketplace determines the dominant technology. The purpose of this book is not to assess the advantage of one digital technology over the other. Rather, its intent is to discuss the fundamental concepts of CDMA and the application of CDMA technology to both cellular and PCS systems.

In this book, we focus on concepts of CDMA for wireless applications and the underlying network needed to support these applications for voice and data communications. Our primary emphasis is on the CDMA systems standardized by the Telecommunications Industry Association (TIA) and the Alliance for Telecommunications Industry Solutions (ATIS) as standards IS-95 and IS-665. There are, of course, other CDMA systems that have been proposed by DoCoMo, Goldengate, Interdigital, Lucent Technologies (AirLoop), and others. These systems are proprietary and are not discussed here. If you are interested in any of the these proprietary systems, contact the manufacturers directly. Other digital standards also use aspects of CDMA; for example, a TDMA system proposed by Omnipoint has been approved by ATIS for trial application. This TDMA system also includes a CDMA capability, but the underlying technology is TDMA. We discussed this system in our previous book, *Wireless and Personal Communications Systems,* Prentice Hall, 1996.

Several books on the market discuss the subject of CDMA. In writing this book, we decided to address the needs of the practicing engineer and the engineering manager by explaining the basis of CDMA and its application to wireless communications in both the cellular and the PCS environments. Students studying a course in telecommunications will also find this book useful as they prepare for a career in the wireless industry. We have incorporated sufficient mathematics so that you can understand the principles of CDMA, and yet we do not attempt to overwhelm you with mathematics. This book can be used by practicing telecommunication engineers involved in the design of cellular/PCS systems and by senior/graduate students in Electrical, Telecommunication, or Computer Engineering curricula. We do assume that you have a basic understanding of the concepts of mobile communications; if not, our previous book will provide that understanding. With selective reading of the chapters, telecommunications managers who are engaged in managing CDMA systems and who have little or no technical background in wireless technologies can gain an understanding of the systems they are managing.

This book covers several aspects of CDMA technology. In chapter 1, we explore the growth in the wireless communications and present market trends. We develop the market and technical needs for digital technologies and discuss their merits when compared to analog technology. We briefly describe the digital technologies used for cellular technology. In chapter 2, we describe different spread spectrum (SS) systems and then focus on the direct sequence spread spectrum (DSSS) technology that is specified in the TIA IS-95 and TIA-T1P1 J-STD-008 CDMA systems. We develop necessary relationships to evaluate the performance of a DSSS system with binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) modulation and provide a relationship to calculate the performance of a CDMA system. We conclude the chapter by discussing the main features of a CDMA system.

In chapter 3, we provide a survey of CDMA standards specifying the air interface (i.e., the messaging between the base station and the mobile station). This chapter highlights the TIA IS-95A call processing model, service configuration and negotiation, and registration by the mobile station. In chapter 4, we present the TIA TR-45/46 reference model, which is a basis for the cellular and PCS standards. We discuss the mobile switching center (MSC)—base station (BS) interface. The effects upon the architecture of a CDMA system are emphasized. We conclude the chapter by discussing the basic and supplementary services that are supported by cellular and PCS standards.

In chapter 5, we introduce the concepts of the seven-layer open-system interconnect (OSI) reference model. We describe the physical layer of the CDMA system and the wideband CDMA (W-CDMA) system. We describe the network and data link layers of the two systems in chapter 6. We discuss the signaling application layer in chapter 7. We include call flows for several typical services supplied to mobile stations using CDMA and W-CDMA. Also, we examine network operations for call origination, call termination, call clearing, mobile station registration, and mobile-assisted handoffs. In chapter 8, we discuss speech-coding algorithms that have been standardized for CDMA telephony. Note that a single speech-coding algorithm has not been adopted across the various types of access technologies since an algorithm may be customized for optimization in the context of the given access technology.

We deal with the basic guidelines for engineering a CDMA system in chapter 9. This chapter discusses several topics that are germaine to the engineering of a CDMA system. These topics include indoor and outdoor propagation models, link budgets, transitioning from analog to CDMA operation, facilities engineering, radio link capacity, and border cells located at a boundary between two service providers. In chapter 10, we concentrate on wireless data systems, including the wide area wireless data system and the high-speed Wireless Local Area Network (WLAN). We discuss the standards activities for wireless data and outline the access methods and error control schemes. We also include data services standards for wideband systems and present highlights of the TIA IS-99, TIA IS-636, and the TIA IS-657 standards. In chapter 11, we focus on the management goals for PCS networks and present the requirements for PCS network management. We discuss the important aspects of the Telecommunications Management Network (TMN) architecture, which can be applied to the management of a PCS network. We conclude the chapter by presenting requirements, as defined by TMN, for five management functions: accounting management, security management, configuration management, fault management, and performance management.

As we previously noted in this preface, the wireless industry deploys various analog and digital technologies. However, mobile subscribers expect seamless operation as they traverse different cellular/PCS systems. We examine the issues of coexistence of CDMA systems with other digital and analog systems in chapter 12. We also describe the associated work on wireless intelligent networks. The wireless industry is seeking means for improving and reducing costs so that the mobile subscriber can experience better service at a reduced price. In chapter 13, we examine several approaches that address these goals. First, service providers are seeking ways to reduce administrative costs by streamlining the service activation procedures for new mobile subscribers. We discuss over-the-air service provisioning (OTASP), which supports this objective. Second, advances in digital technology will make it possible to improve the quality of speech coding at a given data rate. We present a brief discussion of the enhanced variable rate codec (EVRC), which provides better performance than the current standardized 8-kbps speech coder. Third, the wireless industry is seeking improvements to transmission schemes used for the air interface. Resulting improvements will increase the capacity of a radio channel. For mobile subscribers, this increased capacity translates to better service at a lower price. We conclude this chapter with a discussion of three separate approaches for addressing this objective: interference cancellation, multiple beam adaptive antenna arrays, and improvements of the handoff algorithm.

We suggest material in chapters 1, 3–8, 11, and 12 for telecommunication managers. The practicing telecommunication engineer should study the entire book in order to become proficient in the CDMA technology. If this book is used for students with a general background in electromagnetic field theory and digital systems, we suggest using the material in chapters 1–12 for a one-semester course in CDMA technology.

Figures 3.1–3.4, 4.1, 4.2, 8.3, 8.4, 10.3, 10.5, 10.6, 10.8, 10.9, and 13.1 and Tables 3.1–3.5, 4.1–4.5, and 5.2–5.8 are copyrighted by the TIA and are used with permission. (To purchase the complete text of any TIA document, call Global Engineering Documents at 1-800-854-7179 or fax to 303-397-2740.) Table 9.26 is copyrighted by QUALCOMM and is used with permission. The material in chapter 9 is adapted from a Lucent Technologies Technical Education Center course and is used with permission. Some figures and tables have been adapted from our previous text and are used with permission from AT&T.

We acknowledge the many helpful suggestions we received from our reviewers, some known and some anonymous. Robert Buus, Qi Bi, Bruce McNair, Nitan Shan, and E. Lee Sneed provided useful input to help us clearly explain the CDMA concepts without overwhelming you with mathematics. We acknowledge the help of Andrew Smolick in preparing some of the tables in Chapter 9. We give special thanks to Reed Fisher, of Oki Telecom, for his many helpful discussions on the practical and theoretical aspects of CDMA and W-CDMA. One of the authors (JW) is privileged to have known Reed for 25 years as a friend and colleague and describes him as "the person I go to when I have a radio question."

Finally, we acknowledge the assistance of Karen Gettman of Prentice-Hall, Inc. and the staff of BooksCraft, Inc., received during the production of this book.

Vijay Garg
Ken Smolik
Joe Wilkes
August 1996

We dedicate this book to our families.

Vijay Garg
Ken Smolick
Joe Wilkes

CHAPTER 1

Introduction to Code-Division Multiple Access Technology

1.1 INTRODUCTION

Wireless communications have shown a profound effect on our day-to-day lives. In less than 10 years, cellular telephones have attracted about a hundred million subscribers in the United States, Europe, and Asia. This dramatic development is just the start of the forthcoming revolution in telecommunication services referred to as the communication super highway. By the end of this century, telecommunication devices will be associated with the person rather than associated with a home, office, or car. To meet the unprecedented demand for a new mode of telecommunications, several digital technologies emerged at the beginning of the 1990s. All these technologies are seen as stopgaps to provide solutions to specific problems while the world waits for the technology to meet the needs of the 21st century. The vision of the third-generation personal communications network (PCN) is intended to link systems that move information among people anytime, anywhere.

In this chapter, we explore the growth in wireless communications and present market trends. We then point out the need for digital technologies and discuss their advantages over the analog technology. Next, we briefly describe the digital technologies used for cellular telephony and conclude the chapter by providing a summary of the IS-95 CDMA system.

1.2 TRENDS IN WIRELESS COMMUNICATIONS

In the 1980s, many analog cellular networks in the world reached their capacity limits. At the beginning of the 1990s, several digital technologies were introduced to overcome these limitations and to enhance analog cellular networks by adding several new services and features such as facsimile and data transmission and various call-handling features. As the end of 20th century approaches, a vision of the ubiquitous telecommunication services known as the PCS has developed.

There were about 36 million cellular subscribers in the U.S. in 1996. The industrialized countries in the Far East will experience a very high growth rate. It is expected that cellular subscribers in the world will grow at about 20 percent per year. Most of this growth will be handled by digital cellular networks since the analog networks have already reached or will reach their capacity limits.

In the late 1990s, PCS will grow to provide wireless access to the world telephone networks at cost-effective rates for the mass market. PCS will evolve to use a single personal number usable on the wireline and the wireless networks to provide individualized services to the subscriber anywhere, anytime. The services will be delivered using a combination of standards, networks, and products that meet a wide range of user requirements at a reasonable price.

The world is on the edge of a wireless revolution. By the year 2000, there are expected to be about 40 million new PCS users worldwide. Added to the existing cellular users, we anticipate a total of about 200 million wireless telephones. Thus, the wireless communications business presents the most exciting opportunity in telecommunications today and provides these opportunities for both service providers and equipment manufacturers.

1.3 MARKET TRENDS FOR WIRELESS COMMUNICATIONS

The wireless communications market may be a $60 billion industry at the turn of century. Cellular companies continue to see about a 20 percent growth rate in the number of subscribers. Previous predictions for wireless usage have been exceedingly low. Wireless communications is growing in many different markets. For example, in Europe and North America, we are seeing cellular and PCS as an adjunct to wireline services. At the same time, the developing countries are installing first-class telecommunications services for their citizens, with the networks interconnected to the worldwide phone network. PCS offers the opportunity to provide these modern telecommunications services without the expense of implementing the extensive copper infrastructure. For example, India needs modern telecommunications services to support the development of software for itself and other developed countries. These two diverse needs are fueling the wireless expansion around the world.

1.4 NEEDS OF DIGITAL TECHNOLOGIES FOR WIRELESS COMMUNICATIONS

The analog cellular systems were designed 15–20 years ago when the market for wireless phone service was embryonic and not well understood. As the systems using these analog technologies grew, the need for higher capacity digital technologies was identified around the world. As the digital systems were designed, the following needs were identified:

- **Large System Capacity**. An increased number of wireless subscribers requires large system capacity. Digital systems provide much higher capacity than the analog systems because of their improved spectrum efficiency.
- **Low Operations Cost**. The analog cellular networks have operation support systems to provide operation, administration, maintenance, and provisioning (OAM&P) capabilities. Each of these systems has a different user interface, uses a different computing platform, and typically manages one type of network element. As cellular/PCS service providers move into multiple networks with a mixed vendors' environment, they can no longer afford a different management system for each network element. A centralized management system is needed. The digital technology with the application of centralized management approaches lowers OAM&P cost.
- **Revenue Growth**. Digital technology facilitates implementation of new services such as data transmission, facsimile, or several supplementary services that generate additional revenues. Digital technology also can be easily adapted to provide security mechanisms.
- **User Terminal**. In general, digital terminals are smaller and lighter than analog terminals, which makes it easier to carry them around. Because less power is consumed, smaller batteries are required.

1.5 ELEMENTS OF A WIRELESS NETWORK

Public interest in wireless communication has grown rapidly. For the past several years, efforts in wireless communications have been focused on radio technology, where the goal is to increase spectrum efficiency and radio channel capacity. Expanded radio channel capacity is the key objective of a wireless network to meet demand for the indefinite future.

Significant challenges are also arising in the wireline networks to meet the needs of a high-density, high-mobility multimedia environment. As users become accustomed to wireless communications, they expect communications anywhere, anytime, in any medium. This expectation places an extra burden on the wireline networks to keep track of users' locations, to provide seamless communications as users move around, and to implement security procedures. The rapidly expanding wireless networks rely on Intelligent Network (IN) concepts to track users and deliver enhanced services. The switches and databases that perform these functions use Signaling System 7 (SS7) to connect mobile switching centers (MSCs), visitor location registers (VLRs), and home location registers (HLRs). Wireless networks interact with the existing wireline networks to extend information services to mobile stations (MSs). Figure 4.1 shows the elements of a mobile network based on today's cellular/PCS architecture. We discuss the architecture in detail in chapter 4.

Intersystem communications also use the SS7 network. This network has been standardized for the global system of mobile communications (GSM) in CCITT Q.1000 and for North American Digital Cellular in EIA/TIA IS-41. Both standards support communications between switches and data bases via SS7. In North America, the SS7 network employs 56 kbps, while in Europe 64 kbps is used.

1.6 DIGITAL TECHNOLOGIES

There are two basic strategies whereby a fixed spectrum resource can be allocated to different users: narrowband channelized systems and wideband systems.

Two narrowband systems are:

- **Frequency-division multiple access (FDMA)**, where each user is assigned to a different frequency. Guard bands are maintained between adjacent signals to minimize crosstalk between channels (see fig. 1.1).
- **Time-division multiple access (TDMA)**, where each user is assigned to a different time slot.

In a TDMA system, data from each user are carried in time intervals called time slots (see fig. 1.2). Several time slots make up a frame. Each time slot includes a preamble plus information bits addressed to various users, as shown in figure 1.3. The preamble provides identification and information that allows synchronization of the time slot at the intended receiver. Guard times are used between each user's information to minimize crosstalk between channels.

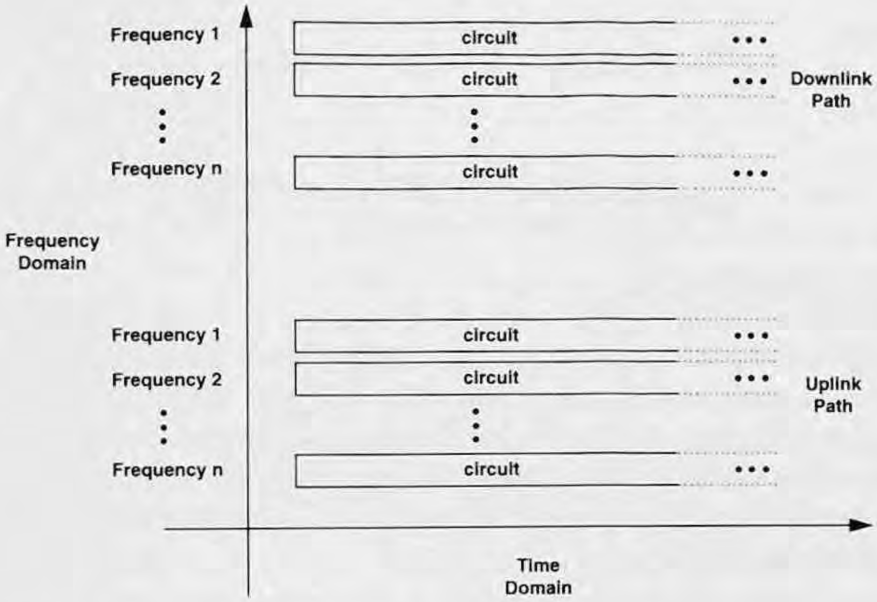

Figure 1.1 Frequency-division multiple access system.

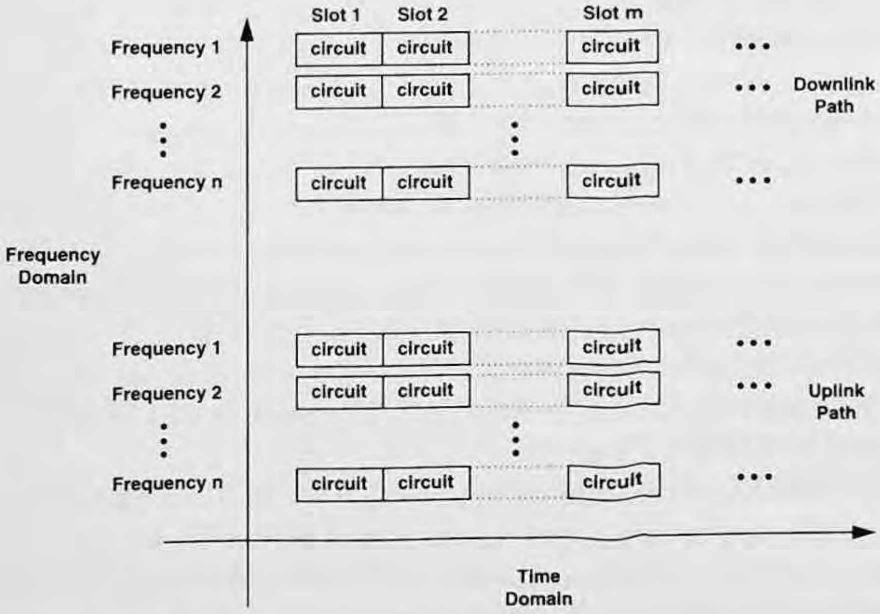

Figure 1.2 Time-division multiple access system.

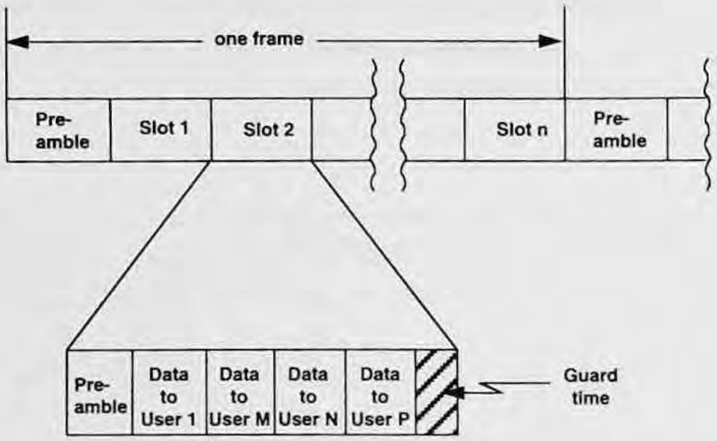

Figure 1.3 TDMA frame and time slot.

In the wideband systems, the entire system bandwidth is made available to each user and is many times larger than the bandwidth required to transmit information. Such systems are referred to as spread spectrum (SS) systems. Even though we limit our discussion to systems that use codes to select users, it is possible to design a TDMA system to have a wide bandwidth.

1.7 SPREAD SPECTRUM TECHNOLOGY

During the late 1980s and early 1990s, the rapid growth in mobile communications put a high demand on system capacity and the availability of the technology for low-cost implementation of cellular and PCS. This growth renewed the interest in commercial applications of SS mobile radios. During the same time, the Federal Communications Commission (FCC) also allowed a liberal unlicensed use of SS radios that prompted the development of a wide variety of commercial SS radio applications.

Among the many multiple-access technologies used for cellular and PCS systems, the digital SS code-division multiple access technology has been adopted as a standard in North America. The standard was developed as an alternative to the IS-54 TDMA system for cellular. The CDMA system promised improved capacity over either the analog AMPS system or the digital TDMA system.

The CDMA system, originally proposed by QUALCOMM for digital cellular phone applications, has been adopted by the Telecommunication Industry Association TR-45 committee as TIA/EIA IS-95 standard for cellular and by the Alliance for Telecommunications Industry Solutions committee T1P1 and TIA-TR46 joint standard J-STD-008 for PCS. Today, several equipment manufacturers offer CDMA systems for both cellular and PCS applications.

The major attributes of the IS-95/J-STD-008 CDMA system follow:

- **System Capacity**. The projected capacity of the CDMA system is higher than that of the existing analog system. The increased system capacity is due to improved coding gain/modulation density, voice activity, three-sector sectorization, and reuse of the same spectrum in every cell.
- **Economies**. CDMA is a cost-effective technology that requires fewer, less-expensive cells and no costly frequency reuse pattern. The average power transmitted by the CDMA mobiles averages about 6–7 mW, which is less than one tenth of the average power typically required by FM and TDMA phones. Transmitting less power means that battery life should be longer.
- **Quality of Service**. CDMA can improve the quality of service by providing robust operation in fading environments and transparent (soft) handoffs. CDMA takes advantage of multipath fading to enhance communications and voice quality. By using a RAKE receiver and other improved signal-processing techniques, each mobile station selects the three strongest multipath signals and coherently combines them to produce an enhanced signal. Thus, the fading multipath nature of the channel is used to an advantage in CDMA. In narrowband systems, fading causes a substantial degradation of signal quality.

  By using a soft handoff, CDMA eliminates the ping-pong effect that occurs when a mobile nears the border between cells, and the call is rapidly switched between two cells. This effect exacerbates handoff noise, increases the load on switching equipment, and increases the chance of a dropped call. In a soft handoff, a connection is made to the new cell while maintaining the connection with the original cell. This procedure ensures a smooth transition between cells, one that is undetectable to the subscriber. In comparison, the analog and other digital systems use a break-before-make connection that increases handoff noise and the chance of a dropped call.

1.8 SUMMARY

In this chapter, we traced the growth in wireless communications and identified the need for a suitable digital technology to handle the future demand. The growth is fueled by the desire in many countries for additional telephone services that are portable/mobile and, in developing countries, as an alternative to the large investment to put copper cable into the ground.

We briefly described narrowband and wideband digital technologies and concluded the chapter by presenting the summary of the features of the IS-95/J-STD-008 SS-CDMA technology.

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CHAPTER 2

Spread Spectrum Systems

2.1 INTRODUCTION

In this chapter, we briefly describe the different types of spread spectrum (SS) systems that are used and then focus on the direct sequence spread spectrum (DSSS) technique that is used in code-division multiple access systems. We develop the necessary relationships to evaluate the performance of a DSSS system with binary phase-shift keying and quadrature phase-shift keying modulation and provide a relationship to calculate the performance of a CDMA system. We conclude the chapter by discussing the main features of the TIA IS-95A system. More details of the CDMA system will be given in chapters 3–8.

2.2 TYPES OF TECHNIQUES USED FOR SPREAD SPECTRUM (SS)

Since the late 1940s, SS techniques have been used for military applications in which clandestine operation is a major objective. SS techniques provide excellent immunity to interference, which may be the result of intentional jamming, and allow transmission to be hidden within background noise. Recently, SS systems have been adopted for civilian applications in wireless telephony systems.

There are three general approaches to implementing SS systems:

- **Direct sequence spread spectrum (DSSS)**, where a carrier is modulated by a digital code in which the code bit rate is much larger than the information signal bit rate (see fig. 2.1). These systems are also called pseudo-noise systems.

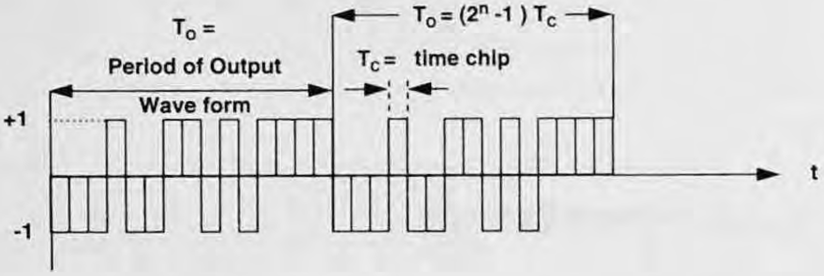

Figure 2.1 Direct sequence spread spectrum approach.

- **Frequency-hopping spread spectrum (FHSS)**, where the carrier frequency is shifted in discrete increments in a pattern generated by a code sequence (see fig. 2.2). Sometimes, the codes are chosen to avoid interference to or from other non-spread-spectrum systems. In a FHSS system, the signal frequency remains constant for a specified time duration, referred to as a time chip T_c. The FHSS system can be either a fast-hop system or a slow-hop system. In a fast-hop system, the frequency hopping occurs at a rate that is greater than the message bit rate. In a slow-hop system, the hop rate is less than the message bit rate. There is, of course, an intermediate situation in which the hop rate and message bit rate are of the same order of magnitude.

  FHSS radio systems experience occasional strong bursty errors, while DSSS radio systems experience continuous but lower-level random errors. With DSSS radio systems, single errors are dis-

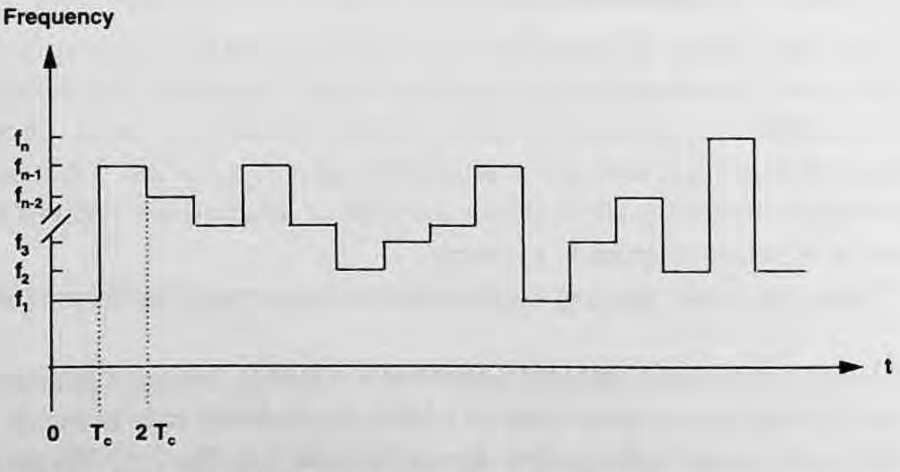

Figure 2.2 Frequency-hopping spread spectrum approach.

persed randomly over time; with FHSS radio systems, errors are distributed in clusters. Bursty errors are attributable to fading or single-frequency interference, which is time and frequency dependent. The DSSS spreads the information in both the time and frequency domains, thus providing time and frequency diversity and minimizing the effects of fading and interference.

- **Time-hopped (TH) spread spectrum**, where the transmission time is divided into intervals called frames (see fig. 2.3). Each frame is divided into time slots. During each frame, one and only one time slot is modulated with a message. All the message bits accumulated in previous frames are transmitted.

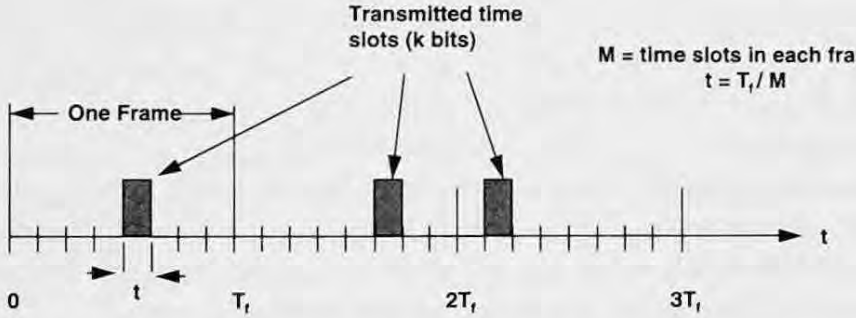

Figure 2.3 Time-hopping spread spectrum approach.

2.3 THE CONCEPT OF THE SPREAD SPECTRUM SYSTEM

The theoretical capacity of any communications channel is defined by C. E. Shannon's channel capacity formula [6]:

$$C = B_w \log_2\left[1 + \frac{S}{N}\right] \qquad (2.1)$$

where B_w = bandwidth in Hertz,
C = channel capacity in bits per second,
S = signal power,
N = noise power.

Equation (2.1) gives the relationship between the theoretical ability of a channel to transmit information without errors for a given signal-to-noise (S/N) ratio and a given bandwidth on a channel. Channel capacity is increased by increasing the channel bandwidth, the transmitted power, or a combination of both.

Shannon modeled the channel at baseband. However, equation (2.1) is applicable to a radio frequency (RF) channel by assuming that the intermediate frequency (IF) filter has an ideal (flat) bandpass response with a bandwidth that is at least $2B_w$. This bound assumes that channel noise is additive white Gaussian noise (AWGN), which is often adopted in the modeling of an RF channel. This assumption is justified since the total noise is generated by random electron fluctuations. The central limit theorem provides us with the assumption that the output of an IF filter has a Gaussian distribution and is frequency independent. For most communications systems that are limited by thermal noise, this assumption is true. For interference-limited systems, this assumption is not true, and the results may be different. The Shannon equation does not provide a method to achieve the bound. Approaching the bound requires complex channel coding and modulation techniques. In many cases, achieving an implementation that provides performance near this bound is impractical due to the resulting complexity.

An analog cellular system is typically engineered to have an S/N ratio of 17 dB[1] or more. CDMA systems can be engineered to operate at much lower S/N ratios since the extra channel bandwidth can be used to achieve good performance at a very low signal-to-noise ratio.

We can rewrite equation (2.1)

$$\frac{C}{B_w} = 1.44 \log_e\left[1 + \frac{S}{N}\right] \tag{2.2}$$

since

$$\log_e\left(1 + \frac{S}{N}\right) = \frac{S}{N} - \frac{1}{2}\left(\frac{S}{N}\right)^2 + \frac{1}{3}\left(\frac{S}{N}\right)^3 - \frac{1}{4}\left(\frac{S}{N}\right)^4 + \cdots \tag{2.3}$$

we use the logarithmic expansion and assume that the S/N ratio is small (e.g., $S/N \leq 0.1$); therefore, we can neglect the higher-order terms to rewrite equation (2.2) as

$$B_w \approx \frac{C}{1.44} \times \frac{N}{S} \tag{2.4}$$

---

[1] This ratio assumes a fading radio environment, which is typical for analog cellular systems that use frequency modulation. In the absence of fading, good FM performance is achievable at lower signal-to-noise ratios.

For any given *S/N* ratio, we can have a low information error rate by increasing the bandwidth used to transmit the information. As an example, if we want a system to operate on a link in which the information rate is 10 kilobits per second (kbps) and the *S/N* ratio is 0.01, we must use a bandwidth of

$$B_w = \frac{10 \times 10^3}{1.44 \times 0.01} = 0.69 \times 10^6 \text{ Hz or 690 kHz}$$

Information can be modulated into the SS signal by several methods. The most common method is to add the information to the spectrum-spreading code before it is used for modulating the carrier frequency (fig. 2.4). This technique applies to any SS system that uses a code sequence to determine RF bandwidth. If the signal that is being sent is analog (voice, for example), the signal must be digitized before being added to the spreading code.

One of the major advantages of an SS system is the robustness to interference. The system processing gain G_p quantifies the degree of interference rejection. The system processing gain is the ratio of RF bandwidth to the information rate and is given as

$$G_p = \frac{B_w}{R} \tag{2.5}$$

Typical processing gains for SS systems lie between 20 and 60 dB. With a SS system, the noise level is determined both by the thermal

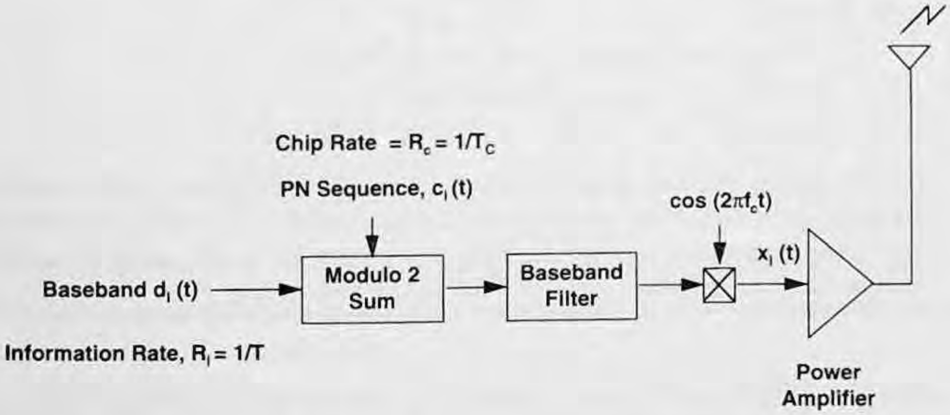

Figure 2.4 Basic DSSS system transmitter.

noise and by interference. For a given user, the interference is processed as noise. The input and output S/N ratios are related as

$$\left(\frac{S}{N}\right)_o = G_p\left(\frac{S}{N}\right)_i \tag{2.6}$$

It is instructive to relate the S/N ratio to the E_b/N_0 ratio[2] where E_b is the energy per bit and N_0 is the noise power spectral density:

$$\left(\frac{S}{N}\right)_i = \frac{E_b \times R}{N_0 \times B} = \frac{E_b}{N_0} \times \frac{1}{G_p} \tag{2.7}$$

From equation (2.6), we can express E_b/N_0 as

$$\frac{E_b}{N_0} = G_p \times \left(\frac{S}{N}\right)_i = \left(\frac{S}{N}\right)_o \tag{2.8}$$

Example 2.1

Calculate the processing gain for a DSSS system that has a 10 megachips per second (Mcps) code clock rate and 4.8-kbps information rate. How much improvement in the processing gain will be achieved if the code generation rate is changed to 50 Mcps? Is there an advantage in going to a higher code generation rate with 4.8-kbps information rate?

We assume that the DSSS waveform has a voltage distribution of $(\sin x)/x$. The power distribution has a form of $[(\sin x)/x]^2$. The bandwidth of the main lobe is equal to the spreading code clock rate:

$$G_p = \frac{1.0 \times 10^7}{4.8 \times 10^3} = 2.1 \times 10^3 = 33.1 \text{ dB}$$

With 50 Mcps,

$$G_p = \frac{5 \times 10^7}{4.8 \times 10^3} = 1.04 \times 10^4 = 40.2 \text{ dB}$$

By increasing the code generation rate from 10 to 50 Mcps, we get only a 7-dB improvement in the processing gain. The effort required to increase the operating speed of a circuit by five times may be much more demanding compared to an improvement of 7 dB in the processing gain.

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[2] The noise power spectral density actually consists of both the thermal noise and interference. Unless stated explicitly, N_0 represents the thermal noise. However, common usage of this ratio assumes that N_0 includes both the thermal noise and the interference. With SS systems, interference is transformed into noise.

2.4 THE PERFORMANCE OF DIRECT SEQUENCE SPREAD SPECTRUM

2.4.1 The Direct Sequence Spread Spectrum System

The DSSS system is a wideband system in which the entire bandwidth of the system is available to each user. A system is defined to be a DSSS system if it satisfies the following requirements:

- The spreading signal has a bandwidth much larger than the minimum bandwidth required to transmit the desired information, which for a digital system is the baseband data.
- The spreading of the data is performed by means of a spreading signal, often called a code signal. The code signal is independent of the data and is of a much higher rate than the data signal.
- At the receiver, despreading is accomplished by the cross-correlation of the received spread signal with a synchronized replica of the same signal used to spread the data.

2.4.2 Coherent Binary Phase-Shift Keying

The simplest form of a DSSS communications system employs coherent binary phase-shift keying (BPSK) for both the data modulation and the spreading modulation. But, the most common form uses BPSK for the data modulation and quadrature phase-shift keying (QPSK) for the spreading modulation. We first consider the simplest case.

The encoded DSSS BPSK signal is given by

$$x(t) = c(t)s(t) = c(t)d(t)\sqrt{2S}\cos\omega_c t \tag{2.9}$$

where $s(t) = d(t)\sqrt{2S}\cos\omega_c t$,
$d(t)$ = the baseband signal at the transmitter input and receiver output,
$c(t)$ = the spreading signal,
S = the signal power,
ω_c = the carrier frequency.

In equation (2.9), we represent the modulo-2 addition of $c(t)$ and $d(t)$ as a multiplication because the binary signals, 0 and 1, represent values of 1 and –1 into the modulator.

The signal $s(t)$ has a $[(\sin x)/x]^2$ spectrum of bandwidth roughly $1/T$ (where T is the periodicity at baseband), while the SS signal $x(t)$ has a similar spectrum but with a bandwidth of approximately $1/T_c$ (where T_c is the periodicity of the spreading signal). From equation (2.5), the processing gain of the system is $G_p = (B_w/R) = T/T_c$. If the interfering signal is represented by $I(t)$, then in the absence of noise (assuming that the interferer limits the system performance—in other words, that the interferer's power level exceeds the thermal noise power), the signal at the receiver is given as

$$[r(t)]^* = x(t) + I(t) \tag{2.10}$$

The receiver multiplies this by the PN waveform to obtain the signal

$$r(t) = c(t)[x(t) + I(t)] = c(t)[c(t)s(t)] + c(t)I(t) = s(t) + c(t)I(t) \tag{2.11}$$

since $c(t)^2 = 1$, $c(t)I(t)$ is the effective noise waveform due to interference.

The conventional BPSK detector output is given as

$$r = d\sqrt{E_b} + n \tag{2.12}$$

where d = the data bit for the T second interval,
E_b = the bit energy,
n = the equivalent noise component.

The spreading-despreading operation does not affect the signal and does not affect the spectral and probability density function of the noise. For this reason, the bit error probability P_b associated with the coherent BPSK SS signal is the same as with the BPSK [13] signal and is given as

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2.13}$$

2.4.3 Quadrature Phase-Shift Keying

For QPSK modulation, we denote the in-phase and quadrature data waveforms as $d_c(t)$ and $d_s(t)$, respectively, and the corresponding pseudorandom noise (PN) binary waveform as $c_c(t)$ and $c_s(t)$. We can represent a QPSK signal as (see fig. 2.5)

$$x(t) = c_c(t)d_c(t)\sqrt{S}\cos\omega_c t + c_s(t)d_s(t)\sqrt{S}\sin\omega_c t \tag{2.14}$$

where each QPSK pulse is of duration $T_s = 2T$.

The in-phase output component is

$$r_c = d_c\sqrt{E_b} + n_c \tag{2.15}$$

where $n_c = \sqrt{2/T_s}\int_0^{T_c} c_c(t)I(t)\cos\omega_c t\,dt$

and the quadrature component is

$$r_s = d_s\sqrt{E_b} + n_s \qquad (2.16)$$

where $n_s = \sqrt{2/T_s}\int_0^{T_c} c_s(t)I(t)\sin\omega_c t\,dt$.

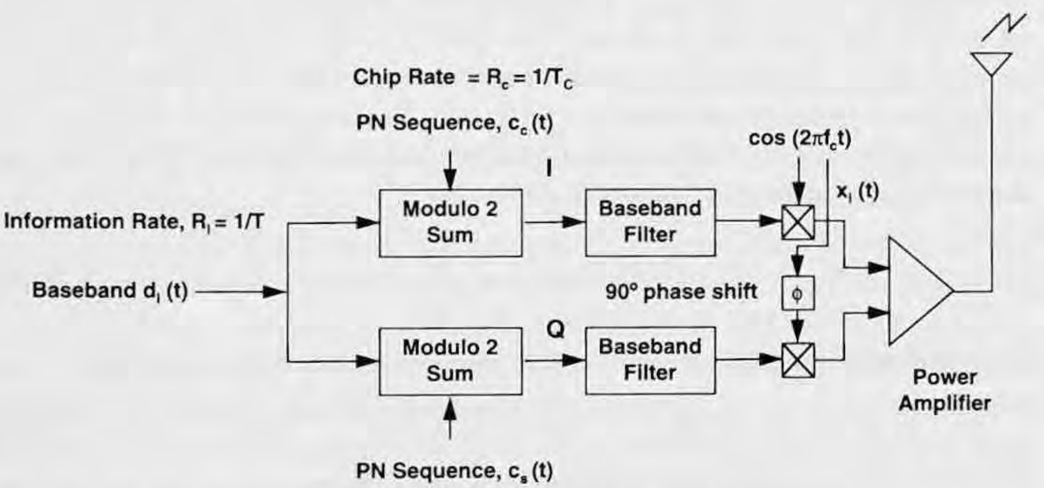

Figure 2.5 DSSS system with BPSK and QPSK transmitter.

QPSK modulation can be viewed as two independent BPSK modulations. Thus, the net data rate is doubled. We consider a special case of QPSK modulation where $c_c(t)$ and $c_s(t)$ are equal and have a value of c. The QPSK symbol energy is also the bit energy (one bit per QPSK signal).

For this case equations (2.15) and (2.16) have the form

$$r_c = d\sqrt{\frac{E_b}{2}} + n_c \qquad (2.17)$$

and

$$r_s = d\sqrt{\frac{E_b}{2}} + n_s \qquad (2.18)$$

where n_c and n_s are zero mean independent with conditional variances

$$\mathrm{Var}\langle n_c|\theta\rangle = (IT_c)(\cos\,\theta)^2 \tag{2.19}$$

and

$$\mathrm{Var}\langle n_s|\theta\rangle = (IT_c)(\sin\,\theta)^2\,. \tag{2.20}$$

Next we use

$$r = \frac{(r_c + r_s)}{2} = d\sqrt{\frac{E_b}{2}} + \frac{(n_c + n_s)}{2} \tag{2.21}$$

as the statistic for decision rule; then

$$\mathrm{Var}\langle(n_c + n_s)/2|\theta\rangle = \frac{1}{4}\,[IT_c(\cos\,\theta)^2 + IT_c(\sin\,\theta)^2] = \frac{IT_c}{4} \tag{2.22}$$

where θ = phase of signal

The final expression for narrowband interference $G_j(f)$ at the demodulator baseband output is given as

$$G_j(f) = \frac{IT_c}{4} = \frac{I}{4f_c} \tag{2.23}$$

For baseband systems, we define the baseband interference $I(f)$ as

$$I(f) = 2G_j(f) \quad 0 \le f \le f_c \tag{2.24}$$

The bit error probability for AWGN is given [13] as

$$P_b = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{2.25}$$

where $Q(u) \approx e^{-u^2/2}(\sqrt{2\pi}u)$, $u \gg 1$.

We assume that the demodulated baseband interference I is represented by AWGN.[3] For coherent PSK demodulation, we have

$$P_b = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{(2I)/(4f_c)}}\right) = \frac{1}{2}\,\mathrm{erfc}\left[\sqrt{2\left(\frac{S}{I}\right)\left(\frac{f_c}{f_b}\right)}\right] \tag{2.26}$$

where $I_{eff} = I/[2(f_c/f_b)]$ is referred to as the effective interference power.

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[3] This is not strictly true since the noise is known, but is sufficient for the purposes of this discussion.

The *effective interference power*, in comparison with the signal power, determines the bit error rate probability P_b of the SS system. Note that the effective interference power is reduced by the ratio of the bandwidth expansion between the baseband signal and the transmitted signal (f_c/f_b).

2.5 THE PERFORMANCE OF A CODE-DIVISION MULTIPLE ACCESS SYSTEM

A traditional narrowband system based on FDMA or TDMA is a dimension-limited system. The number of dimensions is determined by the number of non-overlapping frequencies for FDMA or by the number of time slots for TDMA. In a TDMA system, no additional users can be added once all time slots are assigned. Thus, it is not possible to increase the number of users beyond the dimension limit without causing an intolerable amount of interference to reception of a mobile station at the cell-site receiver.

Spread spectrum systems can tolerate some interference, so the introduction of each additional active radio increases the overall level of interference to the cell site receivers receiving CDMA signals from mobile station transmitters. Each mobile station introduces a unique level of interference that depends on its received power level at the cell site, its timing synchronization relative to other signals at the cell site, and its specific cross-correlation with other CDMA signals.

The number of CDMA channels in the network depends on the level of total interference that can be tolerated in the system. Thus, the CDMA system is limited by interference, and the quality of system design plays an important role in its overall capacity. A well-designed system will have a required bit error probability with a higher level of interference than a poorly designed system. Forward error-correction coding techniques improve tolerance for interference and increase the overall CDMA system capacity.

We assume that at the cell site the received signal level of each mobile user is the same and that the interference seen by each receiver is modeled as Gaussian noise. Each modulation method has a relationship that defines the bit error rate as a function of the E_b/N_0 ratio. If we know the performance of the coding methods used on the signals and tolerance of the digitized voice and the data to errors, we can define the minimum E_b/N_0 ratio for proper system operation. If we maintain operation at this minimum E_b/N_0, we can obtain the best performance of the system. The relationship between the number of mobile users M, the processing gain G_p, and the E_b/N_0 ratio are therefore given as

$$M \approx \frac{G_p}{(E_b/N_0)} \tag{2.27}$$

For a given bit error probability, the actual E_b/N_0 ratio depends on the radio system design and error-correction code. It may approach but never equal the theoretical calculations.

The best performance that can be obtained is defined by the Shannon limit[4] in AWGN. In equation (2.2), if we note that

$$\log_e\left(1 + \frac{S}{N}\right) = \frac{S}{N} - \frac{1}{2}\left(\frac{S}{N}\right)^2 + \frac{1}{3}\left(\frac{S}{N}\right)^3 - \frac{1}{4}\left(\frac{S}{N}\right)^4 + \cdots < \frac{S}{N} \tag{2.28}$$

then, from equation (2.2),

$$\frac{C}{B_w} < \frac{1}{\log_e 2}\left(\frac{S}{N}\right) \tag{2.29}$$

and

$$\frac{C}{B_w} < \frac{1}{\log_e 2}\left(\frac{E_b}{N_0}\right)\left(\frac{C}{B_w}\right). \tag{2.30}$$

Thus,

$$\frac{E_b}{N_0} \geq \log_e 2 = 0.69 = -1.59 \text{ dB} \tag{2.31}$$

provides error-free communications.

For the Shannon limit, the number of users that we can have is

$$M = \frac{G_p}{0.69} = 1.45G_p \tag{2.32}$$

This theoretical Shannon limit shows that CDMA systems can have more users per cell than traditional narrowband systems that are limited by number of dimensions. This limit is theoretical, and in practice a wireless system is typically engineered such that $E_b/N_0 = 6$ dB. However, due to practical limitations on CDMA radio design, it is difficult to accommodate as many users in a single cell as given by equation (2.32). The CDMA cell capacity depends upon many factors. As seen by equation

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[4] This limit is a lower bound [6]. It is assumed that the channel coding has an infinite length to achieve this bound.

(2.32), the upper-bound theoretical capacity of an ideal noise-free CDMA channel is limited by the processing gain G_p. In an actual system, the CDMA cell capacity is much lower than the theoretical upper-bound value. The CDMA cell capacity is affected by the receiver modulation performance, power control accuracy, interference from other non-CDMA systems sharing the same frequency band, and other effects that are currently being discovered.

The CDMA transmissions in neighboring cells use the same carrier frequency and therefore cause interference that we account for by introducing a factor β. This modification reduces the number of users in a cell since the interference from users in other cells must be added to the interference generated by the other mobiles in the user's cell. The practical range for β is 0.4–0.55. The power control accuracy is represented by a factor α. The practical range for α is 0.5–0.9. We designate the reduction in the interference due to voice activity by a factor υ. The practical range for υ is 0.45–1. If directional antennas are used rather than omnidirectional antennas at the base station, the cell is sectorized with A sectors. The antennas used at the cell each radiate into a sector of $360/A$ degrees, and we have an interference improvement factor of λ. For a three-sector cell, the practical value of the improvement factor λ is 2.55. The average values for β, α, υ, and λ are taken as 0.5, 0.85, 0.6, and 2.55, respectively.

Introducing β, α, υ, and λ into equation (2.27) we get

$$M \approx \frac{G_p}{E_b/N_0} \times \frac{1}{1+\beta} \times \alpha \times \frac{1}{\upsilon} \times \lambda \tag{2.33}$$

Example 2.2

Estimate the number of mobile users that can be supported by a CDMA system that uses an RF bandwidth of 1.25 MHz to transmit data at 9.6 kbps. Assume $E_b/N_0 = 6$ dB, the interference from neighboring cells $\beta = 60\%$, the voice activity factor $\upsilon = 50\%$, and the power control accuracy factor $\alpha = 0.8$.

$$G_p = \frac{1.25 \times 10^6}{9.6 \times 10^3} = 130$$

$$\frac{E_b}{N_0} = 6 \text{ dB} = 3.98$$

$$M = \frac{130}{3.98} \times \frac{1}{1+0.6} \times \frac{1}{0.5} \times 0.8 = 32.64 \approx 33 \text{ mobile users per call}$$

The results of this example can be compared with the capacity of an analog FM system with the same frequency allocation (i.e., 41 FM channels). Typically, an analog system is engineered with a frequency reuse pattern equal to 7. With a three-sector configuration, the number of channels per sector equals $41/(7 \times 3) = 2$. This comparison suggests that a DSSS system offers a greater than tenfold improvement in the channel capacity. It is interesting to note that the processing gain of a DSSS system is directly proportional to spectrum expansion, while the processing gain of an FM system is proportional to the square of the frequency expansion.[5] This would seem to imply that the FM system should perform better than the CDMA system; yet it doesn't. There are several reasons for this CDMA performance:

- DSSS techniques take advantage of the voice activity.
- DSSS techniques use the concept of orthogonality for multiple users on a common frequency channel. This concept is applicable across different base stations and sectors.
- DSSS techniques synchronize transmission for all base stations so that soft handoffs (see chapter 7) can be implemented. This approach reduces the level of interference.

Example 2.3

For the CDMA system (TIA IS-95), a chip rate[6] of 1.2288 Mcps is specified for the data rate of 9.6 kbps. E_b/N_0 is taken as 6.8 dB. Estimate the average number of subscribers that can be supported by a sector of the three-sector cell. Assume interference from neighboring cells $\beta = 50\%$, the voice activity factor $\upsilon = 60\%$, the power control accuracy factor $\alpha = 0.85$, and the improvement from sectorization $\lambda = 2.55$.

$$M \approx \frac{G_p}{E_b/N_0} \times \frac{1}{1+\beta} \times \alpha \times \frac{1}{\upsilon} \times \lambda$$

$$G_p = \frac{(1/9.6)}{[1/(1.2288 \times 10^3)]} = 128, \quad \frac{E_b}{N_0} = 6.8 \text{ dB} = 4.7863$$

$$M = \frac{128}{4.7863} \times \frac{1}{1.5} \times \frac{1}{0.6} \times 0.85 \times 2.55 = 64.7$$

$$\text{Subscribers/Sector} = \frac{64.7}{3} = 21.57 \approx 22$$

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[5] For an FM system, the frequency expansion is specified by the deviation ratio.

[6] The chip rate is the frequency of the code clock.

EXAMPLE 2.4

A total of 40 equal-power mobile stations are to share a frequency band through a CDMA system. Each mobile station transmits information at 9.6 kbps with a DSSS BPSK-modulated signal. Calculate the minimum chip rate of the PN code in order to maintain a bit error probability of 10^{-3}. Assume that the interference factor β from the other base stations = 60%, voice activity υ = 50%, and power control accuracy factor α = 0.8. What will be the chip rate if the probability of error is 10^{-4}?

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \approx \frac{e^{-E_b/N_0}}{2\sqrt{\pi(E_b/N_0)}}$$

$$\frac{e^{-E_b/N_0}}{2\sqrt{\pi(E_b/N_0)}} = 10^{-3}$$

$$\frac{E_b}{N_0} \approx 4.8 = 6.8 \text{ dB}$$

$$M = \frac{G_p}{(E_b/N_0)} \times \frac{1}{1+\beta} \times \frac{1}{\upsilon} \times \alpha$$

$$\frac{G_p}{4.8} \times \frac{1}{1.6} \times \frac{1}{0.5} \times 0.8 = 40$$

$$\therefore G_p = 192$$

$$\therefore R_c = 192 \times 9.6 \times 10^3 = 1.843 \text{ Mcps}$$

$$\text{For } P_b = 10^{-4}, \frac{E_b}{N_0} = 8.43 \text{ dB} = 6.9663$$

$$\therefore G_p = 278.5 \text{ and } R_c = 2.652 \text{ Mcps}$$

2.6 PSEUDORANDOM NOISE SEQUENCES

In CDMA systems, pseudorandom noise (PN) sequences are used to perform the following tasks:

- Spread the bandwidth of the modulated signal to the larger transmission bandwidth.
- Distinguish among the different user signals by using the same transmission bandwidth in the multiple-access scheme.

The PN sequences are not random; they are deterministic, periodic sequences. The following are the three key properties of an ideal PN sequence [2]:

- The relative frequencies of zero and one are each 1/2.
- For zeros or ones, half of all run lengths are of length 1; one quarter are of length 2; one eighth are of length 3; and so on.
- If a PN sequence is shifted by any nonzero number of elements, the resulting sequence will have an equal number of agreements and disagreements with respect to the original sequence.

PN sequences are generated by combining the outputs of feedback shift registers. A feedback shift register consists of consecutive two-state memory or storage stages and feedback logic. Binary sequences are shifted through the shift register in response to clock pulses. The contents of the stages are logically combined to produce the input to the first stage. The initial contents of the stages and feedback logic determine the successive contents of the stages. A feedback shift register and its output are called linear when the feedback logic consists entirely of modulo-2 adders.

To demonstrate the properties of PN binary sequence, we consider the linear feedback shift register (see fig. 2.6) that has a four-stage register for storage and shifting, a modulo-2 adder, and a feedback path from

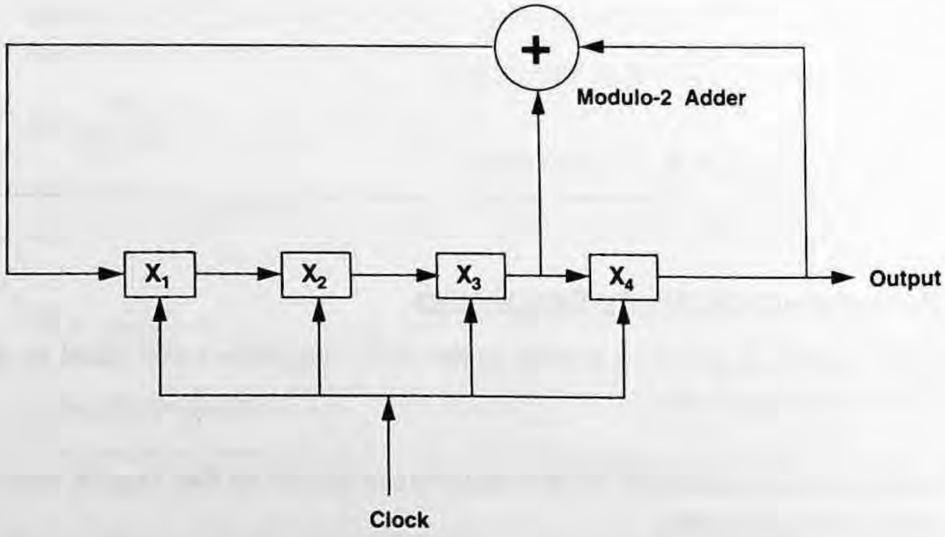


Figure 2.6 Four-stage linear feedback shift register.

adder to the input of the register. The operation of the shift register is controlled by a sequence of clock pulses. At each clock pulse, the contents of each stage in the register is shifted by one stage to the right. Also, at each clock pulse, the contents of stages X_3 and X_4 are modulo-2 added, and the result is fed back to stage X_1. The shift register sequence is defined to be the output of stage X_4. We assume that stage X_1 is initially filled with a 0, and the other remaining stages are filled with 0, 0, and 1 (i.e., the initial state of the register is 0 0 0 1). Next, we perform the shifting, adding, and feeding operations, where the results after each cycle are given in table 2.1.

Table 2.1 Results of Shifting after Each Cycle

Shift	Stage X_1	Stage X_2	Stage X_3	Stage X_4	Output Sequence
0	0	0	0	1	1
1	1	0	0	0	0
2	0	1	0	0	0
3	0	0	1	0	0
4	1	0	0	1	1
5	1	1	0	0	0
6	0	1	1	0	0
7	1	0	1	1	1
8	0	1	0	1	1
9	1	0	1	0	0
10	1	1	0	1	1
11	1	1	1	0	0
12	1	1	1	1	1
13	0	1	1	1	1
14	0	0	1	1	1
15	0	0	0	1	1
16	1	0	0	0	0

We notice that the contents of the registers repeats after $2^4 - 1 = 15$ cycles. The output sequence is given as 0 0 0 1 0 0 1 1 0 1 0 1 1 1 1 (see fig. 2.7), where the left most bit is the earliest bit. In the output sequence, the total number of zeros is 7, and the total number of ones is 8; the numbers differ by 1.

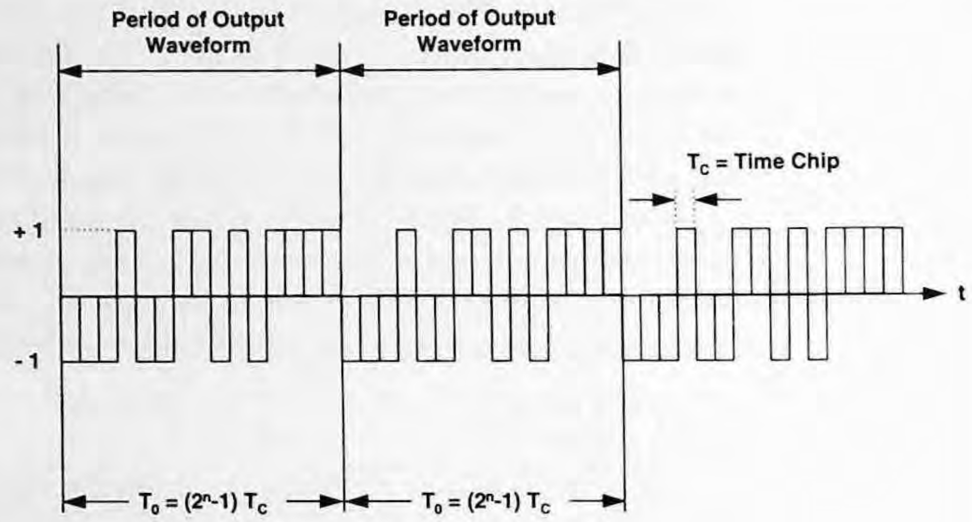


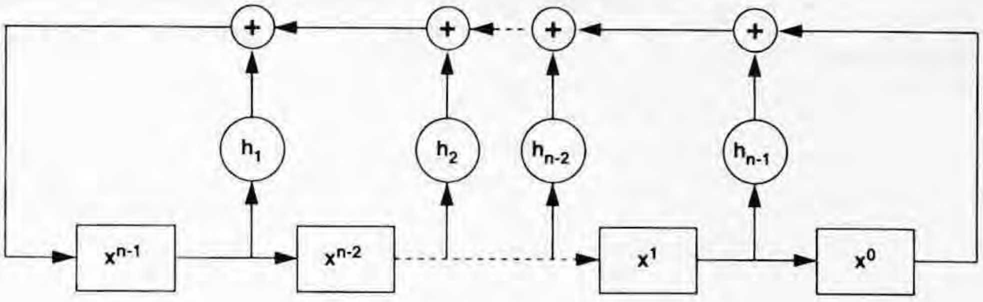
Figure 2.7 Output waveform for four-stage linear feedback shift register.

If a linear feedback shift register reached the zero state at some time, it would always remain in the zero state, and the output sequence would subsequently be all zeros. Since there are exactly $2^n - 1$ nonzero states, the period of a linear n-stage shift register output sequence cannot exceed $2^n - 1$.

The output sequences are classified as either maximal length or nonmaximal length. Maximal length sequences are the longest sequences that can be generated by a given shift register of a given length, whereas all other sequences besides maximal length sequences are nonmaximal length sequences. In the binary shift register sequence generators, the maximal length sequence is $2^n - 1$ chips, where n is the number of stages in the shift registers. Maximal length sequences have the property that, for an n-stage linear feedback shift register, the sequence repetition period in clock pulses is $T_0 = 2^n - 1$. If a linear feedback shift register generates a maximal sequence, then all its nonzero output sequences are maximal, regardless of the initial stage. A maximal sequence contains $2^{n-1} - 1$ zeros and 2^{n-1} ones per period.

2.6.1 Properties of a Maximal Length Pseudorandom Sequence

When an n-stage shift register (see fig. 2.8) is configured to generate a maximal length sequence, the sequence has the following properties:



Note: $h_l = 1$ represents a closed circuit;
$h_l = 0$ represents an open circuit

Figure 2.8 *n*-Stage linear feedback shift register.

- The number of binary zeros differs from the number of ones by at most one chip. The number of binary ones is 2^{n-1} and the number of zeros is $2^{n-1} - 1$, where n is the number of stages in the code generator, and the code length is $2^n - 1$ chips.
- A run is defined as a sequence of a single type of binary digits. The appearance of the alternate digit in a sequence starts a new run. The length of the run is the number of digits in the run. The statistical distribution of ones and zeros is well defined and always the same. Relative positions of the runs vary from code sequence to code sequence, but the number of each run length does not.
- A modulo-2 addition of a maximal linear code with a phase-shifted replica of itself results in another replica with a phase shift different from either of the originals.
- If a period of the sequence is compared term by term with any cyclic shift itself, it is best if the number of agreements differs from the number of disagreements by not more than one count.
- If we transform the binary (0,1) sequence of the shift register output to a binary (+1, −1) sequence by replacing each zero by +1, and each 1 by −1, then the periodic correlation function of the sequence is given by

$$\theta(\tau) = \begin{bmatrix} 2^n - 1, & \tau = 0 \\ -1, & \tau \neq 0 \end{bmatrix} \tag{2.34}$$

where τ = the shift in increments of one chip (see fig. 2.9 as an example of $n = 3$)
n = the number of stages in the shift register.

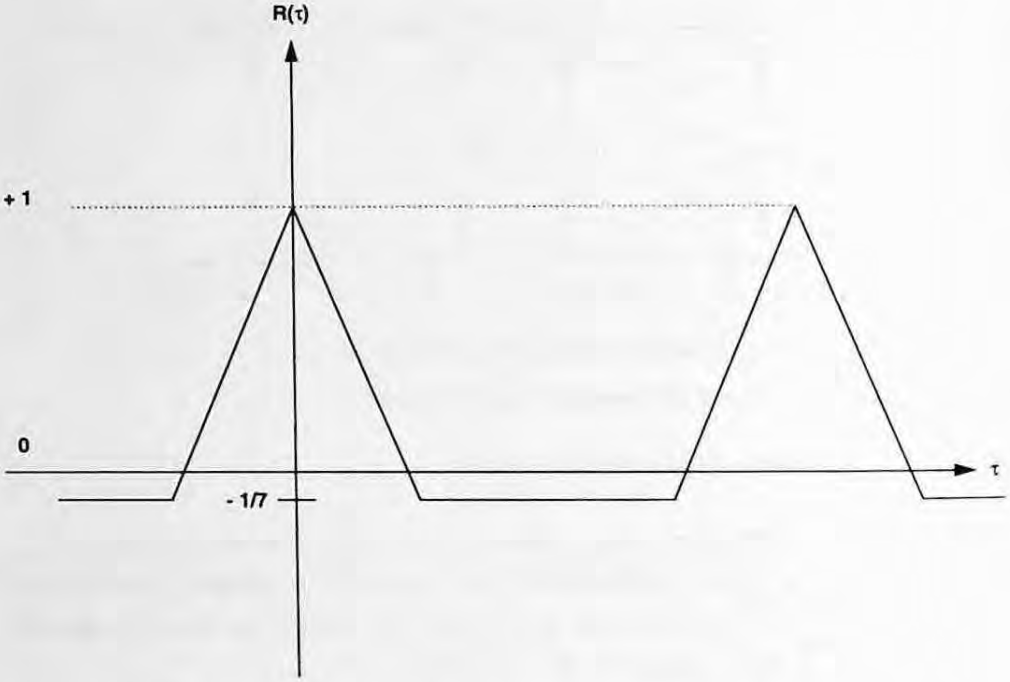


Figure 2.9 Autocorrelation of three-stage linear feedback shift register.

In the region between $\tau = 0$ and $\tau = \pm 1$, the correlation function decreases linearly from $2^n - 1$ to -1 so that the autocorrelation function for a maximal length pseudorandom sequence is triangular with a maximum value at $\tau = 0$ (see example 2.5). With this property, two or more communicators can operate independently, if their codes are phase-shifted more than one chip. For other codes sequences, the autocorrelation properties may be markedly different than the properties of the maximal length sequences.

- Every possible state of a given n-stage generator exists at some time during the generation of a complete code cycle. Each state exists for one and only one clock interval. The exception is that the all-zeros state does not normally occur and is not allowed to occur.

It has been shown [2] that there are exactly $2^{n-(p+2)}$ runs of length p for both ones and zeros in every maximal sequence (except that there is only one run containing n ones and one containing $n - 1$ zeros; there are no runs of zeros of length n or ones of length $n - 1$). The distribution of runs for $2^4 - 1$ chip sequence is given in table 2.2.

Table 2.2 Distribution of Runs for a $2^4 - 1$ Chip Sequence

Run Length	Ones	Zeros	Number of Chips Included
1	2	2	$1 \times 2 + 1 \times 2 = 4$
2	1	1	$1 \times 2 + 1 \times 2 = 4$
3	0	1	$0 \times 3 + 1 \times 3 = 3$
4	1	0	$1 \times 4 + 0 \times 4 = 4$
Total Number of Chips			15

Whether an n-stage linear feedback shift register generates only one sequence with period $2^n - 1$ depends upon its connection vector (see fig. 2.8). Let $h(x)$ be the nth-order polynomial given by

$$h(x) = h_0 + h_1x + h_2x^2 + \cdots + h_nx^n \tag{2.35}$$

We refer to $h(x)$ as the associated polynomial of the shift register with feedback coefficient $(h_0, h_1, h_2, \ldots, h_n)$. Here $h_0 = h_n = 1$, and other feedback coefficients take values 0 and 1. Thus, the polynomial for the four-stage linear feedback shift register, as shown in figure 2.6, is given by

$$h(x) = 1 + x^3 + x^4 \tag{2.36}$$

When $h(x)$ is an irreducible (not factorable) primitive polynomial of degree n, then all sequences generated by $h(x)$ have a maximum period of $2^n - 1$. For an n-stage register, there are $N_p(n)$ maximal sequences that can be generated [10]. $N_p(n)$ is the number of primitive polynomials of degree n:

$$N_p(n) = \left[\frac{2^n - 1}{n}\right]\prod_{i=1}^{k}\frac{P_i - 1}{P_i} \tag{2.37}$$

where P_i is the prime decomposition of $2^n - 1$.

Table 2.3 gives the number of maximal sequences available from register lengths 2–10 and provides an example of primitive polynomial of degree n.

2.6.2 Autocorrelation

The autocorrelation function for a signal $x(t)$ is defined as

$$R_x(\tau) = \int_{-\infty}^{\infty} x(t)x(t + \tau)dt \tag{2.38}$$

Table 2.3 Number of Maximal Sequences Available from Register Lengths 2–10

Number of Stage n	$2^n - 1$	Prime Decomposition of $2^n - 1$	Number of n-sequence $N_p(n)$	Example of Primitive Polynomial of Degree n, $h(x)$
2	3	3	$\frac{3}{2} \cdot \frac{2}{3} = 1$	$1 + x + x^2$
3	7	7	$\frac{7}{3} \cdot \frac{6}{7} = 2$	$1 + x + x^3$
4	15	3×5	$\frac{15}{4} \cdot \frac{2}{3} \cdot \frac{4}{5} = 2$	$1 + x + x^4$
5	31	31	$\frac{31}{5} \cdot \frac{30}{31} = 6$	$1 + x^2 + x^5$
6	63	$3 \times 3 \times 7$	$\frac{63}{6} \cdot \frac{2}{3} \cdot \frac{6}{7} = 6$	$1 + x + x^6$
7	127	127	$\frac{127}{7} \cdot \frac{126}{127} = 18$	$1 + x^3 + x^7$
8	255	$3 \times 5 \times 17$	$\frac{255}{8} \cdot \frac{2}{3} \cdot \frac{4}{5} \cdot \frac{16}{17} = 16$	$1 + x^2 + x^3 + x^4 + x^8$
9	511	7×73	$\frac{511}{9} \cdot \frac{6}{7} \cdot \frac{72}{73} = 48$	$1 + x^4 + x^9$
10	1023	$3 \times 11 \times 31$	$\frac{1023}{10} \cdot \frac{2}{3} \cdot \frac{10}{11} \cdot \frac{30}{31} = 60$	$1 + x^3 + x^{10}$

Autocorrelation refers to the degree of correspondence between a sequence and a phase-shifted replica of itself. An autocorrelation plot shows the number of agreements minus disagreements for the overall length of the two sequences being compared, as the sequences assume every shift in the field of interest. If $x(t)$ is a periodic pulse waveform representing a PN sequence, we refer to each fundamental pulse as a PN sequence symbol or a chip. For such PN waveform of unit chip duration and period $T_0 = 2^n - 1$ chips, the normalized autocorrelation function is expressed as

$R_x(\tau) = \frac{1}{T_0}$ [number of agreements – number of disagreements in a comparison of one full period of sequence with a τ position cyclic shift of the sequence]

The normalized autocorrelation function $R_x(\tau)$ of a periodic waveform $x(t)$ with period T_0 is given as:

$$R_x(\tau) = \frac{1}{R_x(0)}\frac{1}{T_0}\int_{-T_0/2}^{T_0/2} x(t)x(t+\tau)dt \quad \text{for } -\infty < \tau < \infty \tag{2.39}$$

where $R_x(0) = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} x^2(t)dt$

2.6.3 Cross-correlation

The cross-correlation function between two signals $x(t)$ and $y(t)$ is defined as the correlation between two different signals, $x(t)$ and $y(t)$, and is given as

$$R_c(\tau) = \int_{-T_0/2}^{T_0/2} x(t)y(t+\tau)dt \qquad \text{for } -\infty < \tau < \infty \tag{2.40}$$

Example 2.5

Consider a three-stage shift register generator, generating a seven-chip maximal linear code. The reference sequence is 1 1 1 0 0 1 0. Sketch the autocorrelation function if the chip rate is 10 Mcps.

Table 2.4 provides the sequence after each shift and shows the corresponding agreements A and disagreements D with the reference sequence.

Note that the net correlation $A - D$ is -1 for all shifts except for the zero-shift or synchronous condition. This is typical of all n sequences. In the region between zero and plus or minus one chip shift [$\tau = \pm 1/10^6$ seconds], the correlation increases linearly so that the autocorrelation function for an n sequence is triangular as shown in figure 2.9. This characteristic of autocorrelation is used to great advantage in communication systems. A channel can simultaneously support multiple users, if the corresponding codes are phase-shifted more than one chip.

2.6.4 Orthogonal Functions

Orthogonal functions are employed to improve the bandwidth efficiency of a spread spectrum system. Each mobile user uses one member of a set of orthogonal functions representing the set of symbols used for transmission. While there are many different sequences that can be used to generate an orthogonal set of functions, the Walsh and Hadamard sequences make useful sets for CDMA.

Table 2.4 Agreements and Disagreements with Reference Sequence

Shift	Sequence	Agreement, A	Disagreement, D	$A - D$
1	0111001	3	4	−1
2	1011100	3	4	−1
3	0101110	3	4	−1
4	0010111	3	4	−1
5	1001011	3	4	−1
6	1100101	3	4	−1
0	1110010	7	0	7

Two different methods can be used to modulate the orthogonal functions into the information stream of the CDMA signal. The orthogonal set of functions can be used as the spreading code or can be used to form modulation symbols that are orthogonal.

With orthogonal symbol modulation, the information bit stream can be divided into blocks so that each block represents a nonbinary information symbol that is associated with a particular transmitted code sequence. If there are b bits per block, one of the set of $K = 2^b$ functions is transmitted in each symbol interval. The signal at the receiver is correlated with a set of K-matched filters, each matched to the code function of one symbol. The outputs from correlators are compared and the symbol with the largest output is taken as the transmitted symbol.

If we assume a simple one-path channel with perfect power control and negligible additive noise and if we include the interference due to multipath, multiple users, and the decision process of the correlators, the E_b/N_0 ratio can be given as [8]

$$\frac{E_b}{N_0} \approx \frac{G_p}{(M-1)+(K-1)} \tag{2.41}$$

where M = number of mobile users,
G_p = processing gain of the system,
$K-1$ = noise from the outputs of correlators other than the one corresponding to the correct symbol.

We rewrite equation (2.41) as

$$M = \frac{G_p}{E_b/N_0} - K + 2 \tag{2.42}$$

Next we introduce factors β, α, υ, and λ (see section 2.5) in equation (2.42) to get

$$M \approx \frac{G_p}{E_b/N_0} \times \frac{1}{1+\beta} \times \alpha \times \frac{1}{\upsilon} \times \lambda - K + 2 \tag{2.43}$$

$$\eta = \frac{MR}{B_w} = \frac{M \cdot \log_2 KR_s}{B_w} = \frac{M(\log_2 K)}{G_p} \tag{2.44}$$

where η = bandwidth efficiency,
R_s = symbol transmission rate.

Example 2.6

Calculate the bandwidth efficiency of the system using the data in Example 2.2 and assuming an orthogonal code with $K = 2$ symbols. If an orthogonal code with $K = 16$ symbols is used for the system, how many simultaneous mobile users can be supported and what is the bandwidth efficiency of the system?

For $K = 2$ symbols,

$$G_p = \frac{1.25 \times 10^6}{9.6 \times 10^3} = 130 \quad \frac{E_b}{N_0} = 6 \text{ dB} = 3.98$$

$$M \approx \frac{130}{3.98} \times \frac{1}{1+0.6} \times \frac{1}{0.5} \times 0.8 - 2 + 2 = 32.64 \approx 33 \text{ users}$$

$$\eta = \frac{M(\log_2 K)}{G_p} = \frac{33(\log_2 2)}{130} = 25.4 \text{ percent}$$

For $K = 16$ symbols,

$$M \approx \frac{130}{3.98} \times \frac{1}{1+0.6} \times \frac{1}{0.5} \times 0.8 - 16 + 2 = 18.64 \approx 19 \text{ users}$$

$$\eta = \frac{M(\log_2 K)}{G_p} = \frac{19(\log_2 16)}{130} = 58.5 \text{ percent}$$

The bandwidth efficiency of the system is improved by 33.1 percent. The disadvantage of the orthogonal signaling scheme is the complexity of the receiver design. In this example, we need 16 receiver correlators per user channel instead of only 1 required in the simplest design.

The TIA IS-95 CDMA system uses orthogonal functions[7] for the spreading code on the forward channel and orthogonal functions for the

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[7] The IS-665 wideband CDMA system uses the orthogonal codes for spreading in both directions (see chapter 5).

modulation on the reverse channel. The TIA IS-95 CDMA system uses pseudo-orthogonal function for spreads of code on the reverse. One of 64 possible modulation symbols is transmitted for each group of six code symbols. The modulation symbol is one member of the set of 64 mutually orthogonal functions. The orthogonal functions have the following characteristic:

$$\sum_{k=0}^{M-1} \phi_i(k\tau)\phi_j(k\tau) = 0 \quad i \neq j \tag{2.45}$$

where $\phi_i(k\tau)$ and $\phi_j(k\tau)$ = ith and jth orthogonal members of an orthogonal set, respectively,
M = length of the set,
τ = symbol duration.

Walsh functions are generated by codewords rows of special square matrices called Hadamard matrices. These matrices contain one row of all zeros, and the remaining rows each have equal numbers of ones and zeros. Walsh functions can be constructed for block length $N = 2^j$, where j is an integer.

The TIA IS-95 CDMA system uses a set of 64 orthogonal functions generated by using Walsh functions. The modulated symbols are numbered from 0 through 63.

The 64 × 64 matrix can be generated by using the following recursive procedure:

$$H_1 = \begin{bmatrix} 0 \end{bmatrix} \quad H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{2.46}$$

$$H_4 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \quad H_{2n} = \begin{bmatrix} H_N & H_N \\ H_N & \overline{H_N} \end{bmatrix} \tag{2.47}$$

where N is a power of 2 and $\overline{H_N}$ is the transformation of H_N such that 0 becomes 1 and 1 becomes 0.

The period of time needed to transmit a single modulation symbol is called a *Walsh symbol interval* and is equal to 1/4800 second (208.33 μs). The period of time associated with one sixty-fourth of the modulation symbol is referred to as a *Walsh chip* and is equal to 1/307200 second (3.255 μs). Within a Walsh symbol, Walsh chips are transmitted in the order 0, 1, 2, …, 63.

For the forward channel, Walsh functions (figs. 2.10 and 2.11) are used to eliminate multiple access interference among users in the same cell. On downlink, all Walsh functions are synchronized in the same cell and have zero correlation between each other. Four steps are used:

1. The input user data (e.g., digital speech) are multiplied by an orthogonal Walsh function (TIA IS-95 standard uses the first 64 orthogonal Walsh functions).
2. The user data are spread by the base station pilot PN code and transmitted on the carrier.
3. At the receiver, after removing the coherent carrier, the mobile receiver multiplies the signal by the synchronized PN code (associated with the base station).

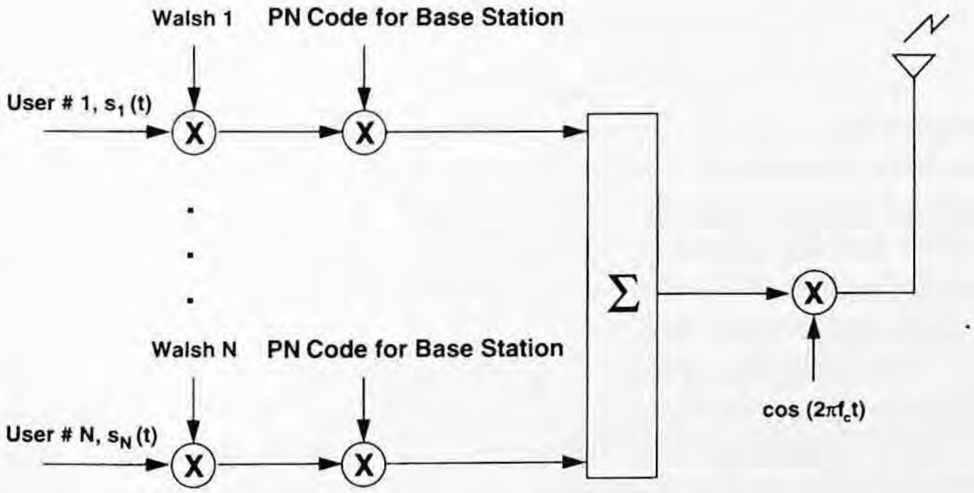

Figure 2.10 Applications of Walsh functions and offset code at the base station.

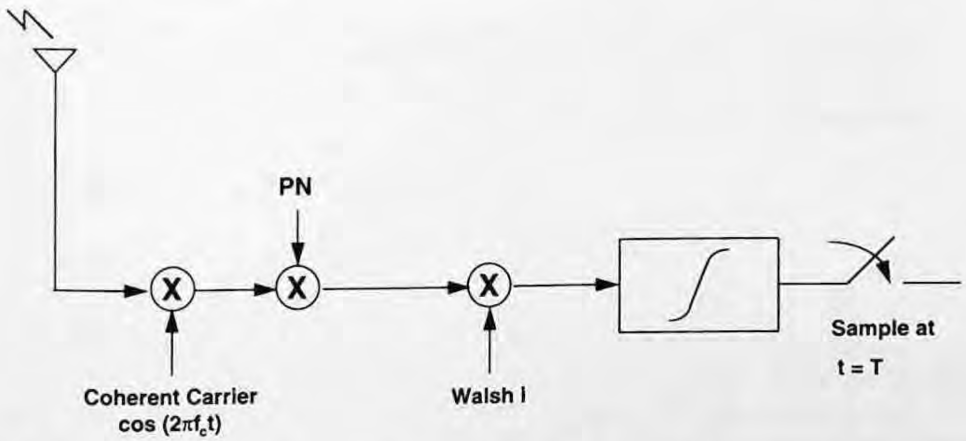

Figure 2.11 Applications of Walsh functions and offset code in the mobile station.

4. The multiplication by the synchronized Walsh function for the *i*th user eliminates the interference due to transmission from the base station to other users.

The Walsh functions form an ordered set of rectangular waveforms taking only two amplitudes +1 and −1. They are defined over a limited time interval T_L, which is known as the time base. If ϕ_i represents the *i*th Walsh function and T_L is the time base, then

$$\frac{1}{T_L}\int_0^{T_L} \phi_i(t)\phi_j(t)dt = 0 \quad \text{for } i \neq j \tag{2.48}$$

and

$$\frac{1}{T_L}\int_0^{T_L} \phi_i^2(t)dt = 1 \quad \text{for all } i \tag{2.49}$$

To correlate the Walsh codes at the receiver requires that the receiver be synchronized with the transmitter. In the forward direction, the base station can transmit a pilot signal to enable the receiver to recover synchronization. The designers of the IS-95 system did not believe that the pilot signal could be recovered at the base station for all mobile stations. Therefore, they used Walsh symbol modulation from the mobile station to the base station.

The designers of the IS-665 wideband CDMA system believe that, with the wider bandwidth, it will be possible to recover the pilot signal at the base station and therefore have designed a symmetric system between base station and mobile station. Chapter 5 discusses this concept in more detail.

Example 2.7

We consider a case where 8 chips per bit are used to generate the Walsh functions. Specify these functions, sketch them, and show that they are orthogonal to each other.

$$H_8 = \begin{bmatrix} H_4 & H_4 \\ H_4 & \overline{H_4} \end{bmatrix} = \begin{bmatrix} 0&0&0&0&0&0&0&0 \\ 0&1&0&1&0&1&0&1 \\ 0&0&1&1&0&0&1&1 \\ 0&1&1&0&0&1&1&0 \\ 0&0&0&0&1&1&1&1 \\ 0&1&0&1&1&0&1&0 \\ 0&0&1&1&1&1&0&0 \\ 0&1&1&0&1&0&0&1 \end{bmatrix} = \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \\ \phi_6 \\ \varphi_7 \\ \phi_8 \end{bmatrix}$$

Figure 2.12 shows the sketches of the eight Walsh functions. We consider ϕ_2 and ϕ_4 to show orthogonality.

$$\frac{1}{T_L}\int \phi_2(t)\phi_4(t)dt = \frac{1}{T_L}[-1\times-1+1\times1+1\times-1+1\times(-1)+(-1)\times(-1)+1\times1+1\times-1+1\times-1] = 0$$

and

$$\frac{1}{T_L}\int \phi_1^2(t)dt = \frac{1}{T_L}[T_L] = 1$$

Similarly, we can show that all eight Walsh functions are orthogonal to each other.

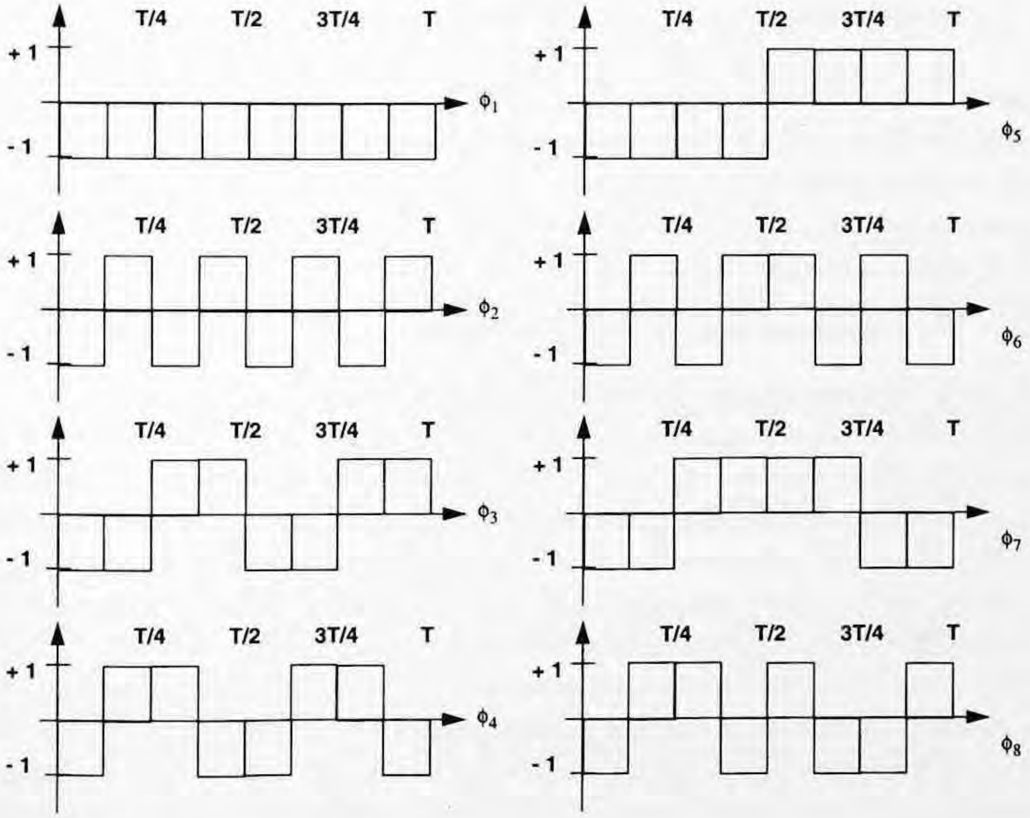

Figure 2.12 Plots of Walsh functions.

Example 2.8

We consider a case where eight chips per bit are used to generate the Walsh functions. Stations A, B, C, and D are assigned the chip sequence 0 1 0 1 0 1 0 1, 0 0 1 1 0 0 1 1, 0 1 1 0 0 1 1 0, and 0 0 0 0 1 1 1 1, respectively. The stations use the chip sequence to send a 1 bit and use negative chip sequences to send a 0 bit (e.g., station A uses 1 0 1 0 1 0 1 0 to send the 0 bit and so on). All chip sequences are pairwise orthogonal. This implies that the normalized correlation of any two distinct chip sequences is 0 and the normalized correlation of any chip sequence with itself is 1. We assume that all stations are synchronized in time; therefore, chip sequences begin at the same instant. When two or more stations transmit simultaneously, their bipolar signals add linearly. For example, if in one chip period three stations output +1 and one station outputs –1, the net result is +2. We consider five different cases when one or more stations transmit (see table 2.5). We want to show that the receiver recovers the bit stream of station C by computing the normalized inner products of the received sequences with the chip sequence of the station C.

Chip Sequence	Binary Values of Chip Sequence
A: 0 1 0 1 0 1 0 1	A: (–1 +1 –1 +1 –1 +1 –1 +1)
B: 0 0 1 1 0 0 1 1	B: (–1 –1 +1 +1 –1 –1 +1 +1)
C: 0 1 1 0 0 1 1 0	C: (–1 +1 +1 –1 –1 +1 +1 –1)
D: 0 0 0 0 1 1 1 1	D: (–1 – 1– 1–1 +1 +1 +1 +1)

The normalized inner products are (see table 2.5)

$$\frac{S_1 \cdot C}{8} = \frac{1 + 1 + 1 + 1 + 1 + 1 + 1 + 1}{8} = 1$$

$$\frac{S_2 \cdot C}{8} = \frac{2 + 0 + 0 + 2 + 0 + 2 + 2 + 0}{8} = 1$$

$$\frac{S_3 \cdot C}{8} = \frac{3 + 1 + 1 - 1 + 3 + 1 + 1 - 1}{8} = 1$$

$$\frac{S_4 \cdot C}{8} = \frac{2 + 0 + 0 - 2 + 2 + 0 + 0 - 2}{8} = 0$$

$$\frac{S_5 \cdot C}{8} = \frac{1 - 1 - 1 - 3 + 1 - 1 - 1 - 3}{8} = -1$$

Thus, the receiver recovers a bit-sequence of 1 1 1 – 0 for station C.

We assume that all the chips are synchronized in time. In a real situation, it is impossible to do so. The sender and receiver are synchronized by having the sender transmit a long enough known chip sequence that the receiver can lock onto it. All other (unsynchronized) transmissions are then seen as random noise.

Table 2.5 Five Cases

Station[a] (A B C D)	Transmitting	Received Chip Sequence
– – 1 –	C	$S_1 = (-1\ +1\ +1\ -1\ -1\ +1\ +1\ -1)$
– – 1 1	C + D	$S_2 = (-2\ 0\ 0\ -2\ 0\ +2\ +2\ 0)$
1 1 1 –	A + B + C	$S_3 = (-3\ +1\ +1\ +1\ -3\ +\ 1+\ 1+1)$
1 1 – –	A + B	$S_4 = (-2\ 0\ 0\ +2\ -2\ 0\ 0\ +2)$
1 1 0 –	A + B + C	$S_5 = (-1\ -1\ -1\ +3\ -1\ -1\ -1\ +3)$

[a] Note: a dash (–) means no transmission by that station.

2.7 TIA IS-95 CDMA SYSTEM

QUALCOMM developed the CDMA radio system for digital cellular phone applications. It was optimized under existing U.S. mobile cellular system constraints. The CDMA system reuses the same frequency in all cells to increase the capacity. The *capacity* is defined as the total number of active users in a large area with many cells. This system design has been standardized by the TIA, and many equipment vendors sell CDMA equipment that meets the standard.

The IS-95 CDMA system operates in the same frequency band as the advanced mobile phone system (AMPS) using frequency-division duplex (FDD) with 25 MHz in each direction.[8] The uplink (mobile to base station) and downlink (base station to mobile) band use frequencies from 869 to 894 MHz and from 824 to 849 MHz, respectively. The mobile station supports CDMA operations on AMPS channel number 1013–1023, 1–311, 356–644, 689–694, and 739–777 inclusive. The CDMA channels are defined in terms of an RF frequency and code sequence. Sixty-four Walsh functions are used to identify the downlink channels, whereas a long PN code with different time shifts is used to identify the uplink channels. Figure 2.13 shows the CDMA channel structure. The modulation and coding features of the CDMA system are listed in table 2.6. We discuss the system in detail in chapters 3–8. There is a PCS version of the specification J-STD-008 for use in the 1800-MHz band.

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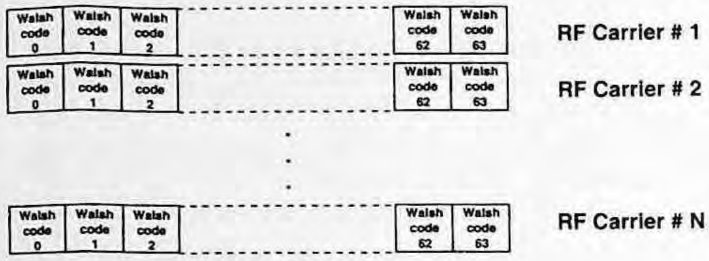
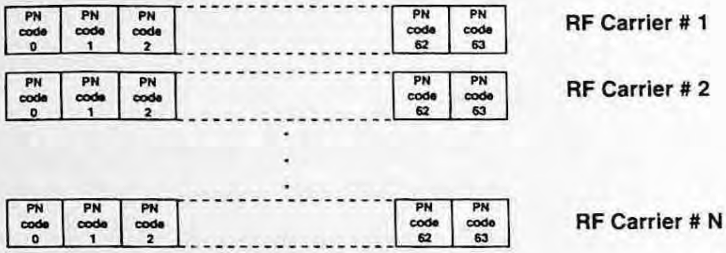
[8] The frequency spectrum for the A-System cellular service provider is split such that the spectrum is not divisible by 1.25 MHz. Thus, the A-System cellular provider cannot partition the spectrum into ten 1.25 CDMA channels. This restriction is not imposed for the B-System, however.



Down Link (Base Station to Mobile) Path



Up Link (Mobile to Base Station) Path

Figure 2.13 End-to-end CDMA operation at 800-MHz radio frequency.

Table 2.6 Modulation and Coding Feature of IS-95 CDMA System

Modulation	Quadrature Phase-Shift Keying
Chip rate	1.2288 Mcps
Nominal data rate	9600 bps
Filtered bandwidth	1.25 MHz
Coding	Convolution with Viterbi decoding
Interleaving	With 20-ms span

Modulation and coding details for the uplink and downlink channels differ. Pilot signals are transmitted by each cell to assist the mobile radio in acquiring and tracking the cell site downlink signals. The strong coding helps these radios to operate effectively at the E_b/N_0 ratio in the 5–7 dB range.

The CDMA system uses power control and voice activation to minimize mutual interference. Voice activation is provided by using a variable rate vocoder that operates at maximum rate of 8 kbps to a minimum rate of 1 kbps, depending on the level of voice activity. With the decreased data rate, the power control circuits reduce the transmitter power to achieve the same bit error rate. A precise power control, along with voice activation circuits, is critical to avoid excessive transmitter signal power that is responsible for contributing the overall interference in the system. Newer coding algorithms at 13 kHz will also be supported.

A time interleaver with 20-ms span is used with error-control coding to overcome rapid multipath fading and shadowing. The time span used is the same as the time frame of voice compression algorithm.

A RAKE processor is used in the CDMA radio to take advantage of a multipath delay greater than 1 μs, which is common in cellular networks in urban and suburban areas.

2.7.1 Downlink

In this section, we summarize the operation of the downlink. For more details see chapter 5. The downlink channels include 1 pilot channel, 1 synchronization (sync) channel, and 62 other channels (if multiple carriers are implemented, pilot channel and sync channels do not need to be duplicated). All the 62 channels can be used for forward traffic, but a maximum of 7 channels can be used as the paging channels. The information on each channel is modulated by an appropriate Walsh function and then modulated by a quadrature pair of PN sequences at a fixed chip rate of 1.2288 Mcps. The pilot channel is always assigned to code channel number zero. If the sync channel is present, it is given the code channel number 32. Whenever paging channels are present, they are assigned the code channel number 1 through 7 (inclusive) in sequence. The remaining code channels are used by forward traffic channels.

The sync channel always operates at a fixed data rate of 1200 bps and is convolutionally encoded to 2400 bps, repeated to 4800 bps and interleaved over the period of the pilot pseudorandom binary sequence.

The forward traffic channels are grouped into sets. Rate set 1 has four elements: 9600, 4800, 2400, and 1200 bps. Rate set 2 contains four elements: 14,400, 7200, 3600, and 1800 bps. All radio systems support rate set 1 on the forward traffic channels. Rate set 2 is optionally supported on the forward traffic channels. When a radio system supports a rate set, all four elements of the set are supported.

The speech is encoded using a variable rate vocoder to generate forward traffic channel data depending on voice activity. Since frame duration is fixed at 20 ms, the number of bits per frame varies according to the traffic rate. Since half rate convolutional encoding is used, it doubles the traffic rate to give rates from 2400 to 19, 200 symbols per second. Interleaving is performed over 20 ms. A long code of $2^{42} - 1$ ($= 4.4 \times 10^{12}$) is generated containing the user's electronic serial number (ESN) embedded in the mobile station long code mask (with voice privacy, the mobile station long code mask does not use the ESN). The scrambled data are multiplexed with power control information that steals bits from the scrambled data. The multiplexed signal remains at 19,200 bps and is changed to 1.2288 Mcps by the Walsh code W_i assigned to the ith user traffic channel. The signal is spread at 1.2288 Mcps by pilot quadrature pseudorandom binary sequence signals, and the resulting quadrature signals are then weighted. The power level of the traffic channel depends on its data transmission rate.

The paging channels provide the mobile stations with system information and instructions, in addition to acknowledging messages following access requests on the mobile stations' access channels. The paging channel data are processed in a similar manner to the traffic channel data. However, there is no variation in the power level on a per-frame basis. The 42-bit mask is used to generate the long code. The paging channel operates at a data rate of 9600 or 4800 bps.

All 64 channels are combined to give single I and Q channels. The signals are applied to quadrature modulators, and resulting signals are summed to form a QPSK signal, which is linearly amplified.

The pilot CDMA signal transmitted by a base station provides a reference for all mobile stations. It is used in the demodulation process. The pilot signal level for all base stations is 4–6 dB higher than a traffic channel with a constant value. The pilot signals are quadrature pseudorandom binary sequence signals with a period of 32,768 chips. Since the chip rate is 1.2288 Mcps, the pilot pseudorandom binary sequence corresponds to a period of 26.66 ms, which is equivalent to 75 pilot channel code repetitions every 2 seconds. The pilot signals from all base stations use the same pseudorandom binary sequence, but each base station is identified by a unique time offset of its pseudorandom binary sequence. These offsets are in increments of 64 chips providing 511 unique offsets relative to zero offset code. These large numbers of offsets ensure that unique base station identification can be obtained, even in dense microcellular environments.

A mobile station processes the pilot channel to find the strongest signal components. The processed pilot signal provides an accurate estimation of time delay, phase, and magnitude of the three multipath components. The three components are tracked in the presence of fast fading and coherently combined to improve signal quality. The chip rate on the pilot channel and on all channels is locked to precise system time, for example, by using the global positioning system (GPS). Once the mobile station identifies the strongest pilot offset by processing the multipath components from the pilot channel correlator, it examines the signal on its sync channel, which is locked to the pseudorandom binary sequence signal on the pilot channel. Since the sync channel is time aligned with its base station's pilot channel, the mobile station finds the information pertinent to this particular base station on the sync channel. The sync channel message contains time of day and long code synchronization to ensure that long code generators at the base station and mobile station are aligned and identical. The mobile station now attempts to access the paging channel and listens for system information. The mobile station enters the idle state when it has completed acquisition and synchronization. It listens to the assigned paging channel and is able to receive and initiate the calls. When informed by the paging channel that voice traffic is available on a particular channel, the mobile station recovers the speech data by applying the inverse of the spreading procedures.

2.7.2 Uplink (Reverse)

In this section, we summarize the operation of the uplink. For more details see chapter 5. The uplink channel is separated from the downlink channel by 45 MHz at cellular frequencies and 80 MHz at PCS frequencies. The uplink uses the same 32,768 chip code as is used on the downlink. The uplink channels are either access channel or reverse traffic channels. There are 62 traffic channels and up to 32 access channels (if multiple carriers are used, it is possible to assign 64 traffic channels to some of them). The access channel enables the mobile station to communicate nontraffic information (e.g., originate calls and respond to paging). The access rate is fixed at 4800 bps. All mobile stations accessing a radio system share the same frequency assignment. Each access channel is identified by a distinct access channel long-code sequence having an access number, a paging channel number associated with the access channel, and other system data. Each mobile station uses a different time shift on the PN code; therefore, the radio system can correctly decode the information from an individual mobile station. Data transmitted on the reverse channel are grouped into 20-ms frames. All data on the reverse channel are convolutionally encoded, block interleaved, and modulated by modulation symbols transmitted for each of the six code symbols. The modulation symbol is one of the 64 mutually orthogonal waveforms that are generated using Walsh functions.

The reverse traffic channel may use either 9600-, 4800-, 2400-, or 1200-bps data rates for transmission. The duty cycle for transmission varies proportionally with data rate, being 100 percent at 9600 bps to 12.5 percent at 1200 bps. An optional second rate set is also supported in the PCS version of CDMA and new versions of cellular CDMA (see chapter 5). The actual burst transmission rate is fixed at 28,800 code symbols per second. Since six code symbols are modulated as one of 64 modulation symbols for transmission, the modulation symbol transmission rate is fixed at 4800 modulation symbols per second. This results in a fixed Walsh chip rate of 307.2 kcps. The rate of spreading PN sequence is fixed at 1.2288 Mcps, so that each Walsh chip is spread by 4 PN chips. Table 2.7 provides the signal rates and their relationship for the various transmission rates on the reverse traffic channel.

Table 2.7 CDMA Reverse Traffic Channel Modulation Parameters

Parameter	9600 bps	4800 bps	2400 bps	1200 bps	Units
PN chip rate	1.2288	1.2288	1.2288	1.2288	Mcps
Code rate	1/3	1/3	1/3	1/3	bits/code symbol
Transmitting duty cycle	100	50	25	12.5	%
Code symbol rate	3 × 9600 = 28,800	28,800	28,800	28,800	sps
Modulation	6	6	6	6	code symbol/ modulation symbol
Modulation symbol rate	28,800/6 = 4800	4800	4800	4800	sps
Walsh chip rate	64 × 4800 = 307.2	307.2	307.2	307.2	kcps
Modulation symbol duration	1/4800 = 208.33	208.33	208.33	208.33	μs
PN chips/code symbol	12,288/ 288 = 42.67	42.67	42.67	42.67	PN chip/ code symbol

Table 2.7 CDMA Reverse Traffic Channel Modulation Parameters (Continued)

Parameter	9600 bps	4800 bps	2400 bps	1200 bps	Units
PN chips/modulation symbol	1,228,800/ 4800 = 256	256	256	256	PN chip/ modulation symbol
PN chips/Walsh chip	4	4	4	4	PN chips/ Walsh chip

Following the orthogonal spreading, the reverse traffic channel and access channel are spread in quadrature. Zero-offset I and Q pilot PN sequences are used for spreading. These sequences are periodic with 2^{15} (32,768 PN chips in length) chips and are based on characteristic polynomials $g_I(x)$ and $g_Q(x)$ (see equations [5.20] and [5.21]).

The maximum-length linear feedback register sequences $I(n)$ and $Q(n)$, based on these polynomials, have a period $2^{15} - 1$ and are generated by using the following recursions:

$$I(n) = I(n - 15) \oplus I(n - 8) \oplus I(n - 7) \oplus I(n - 6) \oplus I(n - 2) \quad (2.50)$$

based on $g_I(x)$ as the characteristic polynomial, and

$$\begin{aligned} q(n) = q(n - 15) \oplus q(n - 12) \oplus q(n - 11) \oplus \\ q(n - 10) \oplus q(n - 9) \oplus q(n - 5) \oplus \\ q(n - 4) \oplus q(n - 3) \end{aligned} \quad (2.51)$$

based on $q_Q(x)$ as the characteristic polynomial, where $I(n)$ and $Q(n)$ are binary numbers (0 and 1) and the additions are modulo-2. To obtain the I and Q pilot sequences, a 0 is inserted in $I(n)$ and $Q(n)$ after 14 consecutive 0 outputs (this occurs only once in each period). Therefore, the pilot PN sequences have one run of 15 consecutive 0 outputs instead of 14. The chip rate for the pilot PN sequence is 1.2288 Mcps, and its period is 26.666 ms. There are exactly 75 repetitions in every 2 seconds. The spreading modulation is offset quadrature phase-shift keying (O-QPSK). The data spread by Q pilot PN sequence is delayed by half a chip time (406.901 ns) with respect to the data spread by I pilot PN sequence (see Chapter 5). Figure 2.14 and Table 2.8 describe the characteristics of O-QPSK.

The Wideband CDMA has some differences in the modulation methods. For more details on both systems see chapter 5.

Table 2.9 defines the signal rates and their relationship on the access channel.

Each base station transmits a pilot signal of constant power on the same frequency. The received power level of the received pilot signal

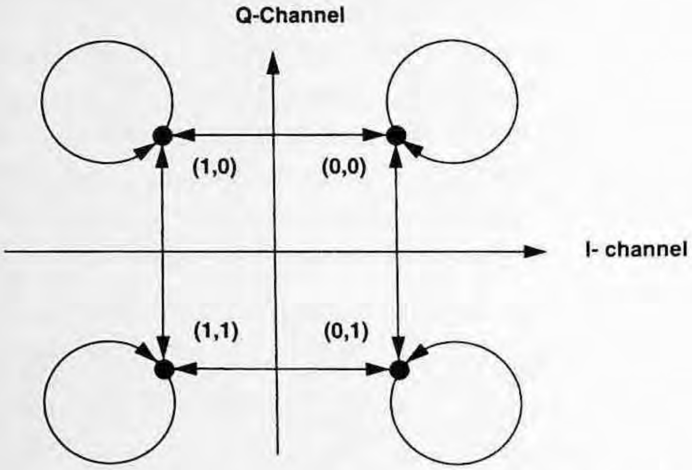


Figure 2.14 Signal constellation and phase transition of O-QPSK use on reverse CDMA channel.

Table 2.8 Reverse CDMA Channel *I* and *Q* Mapping

I	*Q*	Phase
0	0	π/4
1	0	(3π)/4
1	1	–(3π)/4
0	1	π/4

Table 2.9 CDMA Access Channel Modulation Parameters

Parameter	4800 bps	Units
PN chip rate	1.2288	Mcps
Code rate	1/3	bits/code symbol
Code symbol repetition	2	symbols/code symbol
Transmit duty cycle	100	%
Code symbol rate	28,800	sps
Modulation	6	code symbol/modulation symbol
Modulation symbol rate	4800	sps
Walsh chip rate	307.2	kcps
Modulation symbol duration	208.33	μs
PN chips/code symbol	42.67	PN chip/code symbol
PN chips/modulation symbol	256	PN chip/modulation symbol
PN chips/Walsh chip	4	PN chips/Walsh chip

enables the mobile station to estimate the path loss between the base station and the mobile station. Knowing the path loss, the mobile station adjusts its transmitted power such that the base station will receive the signal at the requisite power level. The base station measures the mobile station received power and tells the mobile station to make the necessary adjustment to its transmitter power. One command every 1.25 ms adjusts the transmitted power from the mobile station in the step of ±0.5 dB. The base station uses frame errors reported by the mobile station to increase or decrease the transmitted power.

CDMA provides a soft handoff. As the mobile station moves to the edge of its single cell, the adjacent base station assigns a modem to the call, while the current base station continues to handle the call. The call is handled by both base stations on a make-before-break basis. Handoff diversity occurs with both base stations handling the call until the mobile station moves sufficiently close to one of the base stations, which then exclusively handles the call. This handoff procedure is different than conventional break-before-make or hard handoff procedures. The soft handoff procedure will be discussed in more detail in chapter 7.

In summary, a CDMA system operates with a low E_b/N_0 ratio, exploits voice activity, and uses sectorization of cells. Each sector has 64 CDMA channels. It is a synchronized system with three receivers to provide path diversity at the mobile station and four receivers at the cell site.

2.8 SUMMARY

In this chapter, we first discussed the concept of spread spectrum systems and provided the main features of the direct sequence spread spectrum system used in the IS-95 and IS-665 systems. A key component of spread spectrum performance is the calculation of processing gain of the system, which is the relationship between the input and output signal-to-noise ratio of a spread spectrum receiver. We used the relationship to present some examples that evaluate the performance of a CDMA spread spectrum system.

We presented the Shannon equation for error-free communications and used it to determine that error-free communications is possible (with high delays) for a bit energy-to-noise density ratio, $E_b/N_0 = -1.59$ dB. Spread spectrum systems trade bandwidth for processing gain, and code division systems use a variety of orthogonal or almost orthogonal codes to allow multiple users in the same bandwidth. Thus, CDMA systems can have higher capacity than either analog or TDMA digital systems. However, because of practical constraints on CDMA systems, it is not possible to achieve the Shannon bound in system design. The upper bound of the capacity of a CDMA system is limited by the processing gain of the system. In an actual system, the capacity is lower than the theoretical upper bound. CDMA capacity is affected by receiver modulation performance, power control accuracy, interference from other cells, voice activity, cell sectorization, and the ability to maintain synchronization of the systems. Practical CDMA systems are designed for a value of $E_b/N_0 = 6$ dB.

We described the properties of ideal and practical pseudorandom noise sequences that are used in spread spectrum systems. We then described the Walsh and Hadamard functions that are used in the IS-95 and IS-665 CDMA standards for cellular and PCS. We concluded the chapter by discussing the high-level features of the IS-95 system. We will study the system in more detail in chapters 3–8.

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CHAPTER 3

CDMA Standards

3.1 INTRODUCTION

The standardization of North American cellular operation commenced in the 1970s with the development of analog specifications. Until the late 1980s, analog technology was adequate in satisfying the needs of the market. As penetration of cellular service increased, particularly in urban areas such as Los Angeles and New York, the demand for greater call capacity increased. Thus, time-division multiple access technology was standardized. Even though TDMA offered roughly a threefold increase in the capacity, numerous service providers thought that this increase was inadequate for the future growth in service. Consequently, other technical alternatives were considered by the cellular industry. This chapter examines the standard for code-division multiple access as adopted by the Telecommunications Industry Association for cellular and later PCS systems. The chapter provides an overview of the CDMA standard; later chapters (4–8) cover the standards in more detail.

3.2 BACKGROUND

In 1992, the TIA formed the technical committee TR45.5 to study and to generate cellular standards (800 MHz) for wideband service. At that time, the existing cellular service in North America supported analog and TDMA technologies with a frequency bandwidth of 30 kHz. The TIA desired a wider bandwidth and recommended that a bandwidth greater than 1 MHz be an objective of any standard to be considered by the

TR45.5. The resulting standard became Standard TIA IS-95 (Mobile Station–Base Station Compatibility Standard for Dual-Mode Wideband Spectral System)[1]. This standard supports a direct sequence spread spectrum technology which is a form of CDMA technology with a shared frequency bandwidth of 1.23 MHz. In theory, as many as 64 mobile subscribers can share the frequency spectrum, although interference considerations can limit the maximum number of subscribers to a number that is substantially lower than this maximum value.

The intent of TR45.5 is to enable a service provider to add capacity to an existing analog cellular system. Consequently, TIA IS-95A supports a dual-mode mobile station for both CDMA and analog operation. Dual-mode operation allows a service provider to configure areas of CDMA/analog operation abutting areas of analog-only operation. An IS-95 compatible mobile station searches for a CDMA pilot. If CDMA operation is not detected by the mobile station, the mobile station may search for an analog overhead channel.[2] Furthermore, the mobile station may switch from CDMA to analog operation during a call if a CDMA to analog handoff command is issued by the base station to the mobile station.[3]

The analog capabilities in TIA IS-95 are built upon the analog capabilities of EIA 553 (now TIA IS-91) and TIA IS-54 with a few exceptions. For example, TIA IS-95 does not support the concept of secondary control channels since these channels could interfere with the spectrum assignment of another 1.25-MHz CDMA carrier. Also, TIA IS-95 supports a new control message on the analog overhead channel, which indicates the availability of CDMA, thus facilitating the migration of the mobile station to CDMA operation.

With the availability of a new frequency spectrum (1.8–2.0 GHz) for personal communications systems, TR46 adopted Standards SP-3384

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[1] This standard was later replaced with version IS-95A in 1994. In addition, a Technical Support Bulletin (PN-3570) was issued in 1995 to support the 14.4-kbps physical layer, Service Configuration and Negotiation, and PCS interaction. The title of this TSB is "Telecommunications System Bulletin: Support for 14.4 kbps Data Rate and PCS Interaction for Wideband Spread Spectrum Cellular Systems."

[2] TIA IS-95 is purposely nebulous on this issue. Rather, the exact action is dependent upon the manufacturer. This ambiguity allows a mobile manufacturer to implement mobiles with some product differentiation.

[3] CDMA standards do not support an analog-to-CDMA handoff. Such a handoff is technically complex and would require a very long blank-and-burst message on the analog voice channel. This type of handoff would cause a significant degradation of the voice quality during such handoffs. This capability is being studied by TR45.5 but is not considered a high priority.

that expanded upon IS-95. TR46 was formed by the TIA to formulate standards that addressed the environment encountered in this new radio spectrum and supported services that would attract customers. TR46 studied a number of technologies, one of which was CDMA. A number of new concepts were introduced in SP-3384 (e.g., service negotiation and a 14.4-kbps traffic channel). Some of these concepts were, in turn, adopted by TR45.5 and incorporated in standards TIA IS-95A and TSB PN-3570. At this writing, SP-3384, IS-95A, and TSB PN-3570 specify the basis for CDMA operation in North America. The remainder of this chapter will center around the basic concepts of these standards.

3.3 LAYERING CONCEPTS

TIA IS-95A supports the functionality of the physical layer, the data link layer, and the network layer (see chapter 5 for more details on the various layers). However, TIA IS-95A is not separately structured for each of these layers; rather, the specifications for these layers are somewhat interlaced.

In TIA IS-95A (refer to sections 6.1.1.1–6.1.3.2 and 7.1.1.1–7.1.3.5 of TIA IS-95A) the responsibility of the physical layer (layer 1) is to transmit raw bits over a communications channel (i.e., the sending and receiving of 1s and 0s over the radio channel). This topic will be discussed in chapter 5.

The task of the data link layer (layer 2) is to ensure that the raw transmission is transformed to be error-free for the network layer (refer to sections 6.1.3.3.2–6.2.2.3 and 7.1.3.5–7.1.3.5.11.4 of TIA IS-95A). The data link layer partitions the transmission into data frames every 20 ms, transmits the frames sequentially, error encodes, error detects, acknowledges the reception of frames on either side, may request for retransmission if an error is detected, and retransmits if requested by the other side. If a voice frame is detected as being in error, retransmission is not practical since the next voice frame must be sent in real-time. Sections 6.6.4.1.3 and 7.6.2.1.4 of TIA IS-95A present the acknowledgment procedures on the forward and reverse directions, respectively. In each signaling message, layer 2-related fields are included in order to detect duplicate messages, respond to acknowledgments, and request acknowledgments. Three related fields are ACK_SEQ (3 bits), MSG_SEQ (3 bits), and ACK_SEQ (1 bit) (See table 3.1).

The MSG_SEQ indicates the sequence number of the transmitted signaling message. If either the mobile station or the base station

Table 3.1 Layer 2 Message Fields. (Reproduced under written permission of the copyright holder [TIA].)

Field	Length, bits
MSG_TYPE	8
ACK_SEQ	3
MSG_SEQ	3
ACK_REQ	1
Remainder of message	

requires acknowledgment of a transmitted signaling message, the ACK_SEQ field is set to 1. Generally, the acknowledgment is included in a signaling message on the forward and reverse traffic channels. If no such signaling message needs to be sent and an acknowledgment of a received message is required (i.e., ACK_SEQ = 1), a Mobile Station Acknowledgment Order or Base Station Acknowledgment Order is sent on the reverse or forward traffic channels, respectively. If four or more messages that require acknowledgment are not acknowledged, additional messages that require acknowledgment will not be sent until an acknowledgment is received.

The network layer (layer 3) accepts messages from the source host, converts the messages into packets, and directs the packets toward the destination. Consequently, the network layer does routing of packets and controls the congestion of packets. In EIA/TIA IS-95A, the network layer corresponds to call processing, which will be discussed in section 3.4.

Other CDMA standards build on the three lower layers defined in TIA IS-95A. For example, the standardized version of short message service (SMS)[4] builds on top of IS-95A to provide an SMS relay layer and an SMS transport layer. The SMS teleservice layer interfaces with the SMS transport layer (see chapter 10).

3.4 CALL PROCESSING

As mentioned in section 3.3, call processing is situated at the network layer. The main responsibility of call processing is to accept commands from the source host (which is an IS-96A vocoder if the value of the ser-

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[4] TIA IS-637, Short Message Services for Wideband Spread Spectrum Cellular Systems.

vice option is 1), convert the commands into messages, direct the messages toward the destination, reconvert the messages to commands, and present the commands to the destination (which is an IS-96A vocoder). Consequently, call processing must be able to set up a call from the CDMA mobile station to the destination, which may be a telephone connected through the Public Switched Telephone Network (PSTN), or to another mobile station (analog, CDMA, TDMA, or GSM). Additionally, the cellular system must be able to transfer packets correctly as the mobile station moves from base station to base station during a call.

The call model adopted by TIA IS-95A is essentially the same call model as in the current analog standard EIA-553 (Mobile Station–Land Station Compatibility Specification). This call model supports a call from one calling directory number to one called directory number. Multiple simultaneous calls are not defined, and support is outside the realm of IS-95A.

The network layer also performs the tasks of power control,[5] mobile station lockout,[6] radio channel control,[7] and mobile station control.[8]

As with EIA-553, a mobile station can be addressed by the mobile station identification number (MIN), which is a transformation of the mobile station's directory number. However, with international operation, the MIN may not be unique, and thus the international mobile station identification (IMSI) has been introduced into TIA IS-95A. IMSI consists of 15 digits, while the MIN has 10 digits. The potential problem with identifying the mobile station with the MIN is that 10 digits are not sufficient to guarantee unique addressing for international roaming. Such a situation may occur in the near future if a homed-Mexican mobile

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[5] Power control is the function of the base station. The transmitted RF power of both the mobile and the base station are adjusted so that the frame error rate on the forward traffic channel and the reverse traffic channel is within the desired error rate (e.g., 1 percent).

[6] If the mobile station does not properly respond to the power control commands from the base station, the base station may issue a command to the mobile to prevent further CDMA access by the mobile station. This capability is a safety mechanism to prevent "rogue" mobile stations from overloading the CDMA system and thus severely limiting the traffic capacity.

[7] Radio channel control is the responsibility of the base station in which a CDMA channel is assigned to a call for either setup or handoff.

[8] The base station issues commands to the mobile station in order to affect the mobile station's call state. Examples are paging, alerting (ringing), and releasing the call.

station roams into the United States. Also, the mobile station may be addressed by the electronic serial number (ESN).[9]

Call processing of an IS-95A mobile station is partitioned into four states (see fig. 3.1), which are further partitioned into substates. The four states are

- Mobile station initialization state,
- Mobile station idle state,
- System access state, and
- Mobile station control on the traffic channel state.

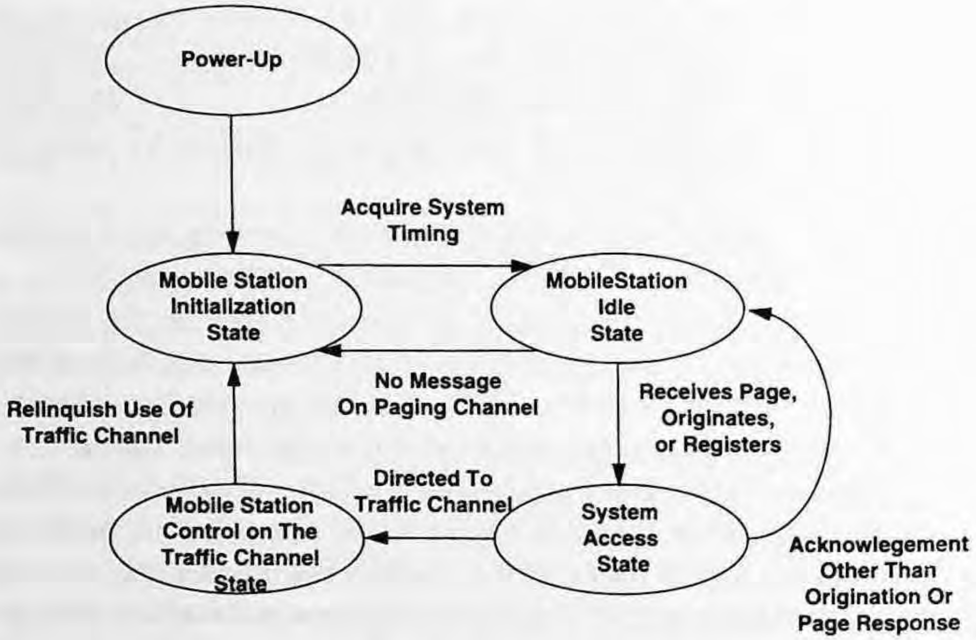

Figure 3.1 Mobile call processing states. (Reproduced under written permission of the copyright holder [TIA].)

3.4.1 Mobile Station Initialization State

The Mobile Station Initialization State consists of four substates as shown in Figure 3.1. In the *system determination substate*, the mobile station selects the cellular system. If the mobile station cannot find a suitable CDMA system, the mobile station may acquire an analog system. In such a case, the mobile station will follow a state model based

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[9] Messages on the paging channel that cannot use the ESN for addressing are Page Message and General Page Message.

upon the model that is specified in EIA-553. The mobile station acquires the pilot channel in the *pilot channel acquisition substate*. Next, the mobile station executes the *sync channel acquisition substate* in which the mobile station obtains the system configuration and timing information from the sync channel (see table 3.2).

Table 3.2 Sync Channel Message. (Reproduced under written permission of the copyright holder [TIA].)

Field	Length, bits
MSG_TYPE (00000001)	8
P_REV	8
MIN_P_REV	8
SID	15
NID	16
PILOT_PN	9
LC_STATE	42
SYS_TIME	36
LP_SEC	8
LTM_OFF	6
DAYLT	1
PRAT	2
RESERVED	3

This information is contained in the sync channel message, which provides such information as the system identification (SID) and network identification (NID) of the acquired system, system time, and the PN offset of base station. The final substate is the *timing change substate*. The mobile station adjusts its timing in preparation for receiving the paging channel, determines the primary paging channel, and initializes its registration process (but does not attempt registration).

3.4.2 Mobile Station Idle State

After completing the timing change substate, the mobile station enters the mobile station idle state. In this state, the mobile station monitors the paging channel, performs registration if required, and executes idle handoffs.

TIA IS-95A uses the term *idle handoff* to indicate that the mobile station has started to monitor a paging channel associated with a different base station than was previously monitored. Note that a mobile station monitors the paging channel of one base station; in other words, a soft handoff is not applicable in this state. The mobile station follows the registration procedures as will be discussed in section 3.5.

A number of tasks are performed by the mobile station while monitoring the paging channel. These tasks are

- Responding to overhead information,
- Responding to pages (mobile termination),
- Responding to mobile station orders,
- Initiating mobile originations,
- Powering down the mobile station, and
- Providing optional support of message transmission.

Both mobile termination and mobile origination are discussed in chapter 7 and will not be covered in this chapter. However, in this state, the mobile station determines if an origination, page response, or a registration is to be generated. The mobile station will access the system with the appropriate access channel message only when it is in the system access state.

Six overhead messages can be transmitted on the paging channel by the base station:

- Systems Parameters message,
- Neighbor List message,
- CDMA Channel List message,
- Extended System Parameters message,
- Access Parameters message, and
- Global Service Redirection message.

The System Parameters message will be discussed in section 3.7. This message also provides information for monitoring pilots and for controlling power. The Neighbor List message provides information about updating the mobile station's neighbor list. This list is used to assist with idle handoffs. The CDMA Channel List message indicates the paging channels that are supported by the base station being monitored by the mobile station. The Access Parameters message defines the parameters used by the mobile station when transmitting to the base station on the access channel (e.g., attempting registration or mobile origination). Finally, the Global Redirection message instructs the mobile station to move to another CDMA band or move to analog service.

3.4.3 System Access State

The mobile station will transition from the mobile station idle state to the system access state if the mobile station is required to send a message on the access channel. This corresponds to the mobile station sending the following messages:

- Origination message (mobile station origination attempt state),
- Page Response message (page response substate),
- Response to an order (mobile station order/message response substate),
- Data Burst message (mobile station message transmission substate), and
- Registration message (registration access substate).

The access procedures are discussed in detail in chapter 7. However, before the mobile station attempts to access the base station, the mobile station will monitor the paging channel until the access parameters have been updated (update overhead information substate), (see fig. 3.2).

3.4.4 Mobile Station Control on the Traffic Channel State

The mobile station is directed to the mobile station control on the traffic channel state if it receives a Channel Assignment message and the mobile station is currently in the access state. This state consists of the following five substates (see fig. 3.3):

- Traffic channel initialization substate,
- Waiting for order substate,
- Waiting for mobile station answer substate,
- Conversation substate, and
- Release substate.

In the *traffic channel initialization substate*, the mobile station successfully receives the base station's transmission on the forward traffic channel and begins transmitting on the reverse traffic channel. If the associated call is mobile-terminated, the mobile station goes into the

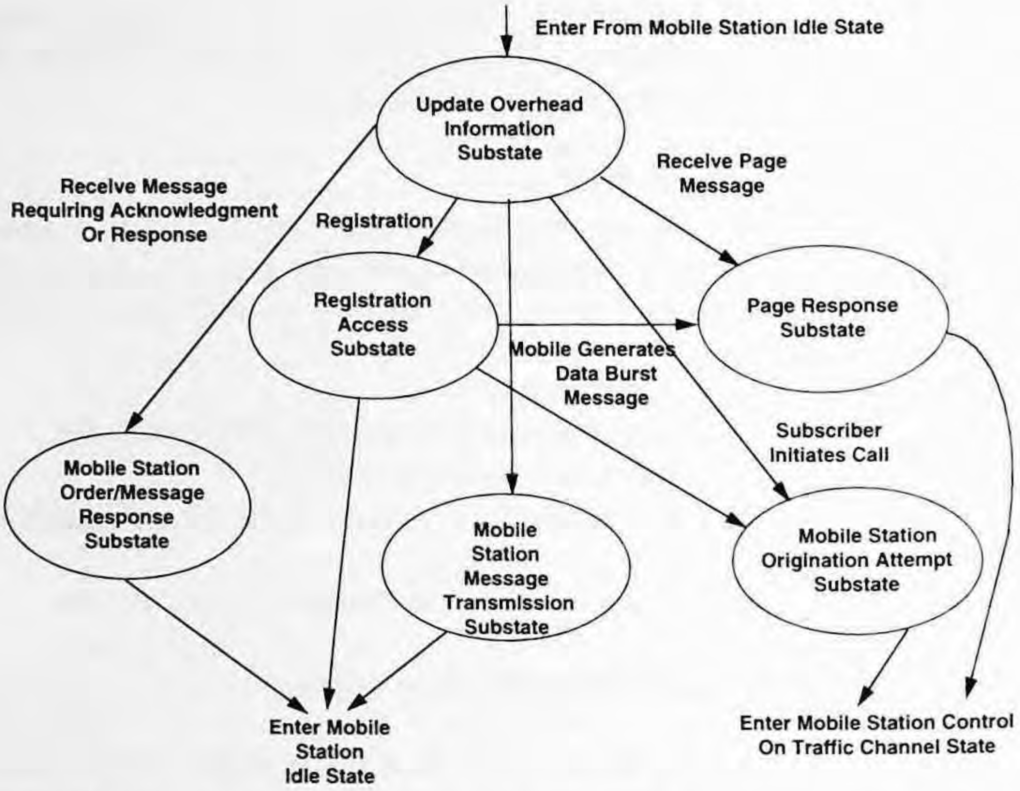

Figure 3.2 System access state. (Reproduced under written permission of the copyright holder [TIA].)

waiting for order substate and waits for an alert with information message (i.e., the mobile station is instructed to ring in order to alert the mobile subscriber). After ringing has been initiated for a mobile-terminated call, the mobile station waits for the mobile subscriber to "go off-hook," and the mobile station consequently moves into the *waiting for mobile station answer substate*. The mobile station transmits and receives traffic packets in the *conversation substate*. Either the mobile station or the base station can initiate a call release, corresponding to the *release substate*.

This section only outlines the mobile station's operation in the mobile station control on the traffic channel state. Chapters 6 and 7 will provide greater detail in the discussion of CDMA messaging and call flows.

3.4.5 Base Station Call States

TIA IS-95A does not invoke as detailed specifications for the base station as for the mobile station. This philosophy is consistent with EIA-553. Needless to say, the base station must operate with the mobile sta-

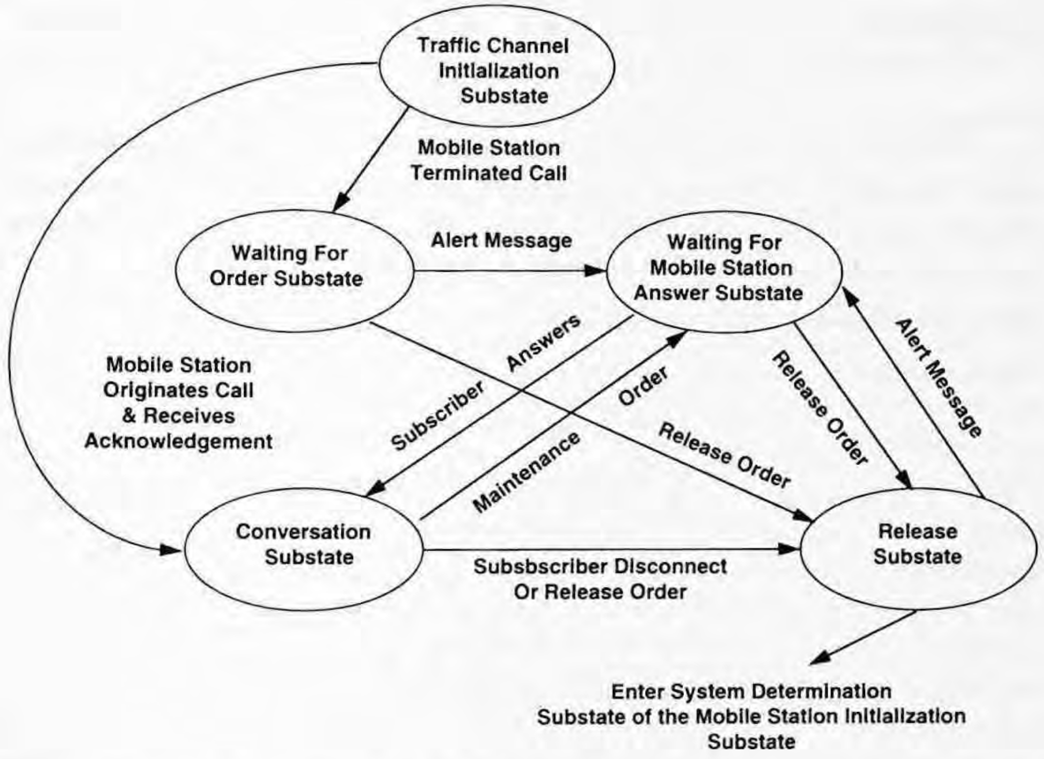

Figure 3.3 Mobile station control on the traffic channel state. (Reproduced under written permission of the copyright holder [TIA].)

tion; however, the manufacturers of base stations are offered more opportunity to differentiate among themselves.

TIA IS-95A defines only the traffic channel processing state, which corresponds to the mobile station control on the traffic channel state.

3.5 SERVICE CONFIGURATION AND NEGOTIATION

Service configuration is the common set of attributes used by the base station and the mobile station for interpreting and building frames on the forward and reverse traffic channels. *Service negotiation* is the process by which a mutually acceptable service configuration is agreed upon by both the base station (network) and the mobile station.

With the variety of services that can be supported on the CDMA air interface, TSB PN-3570 and SP-3384 allow the network and the mobile station to communicate with the appropriate configuration on the forward and reverse traffic channels. The configuration is determined by

- Service option,
- Service option connection reference,

- Forward traffic type, and
- Reverse traffic type.

The *service option* identifies the type of service being supported on a given connection. For example, different services correspond to different vocoder algorithms. TIA TSB-58 documents the 16-bit assignment for each standardized service type (see table 3.3).

Table 3.3 Service Options for CDMA. (Reproduced under written permission of the copyright holder [TIA].)

Service Option Number	Type of Service
1	Basic variable rate voice service (8 kbps)
2	Mobile station loopback (8 kbps)
3	Enhanced variable rate voice service (8 kbps)
4	Asynchronous data service
5	Group 3 facsimile
6	Short message service
7	Packet data service (Internet)
8	Packet data service (CDPD)
9	Mobile station loopback (13 kbps)
10	STU-III service option
11–32,767	Reserved for standard service options
32,768–65,535	Reserved for proprietary service options

Only the lower 32,768 values can be assigned to standardized services. In addition, the higher 32,768 values can be assigned to manufacturers for proprietary services, thus allowing some service differentiation among manufacturers. The *forward traffic type* specifies the physical link from the base station to the mobile station, while the *reverse traffic type* defines the physical link from the mobile station to the base station. Service configuration permits different configurations in the reverse and forward directions. While configuration asymmetry is not useful for voice services, it is very amenable to data services for which data rates are different in the forward and reverse directions. In order to specify the physical link, both the data rate and the multiplex option are needed. CDMA standards currently support two data rates: 9.6 and 14.4 kbps. These values correspond to the raw data rates and include both the transmitted information and error protection. Thus, 8.6 and 13.35 kbps of information can be transmitted on the respective data rates.

The multiplex option enables two logical channels to be transmitted on the same physical traffic channels. The primary channel is usually configured, while the second logical channel, called the *secondary traffic channel*, is logically superimposed if the multiplex option is equal to 2. If the multiplex option is equal to 1, only the primary traffic channel is configured. It should be noted that the multiplex options can be different for the forward and reverse directions.

Multiple service connections may be established on the same physical traffic channel (as specified by the rate set and multiplex option). Even though the call model as adopted by TIA IS-95A does not support multiple call appearances, multiple connections may be simultaneously established under certain configurations. For example, two simultaneous connections can be supported on the same physical link if connection 1 uses the primary traffic channels in the forward and reverse direction and connection 2 uses the secondary traffic channels in the forward and reverse directions. As many as four connections can be simultaneously established if each connection is unidirectional and uses one traffic channel type (i.e., either the primary or secondary channel). If, however, each channel is terminated at different end points, then a multiple dialing arrangement is required since the CDMA call model does not cover such scenarios.

3.6 CONCEPT OF SYSTEM IDENTIFICATION AND NETWORK IDENTIFICATION

A *network*, as identified by the network identification (NID), can selectively provide CDMA service within a CDMA system, as identified by the system identification (SID).

A network is thus a subset of a CDMA system. If a base station indicates that its associated NID = 0 in the System Parameters message, which is broadcast on the paging channel as an overhead message, then that base station should not be considered as part of the specific network.

The mobile station contains a list of SID,NID pairs in the number assignment module (NAM). The mobile station must have at least one SID,NID pair. If the stored SID,NID pair has the NID value equal to 65,535 (2^{16}–1), then the mobile station will consider the associated SID, regardless of the NID, as the home system.

As with EIA-553, a cellular system is identified by the systems identification, which is represented by a 15-bit field. However, TIA IS-95A introduces an additional dimension for defining a network with the concept of the network identification, which is represented by a 16-bit field. Thus, a network is uniquely specified by the pair SID,NID (see fig. 3.4).

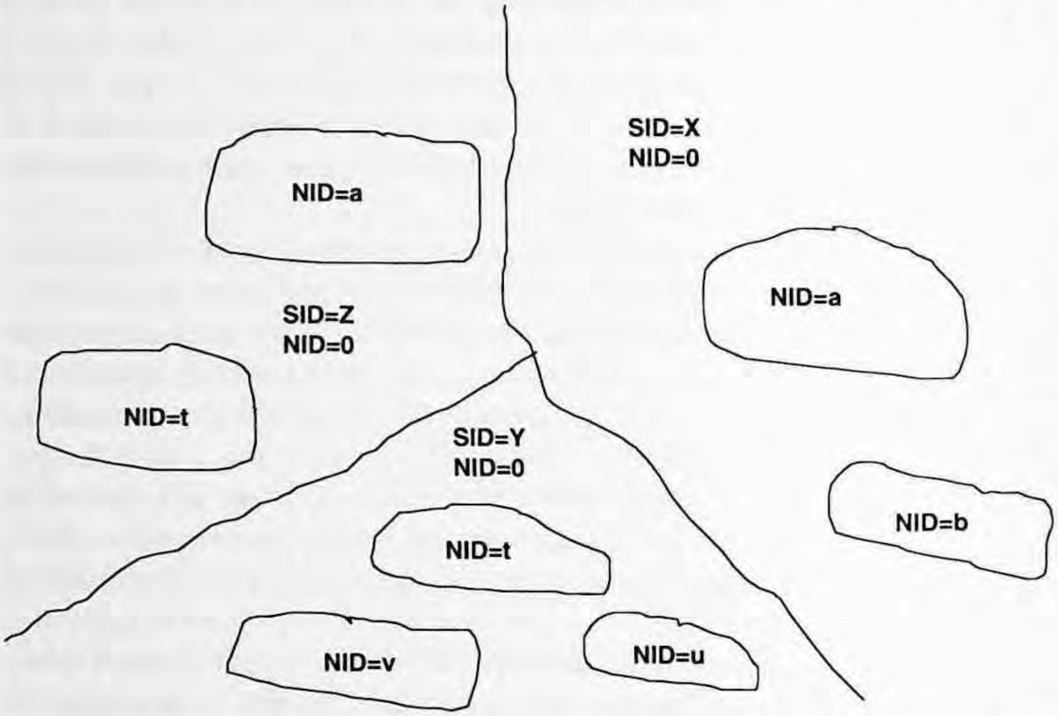

Figure 3.4 Partitioning of systems and networks. (Reproduced under written permission of the copyright holder [TIA].)

The mobile station's NAM contains at least one SID,NID pair and, thus, may have multiple pairs to designate the mobile station's home network. If the SID,NID pair transmitted in the System Parameters message is not included in the mobile station's NAM, the mobile station will consider itself as a roamer in the given network (i.e., it is located in a foreign NID). Similarly, if the SID is not contained in one of the NAM's pairs, the mobile station determines that it is a roamer in the given system (i.e., the mobile station is in a foreign SID). If the NID equals all zeros in the System Parameters message, then the broadcasting base station is not included in a specific network. In other words, all mobiles may access that base station.

3.7 REGISTRATION

Registration is a process by which a mobile station informs the network about pertinent status parameters. Practical registration parameters are relevant to location, time, and activation status. In the following discussion on registration, the base station actions are presented. When a mobile station registers, the mobile station will send a registration message to the base station (see table 3.4).[10]

Table 3.4 Content of Mobile Station Registration Message. (Reproduced under written permission of the copyright holder [TIA].)

Field	Length, bits
MSG_TYPE (00000001)	8
ACK_SEQ	3
MSG_SEQ	3
ACK_REQ	1
VALID_ACK	1
ACK_TYPE	3
MSID_TYPE	3
MSID_LEN	4
MSID	8 x MSID_LEN
AUTH_MODE	2
AUTHR	0 or 18
RANDC	0 or 8
COUNT	0 or 6
REG_TYPE	4
SLOT_CYCLE_INDEX	3
MOB_P_REV	8
SCM	8
MOB_TERM	1
RESERVED	6

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[10] A number of fields are not directly relevant to the registration process. The AUTH_MODE, AUTHR, RANDC, and the COUNT fields are applicable to authentication. The MSID_TYPE, MSID_LEN, and the MSID fields identify the addressing type of the mobile (e.g., the IMSI or the ESN of the mobile). The SLOT_CYCLE_INDEX and SLOTTED_MODE fields are used so the mobile can be paged at certain times, thus reducing the battery consumption. The MOB_P_REV and EXT_SCM fields identify the mobile station's hardware and software.

TIA IS-95A supports autonomous registration, ordered registration, and parameter-change registration. With *autonomous registration*, a mobile station will register without an explicit command from the base station. Autonomous registration will be discussed in detail later in this section. TIA IS-95A uses the term *implicit registration*, which is nothing more than the base station receiving an origination message or a page response message; hence, the mobile station's location status is known to the cellular system. A mobile station attempts a *parameter-change registration* if specific mobile station parameters are modified and if PARAMETER_REG equals 1 in the System Parameters message (see table 3.5).[11]

The relevant mobile station parameters that result in a parameter change registration are the preferred slot cycle index (SLOT_CYCLE_-INDEX), station class mark (SCM), and call termination enable indicators. Additionally, a parameter-change registration will be attempted if the SID,NID pair that is contained in the System Parameters message does not match any pair stored in the mobile station's SID_NID_LISTs. The topic of SID and NID and the relationship to roaming was covered earlier. If the PARAMETER_REG field = 1 in the System Parameters message, parameter-change registration is attempted even if autonomous registration is not enabled.[12]

The mobile station responds with an *ordered registration* if ordered by the base station with a Registration Request Order on the paging channel. This procedure should not be used normally since the capacity

---

[11] T_ADD, T_DROP, T_COMP, and T_TDROP set the thresholds for possible handoffs and are discussed in chapter 9. SRCH_WIN_N, SRCH_WIN_R, and SRCH_WIN_A are parameters used by the mobile station when it searches for candidate pilots. The mobile station sends a Power Measurement Report message based upon conditions set by PWR_REP_THRES, PWR_REP_FRAMES, PWR_THRES_ENABLE, PWR_PERIOD_ENABLE, and PWR_REP_DELAY. This message supports the control of the mobile station's transmitted power.

[12] One necessary condition for autonomous registration to be active is REG_ENABLEDs = YES. This will occur if one of the following logical statements is true:

> The mobile is not roaming, HOME_REG field = 1 in the System Parameters message, and MOB_TERM_HOME = 1 in the mobile station's NAM.
>
> The mobile is a foreign NID roamer, FOR_NID_REG = 1 in the System Parameters message, and MOB_TERM_FOR_NID = 1 in the mobile station's NAM.
>
> The mobile is a foreign SID roamer, FOR_SID_REG = 1 in the System Parameters message, and MOB_TERM_FOR_SID = 1 in the mobile station's NAM.

Table 3.5 Content of System Parameters Message Transmitted by a Base Station.
(Reproduced under written permission of the copyright holder [TIA].)

Field	Length, bits	Field	Length, bits
MSG_TYPE (00000001)	8	BASE_LAT	22
PILOT_PN	9	BASE_LONG	23
CONFIG_MSG_SEQ	6	REG_DIST	11
SID	15	SRCH_WIN_A	4
NID	16	SRCH_WIN_N	4
REG_ZONE	12	SRCH_WIN_R	4
TOTAL_ZONES	3	NGHBR_MAX_AGE	4
ZONE_TIMER	3	PWR_REP_THRESH	5
MULT_SIDS	1	PWR_PERIOD_FRAMES	4
MULT_NIDS	1	PWR_THRESH_ENABLE	1
BASE_ID	16	PWR_PERIOD_ENABLE	1
BASE_CLASS	4	PWR_REP_DELAY	5
PAGE_CHAN	3	RESCAN	1
MAX_SLOT_CYCLE_INDEX	3	T_ADD	6
HOME_REG	1	T_DROP	6
FOR_SID_REG	1	T_COMP	4
FOR_NID_REG	1	T_TDROP	4
POWER_UP_REG	1	EXT_SYS_PARAMETER	1
POWER_DOWN_REG	1	RESERVED	2
PARAMETER_REG	1	GLOBAL_REDIRECT	1
REG_PRD	7		

of the paging channel is reduced and since autonomous registration procedures should be adequate.[13]

The mobile station will automatically attempt *autonomous registration* if the mobile station determines that a designated event has

---

[13] IS-95A also refers to traffic channel registration as a form of registration. However, it is really a notification by the base station that the mobile is registered when the mobile is on the traffic channel (i.e., a CDMA call has been established). In such cases, the base station will send a Mobile Station Registered message.

occurred and that the particular type of autonomous registration is enabled by the cellular system. The cellular system enables (allowed forms of) autonomous registration by configuring the appropriate fields in the system parameters message.

TIA IS-95A supports the following types of autonomous registration:

- Power-up,
- Power-down,
- Timer-based,
- Zone-based, and
- Distance-based.

The TIA IS-95A standard allows *power-up registration* and *power-down registration* to be used independently of each other. However, the service provider most likely will use power-down registration only if power-up registration is activated. Power-up registration is performed when the battery power to the mobile station is activated. To prevent multiple registrations when the power is quickly turned on and off, the mobile station delays any action for 20 seconds before registering after power turn-on. The base station activates power-up registration by setting the POWER_UP_REG field in the System Parameters message to 1. Power-down registration is executed by the mobile station when the mobile subscriber deactivates the mobile station by turning off the mobile station. In such cases, if the POWER_DOWN_REG field is set to 1, and if the mobile station was previously registered in the given service area, the mobile station will not power down until completing a registration attempt.

Timer-based registration is a variation of autonomous registration that is supported in EIA-553 standards. A comparison is outside the scope of this writing. However, TIA IS-95A resolves a number of related deficiencies. With timer-based registration, the mobile station registers at regular intervals. The mobile station maintains the timer. Timer-based registration is activated by the base station if REG_PRD is not equal to 0000000. If so, the maximum count of the timer is $2^{\mathrm{REG\_PRD}/4}$, where REG_PRD is the registration period. This timer is incremented once every 80 ms and is derived from the paging channel slot counter (note that each time slot is 80 ms in duration). When the timer reaches the maximum count and timer-based registration is enabled, the mobile station will generate a registration message, and the timer is reset. This timer is also reset on power-up, after each successful autonomous registration and after implicit registration. When the mobile station powers up, the timer is set to a random number, thus randomizing a mobile station with respect to other mobiles.

Zone-based registration is the fourth type of autonomous registration. This presupposes that the service provider groups base stations into zones. Each base station broadcasts its zone number. Different zone numbers may be associated for sectors of a given base station. The zone identification associated with the base station is contained in the 12-bit field REG_ZONE of the System Parameters message. If zone-based registration is disabled, the TOTAL_ZONES field of this message is set to 000. If the mobile station determines that the zone number has changed (by monitoring the System Parameters message on the paging channel), the new zone number is not in the stored zone list, and zone-based registration is enabled, the mobile station will register by sending a registration message on the access channel.

The mobile station will store a list of zones in which the mobile station has registered. Each registered zone corresponds to an entry in the ZONE_LIST, which consists of the zone number (REG_ZONE) and the SID,NID pair associated with the zone. The maximum number of entries is determined by the TOTAL_ZONES, which is controlled by the base station in the System Parameters message. If the associated timer has expired (the duration is determined by the ZONE_TIMER in the System Parameters message), the entry will be deleted.

Distance-based registration is the last type of autonomous registration. For distance-based registration to be active, the REG_DIST field in the System Parameters message must be nonzero. If so, the mobile station will register each time the mobile station travels this distance after the previous registration. The distance is determined by

$$\frac{\sqrt{(\Delta lat)^2 + (\Delta long)^2}}{16} \tag{3.1}$$

where Δlat is calculated from the BASE_LAT and $\Delta long$ is calculated from the BASE_LONG as contained in the System Parameters message.

The unit of BASE_LAT and BASE_LONG is 0.25 angular seconds, which corresponds to approximately 25 feet. Δlat is the difference in the current base station's latitude with respect to the latitude of the base station in which the mobile station last registered. $\Delta long$ is the corresponding difference in the longitude.

A system provider may use none or all types of autonomous registration. Most likely, a subset of available types of registration will be supported by a cellular system. For example, the service provider may choose to support power-up, power-down, and zone-based registration simultaneously. However, it is doubtful that both zone-based registration and distance-based registration would be simultaneously activated.

3.8 WIDEBAND CDMA STANDARDS

The previous sections discussed current CDMA standards (i.e., TIA IS-95A and TIA PN-3570) that support a frequency bandwidth of 1.25 MHz. Even though the titles of the corresponding standards imply wideband CDMA, only standard J-STD-007 (PCS-1900 Air Interface Wideband PCS Standard) currently supports larger frequency bandwidths of 5, 10, and 15 MHz. To facilitate discussion, the former set of standards is identified as CDMA, while the latter standard is referenced as W-CDMA.

In addition, there are differences in the network layer (layer 3). Unlike CDMA, W-CDMA incorporates a call model based upon the ISDN call model. A call reference is included in call establishment messages. Thus, it is possible for multiple call appearances (multiple simultaneous calls) to be implemented. W-CDMA does not support the complete suite of registration types; only power-on, power-off, and zone-based registrations are defined. Like CDMA, W-CDMA supports the equivalent of soft handoffs and hard handoffs. However, W-CDMA refers to these two types of handoffs as Type A handoffs and Type B handoffs, respectively. For more details on W-CDMA see chapters 5–7.

3.9 SUMMARY

The purpose of this chapter is to provide a survey of the CDMA standards specifying the air interface (i.e., the messaging between the base station and the mobile station). Even though TIA IS-95A is not explicitly structured as such, three protocol layers are implied: the physical, the data link, and the network layers. The call model is basically the same call model that is incorporated in the existing analog standards (EIA-553) with four call states: mobile station initialization, mobile station idle, mobile access, and mobile station control on the traffic channel. Each of these states is further partitioned into substates. For each call, either the mobile station or the network may negotiate for a service type, which is specified by the service option. In practice, the majority of calls correspond to a default value such as basic variable rate voice service.

This chapter also discusses the types of autonomous registration, which supports the mobility function. CDMA operation supports power-up, power-down, time-based, zone-based, and distance-based registration.

3.10 REFERENCES

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CHAPTER 4

System Architecture for Wireless Communications

4.1 INTRODUCTION

A wireless system, whether for cellular operation (i.e., 850 MHz), or for personal communication systems operation (i.e., 1.8 GHz), must support communication with the mobile station and interact with the Public Switched Telephone Network. As the mobile station changes its location during a call, the wireless system must ensure that the connection between the mobile station and the PSTN is maintained.

A wireless system consists of discrete logical components that may be either discrete physical entities or physically located with another logical entity. It is necessary that these functional entities interact in order to coordinate operation. Such interaction is achieved by messaging over interfaces between two entities. If two functional entities are physically separate and if the interface is standardized, it is possible that the service provider can purchase products from different manufacturers. However, successful operation is not guaranteed since the associated standard often does not cover all facets of operation. This may necessitate testing between manufacturer's equipment to eliminate differences that jeopardize proper interaction.

This chapter discusses functional entities and the standardized interfaces between those entities that have been standardized by the wireless communication industry.

4.1.1 TR-45/TR-46 Reference Model

Key to the North American Systems is the use of a common reference model from the cellular standards group TR-45. When work started on PCS, the TR-46 standards group adopted the TR-45 reference model for PCS, but with some minor changes in the names of the elements. A second reference model has been proposed by T1P1, but it is similar to the TR-45/TR-46 model. The names of each of the network elements are similar and some of the functionality is partitioned differently between the models. The main difference between the two reference models is how mobility is managed. Mobility is the capability for users to place and receive calls in systems other than their home system. In the T1P1 reference model, the user data and the terminal data are separate; thus, users can communicate with the network via different mobile stations. In the TR-45/TR-46 reference model, only terminal mobility is supported. A user can place or receive calls at only one terminal (the one the network has identified as owned by the user). The T1P1 functionality is migrating toward independent terminal and user mobility, but all aspects of it are not currently supported. In chapter 11 we will discuss a wireless intelligent network (WIN) architecture and reference model that overcomes some of the mobility problems in the current architecture. Figure 4.1 shows the TR-45/TR-46 reference model.

4.1.2 Elements of the Reference Model

The main elements of the reference model follow:

- **Mobile Station (MS):** The MS terminates the radio path on the user side and enables the user to gain access to services from the network. The MS can be a stand-alone device or can have other devices (e.g., personal computers and fax machines) connected to it.
- **Base Station (BS):** The base station terminates the radio path and connects to the mobile switching center. The base station is often segmented into the BTS and the BSC:
  - ✘ *Base Transceiver System (BTS):* The BTS consists of one or more transceivers placed at a single location and terminates the radio path on the network side. The BTS may be either co-located with a BSC or independently located.
  - ✘ *Base Station Controller (BSC):* The BSC is the control and management system for one or more BTSs. The BSC

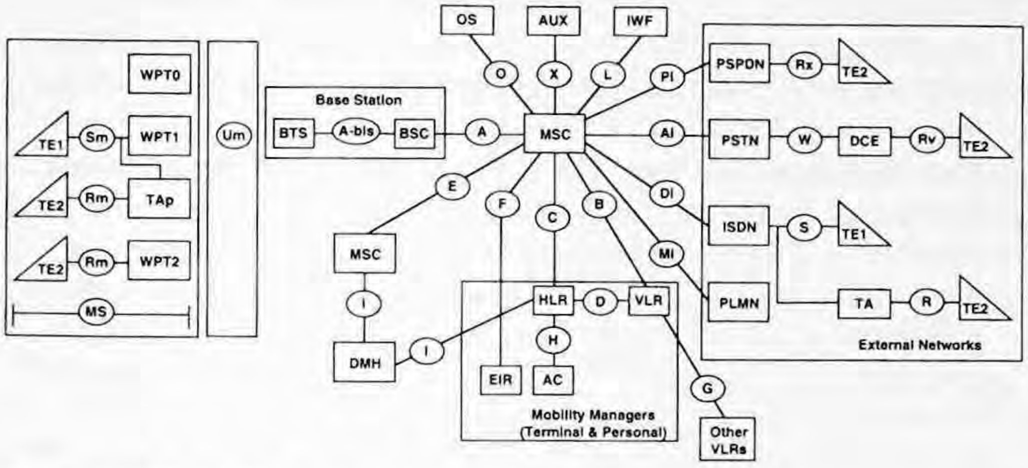

Figure 4.1 TR-45/TR-46 reference model. (Reproduced under written permission of the copyright holder [TIA]. At time of publication, the standard that contains this figure was not finalized. Check with TIA for the correct version.)

exchanges messages with both the BTS and the MSC. Some signaling messages may pass through the BSC transparently.

- **Mobile Switching Center (MSC):** The MSC is an automatic system that interfaces the user traffic from the wireless network to the wireline network or other wireless networks. The MSC functions as one or more of the following:
  - ✗ *Anchor MSC*—the first MSC providing radio contact in a call.
  - ✗ *Border MSC*—an MSC controlling BTSs adjacent to the location of a mobile station.
  - ✗ *Candidate MSC*—an MSC that could possibly accept a call or a handoff.
  - ✗ *Originating MSC*—the MSC directing an incoming call toward a mobile station.
  - ✗ *Remote MSC*—the MSC at the other end of an intersystem handoff trunk.
  - ✗ *Serving MSC*—the MSC currently providing service to a call.
  - ✗ *Tandem MSC*—an MSC providing only trunk connections for a call in which a handoff has occurred.
  - ✗ *Target MSC*—the MSC selected for a handoff.
  - ✗ *Visited MSC*—an MSC providing service to the mobile station.
- **Home Location Register (HLR):** The HLR is the functional unit used for management of mobile subscribers by maintaining all subscriber information (e.g., electronic serial number, directory number, international mobile station identification, user profiles, and

current location). The HLR may be co-located with a MSC as an integral part of the MSC or may be independent of the MSC. One HLR can serve multiple MSCs, or an HLR may be distributed over multiple locations.

- **Data Message Handler (DMH):** The DMH is used for collecting billing data and is described in chapter 11.
- **Visited Location Register (VLR):** The VLR is linked to one or more MSCs. The VLR is the functional unit that dynamically stores subscriber information (e.g., ESN, directory number, and user profile information) obtained from the user's HLR when the subscriber is located in the area covered by the VLR. When a roaming MS enters a new service area covered by an MSC, the MSC informs the associated VLR about the MS by querying the HLR after the MS goes through a registration procedure.
- **Authentication Center (AC):** The AC manages the authentication or encryption information associated with a individual subscriber. As of the writing of this book, the details of the operation of the AC have not been finalized. The AC may be located within an HLR or MSC or may be located independently of both.
- **Equipment Identity Register (EIR):** The EIR provides information about the mobile station for record purposes. As of the writing of this book, the details of the operation of the EIR have not been defined. The EIR may be located within a MSC or may be located independently of it.
- **Operations Systems (OSs):** The OSs are responsible for overall management of the wireless network. See chapter 10 for a full description of the OAM&P functions.
- **Interworking Function (IWF):** The IWF enables the MSC to communicate with other networks. See chapter 12 for details on interworking.
- **External Networks:** These communications networks include the Public Switched Telephone Network (PSTN), the Integrated Services Digital Network (ISDN), the Public Land Mobile Network (PLMN), and the Public Switched Packet Data Network (PSPDN).

The following interfaces are defined among the various elements of the system:

- **BS to MSC (A-Interface):** The interface between the base station and the MSC supports signaling and traffic (both voice and data).

A-Interface protocols have been defined using SS7, ISDN BRI/PRI, and frame relay.

- **BTS to BSC Interface (A_{bis}):** If the base station is segmented into a BTS and BSC, this internal interface is defined.
- **MSC to PSTN Interface (A_i):** This interface is defined as analog interface using either dual-tone multifrequency (DTMF) signaling or multifrequency (MF) signaling.
- **MSC to VLR (B-Interface):** This interface is defined in the TIA IS-41 protocol specification [4].
- **MSC to HLR (C-Interface):** This interface is defined in the TIA IS-41 protocol specification.
- **HLR to VLR (D-Interface):** This interface is the signaling interface between an HLR and a VLR and is based on SS7. It is currently defined in the TIA IS-41 protocol specification.
- **MSC to ISDN (D_i-Interface):** This is the digital interface to the PSTN and is a T1 interface (24 channels of 64 kbps) and uses Q.931 signaling.
- **MSC-MSC (E-Interface):** This interface is the traffic and signaling interface between wireless networks. It is currently defined in the TIA IS-41 protocol specification.
- **MSC to EIR (F-Interface):** Since the EIR is not yet defined, the protocol for this interface is not defined.
- **VLR to VLR (G-Interface):** When communications are needed between VLRs, this interface is used. It is defined by TIA IS-41.
- **HLR to Authentication Center (H-Interface):** The protocol for this interface is not defined.
- **DMH to MSC (I-Interface):** This interface is described in chapter 11.
- **MSC to the IWF (L-Interface):** This interface is defined by the inter-working function.
- **MSC to PLMN (M_i-Interface):** This interface is to another wireless network.
- **MSC to OS (O-Interface):** This is the interface to the operations systems. It is currently being defined in ATSI standard body T1M1 (see chapter 11).
- **MSC to PSPDN (P_i-Interface):** This interface is defined by the packet network that is connected to the MSC.

- **Terminal Adapter (TA) to Terminal Equipment (TE) (R-Interface):** These interfaces will be specific for each type of terminal that will be connected to a MS.
- **ISDN to TE (S-Interface):** This interface is outside the scope of PCS and is defined within the ISDN system.
- **Base Station to MS (U_m-Interface):** This is the air interface. Chapters 5–8 will discuss this interface in detail.
- **PSTN to DCE (W-Interface):** This interface is outside the scope of PCS and is defined within the PSTN system.
- **MSC to AUX (X-Interface):** This interface depends on the auxiliary equipment connected to the MSC.

4.2 STANDARDIZATION OF THE MSC-BS INTERFACE

North American Standards, until recently, have not addressed the standardization of the BS-MSC interface (the A-interface in the network reference model of fig. 4.1). However, the wireless service providers are experiencing explosive growth in North America and are consequently finding it necessary to purchase equipment from multiple equipment manufacturers. Thus, the wireless industry has pressed for standards specifying the A-interface. At this time, however, the BTS-BSC interface (i.e., the A_{bis} interface) is not being addressed. The TIA TR-45 Committee is currently developing standards for the A-interface. TIA IS-634 (MSC-BS interface for 800 MHz) has the following objectives:

- Develop the MSC-BS interface based on the TIA TR-45 network reference model;
- Partition the responsibility of functions provided between the base station and the mobile switching center without dictating specific implementation;
- Support North American air interface signaling protocols including EIA/TIA IS-95A;
- Support all the services offered to mobile subscribers operating under North American standards.

TIA IS-634 is partitioned into six major sections

- Functional Overview (IS-634.1),
- Call Processing and Supplementary Services (IS-634.2),
- Radio Resource Management (IS-634.3),
- Mobility Management, Authentication, and Privacy (IS-634.4),

- Layer 1 & 2 and Tererestrial Facility Management (IS-634.5), and
- Messages, Parameters, and Timer Definitions (IS-634.6).

TIA IS-634 defines MSC-BS messages, message sequencing, and mandatory timers at the base station and the mobile switching center. The discussion of this standard will be limited to the architectural impact of the MSC-BS interface rather than upon the associated message flow. In TIA IS-634, the base station is really the base station controller; thus, multiple BTSs may be connected to the base station. Also, TIA IS-634 refers to the BTS as the cell. Of course, the BTS and the BSC can be co-located.

Call processing, radio resource management, mobility management, and transmission facilities management are separate functions that are supported by the applications layer (see fig. 4.2).

The underlying transport mechanism for the applications layer is ISDN with the physical layer specified by ANSI T1.101, the message transfer part (MTP) specified by ANSI T1.111, and the signaling connection control part (SCCP) specified by ANSI T1.112. The physical interface supports one or more 1.544-Mbps digital transmission facilities, each providing twenty-four 56-kbps or 64-kbps channels. Each channel can be used for traffic or for signaling. The MTP and the SCCP support only signaling messages, whereas the physical layer supports both signaling messages and traffic messages. Traffic messages carry voice transmission. TIA IS-634 allows the transcoder (vocoder) to reside either at the

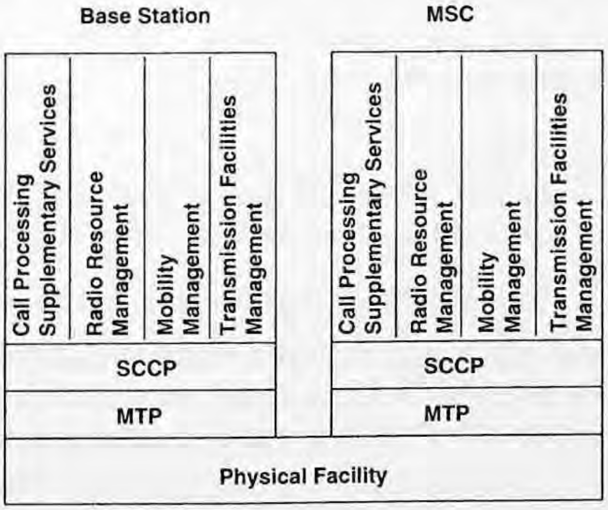

Figure 4.2 TIA IS-634 functions. (Reproduced under written permission of the copyright holder [TIA].)

base station or "very near" to the mobile switching center. In the first case, an entire DS0[1] (64 kbps) connection is required for each call, whereas the second case does not necessitate an entire DS0 connection.

At the applications layer, the call processing and mobility management function are connected between the mobile station and the mobile switching center, while the radio resource management and the transmission facilities management functions are connected between the base station and the mobile switching center. Accordingly, the base station application part (BSAP), which is the applications layer signaling protocol, is divided into two subapplications parts. The first is called the base station management application part (BSMAP). The BSMAP messages are sent between the base station and the mobile switching center. The second is the direct transfer application part (DTAP) in which messages are sent between the mobile station and the mobile switching center. The base station acts as a transparent conduit for DTAP messages. The base station merely maps the messages going to/from the mobile switching center into the appropriate air interface signaling protocol (e.g., TIA/EIA IS-95A). This approach simplifies the role of the base station for call processing and mobility management.

The base station associates the DTAP messages with a particular mobile station and call using a transaction identification. The BSAP messages are transferred over an SCCP connection. The DTAP and BSMAP layer 3 messages between the base station and the mobile switching center are contained in the user data field of SCCP frames. The data field is supported in connection request (CR), connection confirm (CC), released (RLSD), and data (DT) SCCP frames for mobile stations having one or more active transactions. The layer 3 user data field is partitioned into three components (see fig. 4.3):

- BSAP message header;
- Distribution data unit, which includes the Length Indicator and the Data Link Connection Identifier (DLCI)—only DTAP message; and
- Layer 3 Message.

The BSAP message header consists of the message discrimination and the data link connection identifier, which is applicable only for DTAP messages. The D-bit (bit 0) of the message discrimination octet is set to 1

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[1] A DS0 is a 64-kbps pulse code modulation (PCM) transport facility and is a single 64-kbps time slot on a T1 carrier.

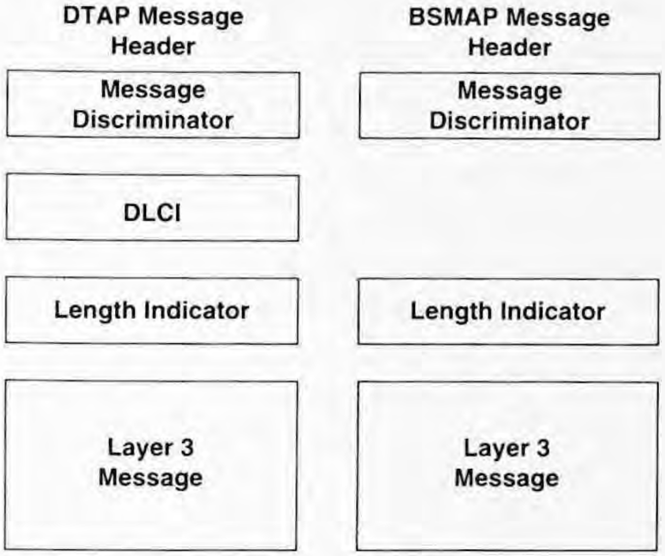

Figure 4.3 Layer 3 data field.

for a DTAP message and set to 0 for a BSMAP message. The distribution data unit consists of the length indicator octet, which gives the number of octets following the length indicator. The layer 3 message will be discussed in greater detail.

The DTAP messages apply only to mobility management and to call processing (including supplementary services) functions, whereas BSMAP messages are associated with radio resource management and call processing (to a lesser degree). Each DTAP message contains the protocol discriminator octet, which identifies the associated procedure (i.e., call control, mobility management, radio resource management, and facilities management). All DTAP and BSMAP messages are identified by the message type octet.

The remaining part of this section provides greater detail for each function supported by the BSAP.

4.2.1 Supported Architectural Configurations

TIA IS-634 makes a number of assumptions regarding the underlying CDMA architecture. The basic architecture is shown in figure 4.4.

The main entities are the mobile switching center (MSC), the transcoder (XC), the base station (BS), the base transceiver system (BTS), and the mobile station (MS). The MS is not shown in figure 4.4, but the MS communicates with the BTS over the air interface. The func-

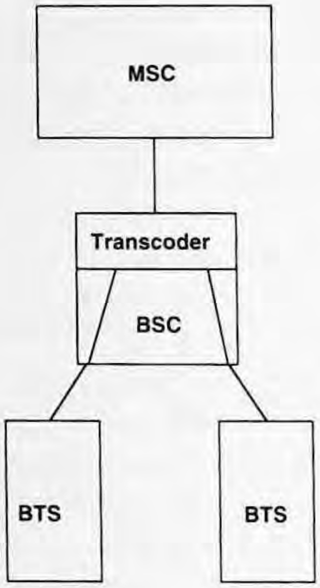

Figure 4.4 Basic CDMA architecture.

tions associated with the MSC and the MS were discussed in section 4.1. TIA IS-634 assumes that the base station is really the BSC. One or more BTSs are connected to the BSC.

The transcoder supports both voice coding (vocoder) and diversity reception. Diversity reception allows the transcoder to pick the "best" frame when multiple connections are established during a soft handoff. Diversity reception distinguishes CDMA technology from current digital technology. To be more specific, the XC is responsible for the following:

- Distribution of speech/data on the forward traffic channel to all BTSs associated with a call. During a soft handoff, multiple BTSs are simultaneously assigned to the call. The XC selects the best speech/data frame from all BTSs associated with the call on the reverse traffic channel. This implies that signal quality characteristics of the speech/data frame are provided to the transcoder.
- Decode QCELP[2] format to PCM format for voice frames sent on the reverse traffic channel. If the call is a data call, this task is bypassed.

[2] QUALCOMM code-excited linear prediction (QCELP) is the CDMA speech processing algorithm that is specified in TIA IS-96A. The algorithm is based on code-excited linear prediction. See chapter 8 for more information.

- Decode PCM format to QCELP format for voice frames sent on the forward traffic channel. If the call is a data call, this task is bypassed.
- Rate adapt voice frames to fully use the transmission bandwidth of the assigned terrestrial circuits. This task is bypassed for data calls.
- Rate adapt compressed voice PCM format into a circuit switched subrate channel on a DS0 facility. One common compression approach is adaptative differential pulse code modulation (ADPCM). Compression uses the fact that voice activity is less than 100 percent of the total duration. Typically, the actual voice activity is approximately 50 percent.
- Provide a control capability of inserting blank and burst or dim and burst signaling into the voice transmission on the forward traffic channel.

The transcoder is considered as a logical part of the BS, although the transcoder can be physically located at the BS, or at the MSC, or somewhere between the BS and the MSC. The terrestrial facility connects the transcoder to the MSC. The terrestrial facility may be full-rate (56 kbps or 64 kbps), subrate, PSTN, bypass, or PSTN/bypass. If only the BS is associated with a call, the terrestrial facility is connected to the PSTN. If a call is configured for a soft handoff between two base stations, another terrestrial facility is required to connect the transcoder at the target BS with the transcoder at the source BS. Such a circuit is called a bypass facility. A bypass/PSTN facility is initially a bypass connection but subsequently is a PSTN connection. The connection between the transcoder and the BS is not addressed in TIA IS-634.

The transcoder and the BS may be physically co-located or externally connected by a full-rate or subrate facility if the transcoder is located near or at the MSC. The BSC may support multiple BTSs. Thus, if a call is in a soft handoff using only BTSs connected to a given BSC, no messaging between the MSC and the BS are necessary.

BTSs are uniquely identified by the cell global identification (CGI). The CGI is composed of four components:

- Mobile Country Code (MCC),
- Mobile Network Code (MNC),
- Location Area Code (LAC), and
- Cell Identity (CI).

TIA IS-634 supports addressing modes to identify a BTS by the CGI, or by the CI, or by a combination of the LAC, MCC, and MNC, or by the associated BS.

4.2.2 Call Processing and Supplementary Services

TIA IS-634 supports call setup (mobile origination and mobile termination) as well as supplementary services (e.g., call waiting) and call release. However, the support of handoffs during a call is considered as part of the radio resource management function, which will be discussed in section 4.3.2.

Most of the messages associated with call processing and supplementary services are DTAP messages. For these messages, the role of the base station is minimized since the base station "passes" the messages to the mobile station.

The initial BS-MSC message in the call setup procedure includes the mobile identity. The mobile identity can be the mobile identification number (MIN), the mobile station electronic serial number (ESN), or the international mobile subscriber identifier (IMSI). The identity type is selected by either the mobile station or the wireless network. For a mobile origination, the initial BS-MSC message is the connection management service request, and for a mobile termination, the initial BS-MSC message is the paging request. However, the initial message from the base station to the mobile switching center at call setup is an encapsulated DTAP message within a BSMAP message. The mobile switching center sends an assignment request message, which contains the terrestrial channel. Also, the mobile switching center may select the radio channel or provide channel parameters and allow the base station to choose the radio channel at the appropriate BTS.

Unique call processing for mobile-to-mobile calls are currently under study. Tables 4.1 and 4.2 list the messages defined by TIA IS-634 for call processing and supplementary services, respectively.

4.2.3 Radio Resource Management

Once a call has been established (i.e., call setup has been successfully completed), the base station is responsible for maintaining a reliable radio link between the mobile station and the base station. This responsibility requires that the base station perform the following tasks:

- Radio channel supervision,

Table 4.1 Call Processing Messages. (Reproduced under written permission of the copyright holder [TIA].)

Message Name	Direction	Message Type
CM Service Request	BS → MSC	DTAP
Paging Request	MSC → BS	BSMAP
Paging Response	BS → MSC	DTAP
Setup	BS ↔ MSC	DTAP
Emergency Setup	BS → MSC	DTAP
Alerting	BS ↔ MSC	DTAP
Call Confirmed	BS → MSC	DTAP
Call Proceeding	MSC → BS	DTAP
Connect	MSC → BS	DTAP
Connect Acknowledge	BS ↔ MSC	DTAP
Progress	MSC → BS	DTAP
Release	MSC ↔ BS	DTAP
Release Complete	MSC ↔ BS	DTAP
Assignment Request	MSC ↔ BS	BSMAP
Assignment Complete	BS → MSC	BSMAP
Assignment Failure	BS → MSC	BSMAP
Privacy Mode Command	MSC → BS	BSMAP
Privacy Mode Complete	BS → MSC	BSMAP
Clear Request	BS → MSC	BSMAP
Clear Command	MSC → BS	BSMAP
Clear Complete	BS → MSC	BSMAP

- Radio channel management, and
- Initiation and execution of handoffs.

The objective for each of these tasks is common for all radio technologies, although the actual implementation is dependent on the associated technology.

The support of soft handoffs is one capability that distinguishes CDMA from other access technologies. Thus, TIA IS-634 supports the procedures associated with soft handoffs. These procedures are

Table 4.2 Supplementary Service Messages. (Reproduced under written permission of the copyright holder [TIA].)

Message Name	Direction	Message Type
Send Burst DTMF[a]	BS ↔ MSC	DTAP
Send Burst Acknowledge	BS ↔ MSC	DTAP
Start DTMF	BS → MSC	DTAP
Start DTMF Acknowledge	MSC → BS	DTAP
Stop DTMF	BS → MSC	DTAP
Stop DTMP Acknowledge	MSC → BS	DTAP
Flash with Information	BS ↔ MSC	DTAP

a. Dual-Tone Multifrequency

- IS-95 Add Target Procedure,
- IS-95 Drop Target Procedure, and
- IS-95 Drop Source Procedure.

The source BS is the BSC, which controls the transcoder. If either a hard or soft handoff is to be configured with a target BTS that is connected to another BSC (target BS), then a handoff-required message is sent to the mobile switching center. The mobile switching center then sends a handoff request to the target BS. At the same time, only one target BS can be addressed.

Table 4.3 summarizes messages associated with radio resource management.

4.2.4 Mobility Management

Mobility management is implemented using DTAP messages. The purpose of the mobility management function is to support registration and deregistration of a mobile. In addition, this function encompasses authentication and voice privacy. Authentication includes authentication challenge and shared secret data (SSD) update. There is little differential impact upon the BS-MSC architecture in order to support this function.

Messages associated with mobility management are listed in table 4.4.

4.2.5 Transmission Facilities Management

The transmission facilities management function is responsible for the management of terrestrial circuits. *Terrestrial circuits* are transmission facilities that carry traffic (voice or data) and signaling information

Table 4.3 Handoff Messages. (Reproduced under written permission of the copyright holder [TIA].)

Message Name	Direction	Message Type
Strength Measurement Request	BS ↔ MSC	BSMAP
Strength Measurement Response	BS ↔ MSC	BSMAP
Strength Measurement Report	BS ↔ MSC	BSMAP
Handoff Required	BS → MSC	BSMAP
Handoff Request	MSC → BS	BSMAP
Handoff Request Acknowledge	BS → MSC	BSMAP
Handoff Failure	BS → MSC	BSMAP
Handoff Command	MSC → BS	BSMAP
Handoff Required Reject	MSC → BS	BSMAP
Handoff Commenced	BS → MSC	BSMAP
Handoff Complete	BS → MSC	BSMAP
Handoff Performed	BS → MSC	BSMAP
Soft Handoff Drop Target	BS ↔ BS	BSMAP
Soft Handoff Drop Source	BS ↔ BS	BSMAP

Table 4.4 Mobility Management Messages. (Reproduced under written permission of the copyright holder [TIA].)

Message Name	Direction	Message Type
Authentication Request	MSC → BS	DTAP
Authentication Reject	MSC → BS	DTAP
SSD Update Request	MSC → BS	DTAP
Base Station Challenge	BS → MSC	DTAP
Base Station Challenge Response	MSC → BS	DTAP
SSD Update Response	BS → MSC	DTAP
Location Updating Request	BS → MSC	DTAP
Location Updating Accept	MSC → BS	DTAP
Location Updating Reject	MSC → BS	DTAP
Parameter Update Request	MSC → BS	DTAP
Parameter Update Confirm	BS → MSC	DTAP

between the MSC and the BS. Furthermore, different facilities may carry traffic information from facilities carrying signaling information. Currently, TIA IS-634 does not address the facilities between the BS and the transcoder and between the BSC and BTSs. Each facility may be blocked/unblocked and allocated/deallocated by the transmission facilities management function. For digital technologies (e.g., CDMA), this function can disable the transcoders at both the originating end and the terminating end for mobile-to-mobile calls. This action eliminates the need for vocoder tandeming, which degrades the voice quality of a call. However, TIA IS-634 does not explicitly address this capability for calls spanning multiple BSs.

Table 4.5 summarizes the message types associated with transmission facilities management.

Table 4.5 Transmission Management Messages. (Reproduced under written permission of the copyright holder [TIA].)

Message Name	Direction	Message Type
Overload	MSC ↔ BS	BSMAP
Block	BS → MSC	BSMAP
Block Acknowledge	MSC → BS	BSMAP
Unblock	BS → MSC	BSMAP
Unblock Acknowledge	MSC → BS	BSMAP
Reset	BS ↔ MSC	BSMAP
Reset Acknowledge	BS ↔ MSC	BSMAP
Reset Circuit	BS ↔ MSC	BSMAP
Reset Circuit Acknowledge	BS ↔ MSC	BSMAP
Transcoder Control Request	MSC ↔ BS	BSMAP
Transcoder Control Acknowledge	MSC ↔ BS	BSMAP

4.3 SERVICES

With the reference model described previously, there are enough capabilities to support a wide range of telecommunications services over cellular or *personal communications systems*. Many of these services are similar to those of the wireline network; some are specific to the untethered approach that wireless provides. The services defined here are based on a mobile application part (MAP) that is supported by the IS-41 intersystem communications protocol. We discuss the services from the point of view of a CDMA (or wideband CDMA) phone, but the services provided by other air interfaces are the same. The main difference is how handoffs are handled in a CDMA system. We will therefore examine handoffs in detail.

4.3.1 Basic Services

The standards body T1P1 is in the process of defining basic call functions and supplementary services for PCS. Similarly, services for cellular systems are defined in TIA SP-2977. However, the objective of defining services is to provide transparency for the mobile subscriber regardless of the underlying technology of the serving cellular or PCS system.

The T1P1 Stage Two Service description [7] defines 15 basic services (information flows) that can be grouped as follows:

- Registration and deregistration functions support the process where an MS informs a personal communications system of its desire to receive service and its approximate location. These include
    - ✘ Automatic registration,
    - ✘ Terminal authentication and privacy (using private key cryptography),
    - ✘ Terminal authentication and privacy (using public key cryptography),
    - ✘ User authentication and validation,
    - ✘ Automatic personal registration,
    - ✘ Automatic personal deregistration,
    - ✘ Personal registration, and
    - ✘ Personal deregistration.
- The registration and deregistration process requires that an MS identify itself to the PCS network and requires that the PCS network communicate with the home PCS network to obtain security and service profile information.
- Roaming is the process where an MS registers and receives service in a personal communications system other than its home system.
- Call establishment, call continuation, and termination procedures include
    - ✘ Call origination,
    - ✘ Call delivery (call termination),
    - ✘ Call clearing,

- ✘ Emergency (E911) calls, and
- ✘ Handoff.

4.3.2 Supplementary Services

Supplementary services are defined in IS-104 "Personal Communications Service Descriptions for 1800 MHz" (PN-3168). The IS-41 C specification defines them as those services that can be made available to users as they roam. Obviously, these services would also be available to users in their home systems. Additional services may be available in a specific home PCS or cellular system, but users would not necessarily have them available in other systems since no common set of procedures and protocols have been defined to support other services.

Supplementary services follow:

- **Automatic Recall** allows a wireless subscriber calling a busy number to be notified when the called party is idle and have the PCS network recall the number.
- **Automatic Reverse Charging (ARC)** allows a wireless subscriber to be charged for calls to a special ARC number. This service is similar to wireline 800 service in North America.
- **Call Hold and Retrieve** allows a wireless subscriber to interrupt a call and return to the call.
- **Call Forwarding (CF)—Default** represents the ability to redirect a call to an MS in three situations: unconditional, busy, and no answer. The MS call forwarding features build upon the MS call terminating capability. Under all these features, calls may be forwarded by the network to another mobile station or to a DN associated with a wireline interface. There are no additional information flows for MS-CF beyond the information flow for MS call terminating.
- **Call Forwarding—Busy** permits a called PCS subscriber to have the system send incoming calls addressed to the called personal communications subscriber's personal number to another personal, terminal, or directory number when the PCS subscriber is engaged in a call. With personal call forwarding—busy activated, a call incoming to the PCS subscriber will be automatically forwarded to the forward-to number whenever the PCS subscriber is already engaged in a prior call.
- **Call Forwarding—No Answer** permits a called PCS subscriber to have the system send all incoming calls addressed to the called PCS

subscriber's personal number to another personal, terminal, or directory number when the PCS subscriber fails to answer or doesn't respond to paging. With personal call forwarding—no answer activated, a call coming in to the PCS subscriber will be automatically forwarded to the designated forward-to number whenever the PCS subscriber does not respond to the page or if the PCS subscriber does not answer within a specified period after transmission of the alert indication.

- **Call Forwarding—Unconditional** permits a PCS user to send incoming calls addressed to the PCS subscriber's personal number to another MS or directory number (forward-to number). The ability of the served PCS subscriber to originate calls is unaffected. If this service is activated, calls are forwarded independent of the state of the MS (busy, idle, etc.).
- **Call Transfer** permits a PCS user to transfer a call to another number on or off the PCS switch. When a call is transferred, the PCS personal terminal is then available for other calls.
- **Call Waiting** provides notification to a PCS subscriber of an incoming call while the user's mobile station is in the busy state. Subsequently, the user can either answer or ignore the incoming call. With call waiting activated, a new incoming call attempt to the PCS user who is already engaged in conversation on a prior call will receive a notification signal. This may be repeated a short time later if the PCS user takes no action. The calling party will hear an audible ringing signal either until the call attempt is aborted or the PCS user acknowledges the waiting call. The PCS user may indicate acceptance of the waiting call by (1) placing the existing call on hold or (2) releasing the existing call.
- **Calling Number Identification Presentation (CNIP)** is a supplementary service offered to a called party. It provides to the called party the number identification of the calling party. If the calling party has subscribed to calling number identification restriction, the calling number will not be presented.
- **Calling Number Identification Restriction (CNIR)** is a supplementary service offered to a calling party. It restricts presentation of that party's calling number identification to the called party. When the CNIR service is applicable and activated, the originating network provides the destination network with a notification that the calling number identification is not allowed to be presented to the called party. The CNIR may be offered with several options. Sub-

scription options applied are (1) not subscribed (inactive for all calls); (2) permanently restricted (active for all calls); (3) temporarily restricted (specified by user per call)—default: restricted; and (4) temporarily allowed (specified by user per call)—default: allowed.

- **Conference Calling** is similar to three-way calling except when more than three parties are involved in the call.
- **Do Not Disturb** allows a wireless subscriber to direct that all incoming calls stop at the PCS switch and not page the mobile station.
- **Flexible Alerting** allows a call to a directory number to be branched into multiple attempts to alert several subscribers. The subscribers may have wireless or wireline terminations.
- **Message Waiting Notification** is the service where a message is sent to the MS to inform the user that there are messages stored in the network that the user can access.
- **Mobile Access Hunting** is the service where call delivery is presented to a series of terminating numbers. If the first number is not available, the system will try the second and continue down a list. The terminating numbers can be mobile or nonmobile numbers anywhere in the world.
- **Multilevel Precedence and Preemption (MLPP)** permits a group of wireless subscribers to have access to wireless service where higher-priority calls will be processed ahead of lower priority calls and may preempt (i.e., force the termination of) lower-level calls. Only calls within the same group will override each other.
- **Password Call Acceptance** is the service where calls to the wireless subscriber are interrupted and the calling party is asked to correctly enter a password before the mobile station is paged.
- **Preferred Language** is the capability for users to hear all network announcements in their preferred languages.
- **Priority Access and Channel Assignment** allows the service provider to provide capabilities to a subscriber that allows priority access to radio resources. This service permits emergency services personnel (e.g., police, fire, and rescue squads) priority access to the system. Multiple levels of access may be defined.
- **Remote Feature Call** permits a wireless subscriber to call a special directory number (from a wireless or wireline phone) and, after correctly entering account code information and a PIN, change the operation of one or more features of the service. For example, the selective call list can be modified by this capability.

- **Selective Call Acceptance** is the service where a wireless subscriber can form a list of those directory numbers that will result in the mobile station being paged. All other directory numbers will be blocked.
- **Subscriber PIN Access** is the ability to block access to the mobile station until the correct personal identification number (PIN) is entered into the MS.
- **Subscriber PIN Intercept** is the ability for a wireless subscriber to bar outgoing calls unless the correct PIN is entered. This feature can be implemented in the network or in the MS.
- **Three-Way Calling** permits a PCS user authorized for three-way calling to add a third party to an established two-way call regardless of which party originated the established call. To add a third party, the PCS user sends a request for three-way calling service to the service provider, which puts the first party on hold. The PCS user then proceeds to establish a call to the third party. A request by the controlling user, for disconnection of third party (i.e., last added party), will release that party and will cause the three-way connection to be disconnected and return the call to its original two-way state. If either of the noncontrolling parties to an established three-way call disconnects, the remaining two parties are connected as a normal two-way call. If the controlling PCS user disconnects, all connections are released.
- **Voice Message Retrieval** is service where the user can retrieve voice messages stored in the network. These messages are typically left by parties calling the user while the user was busy, did not answer, or was not registered with a system.
- **Voice Privacy** is the service where the user's voice traffic over the radio link is encrypted to prevent casual eavesdropping. With a personal communications system, in the United States, this is a required feature and is not optional.
- **Short Message Service** permits alpha and alphanumeric short messages to be sent to or from a mobile station.

4.4 SUMMARY

In this chapter, we presented the TR-45/TR-46 reference model, which is used by standards committees as the basis of describing network interfaces. The main elements of this model are the mobile station, base station, mobile switching center, home location register, and visited location register. Next, we discuss the MSC-BS interface (TIA IS-634), which standardizes the messaging between the base station and the mobile switching center. Messages between the BS and the MSC are categorized into two types: base station application part and direct transfer application part. Messages can be associated with one of the following functions: call processing and supplementary services, radio resource management, mobility management, and terrestrial facility management. The effects upon the architecture of a CDMA system are emphasized. Finally, we present a discussion about basic and supplementary services that are supported by cellular and PCS standards. From the point of view of the mobile subscriber, these services are independent of the air interface type (e.g., analog, TDMA, CDMA).

4.5 REFERENCES

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CHAPTER 5

Physical Layer of CDMA

5.1 INTRODUCTION

In chapter 2, we introduced the CDMA system used for cellular and personal communications systems in North America as embodied in the design standardized by the TIA and ATIS in IS-95A for a cellular system and J-STD-008 for a personal communications system. In this chapter, we will discuss this system in more detail and also describe the W-CDMA system standardized as J-STD-015 (and IS-665) for a personal communications system. The W-CDMA system is also expected to be used in Asia. The W-CDMA system is similar to the CDMA system, but there are some differences, which we will describe. In this chapter, we will discuss how a data (or voice-encoded) signal is modulated by a CDMA transmitter and demodulated by a CDMA receiver.

In CDMA, the entire 1.25-MHz transmission bandwidth is occupied by every station (see section 5.3 for the frequency bands used by a base station). In the forward direction (base station to mobile station), Walsh codes are used to distinguish different channels. On the reverse channel (mobile station to base station), different pseudorandom noise (PN) sequences are used to distinguish different channels. The Walsh functions are chosen so that the set of functions are all orthogonal to each other. All base stations in the system are on the same frequency and use the same set of time-shifted Walsh functions. Every base station in the system is synchronized to every other base station in the system. Different base stations use time-shifted versions of the PN sequence to permit mobile stations to select transmissions from different base stations. Thus, for CDMA, the frequency reuse factor *N* is 1. The PN sequences used by the MS are found by computer simulation and are chosen to have low autocorrelation and cross-correlation properties. The W-CDMA system uses Walsh functions in both directions for bandwidths of 5.0 and 10.0 MHz and Hadamard functions in both direction for a bandwidth of 15 MHz.

In this chapter, we first describe the Open System Interconnect reference model, which is used to construct the protocols for the CDMA and W-CDMA systems. We then examine the physical layer of the CDMA and W-CDMA systems in the rest of this chapter. In chapter 6, we examine the layer 2 and 3 functions for both systems; in chapter 7, we examine the applications functions (call processing); and in chapter 8, we examine the speech-coding methods.

5.2 OPEN SYSTEMS INTERCONNECT REFERENCE MODEL

Recently, the International Standards Organization (ISO) has developed a reference model for data communications. The Open Systems Interconnect (OSI) reference model is used by many computer systems for computer-to-computer communications. In the model, seven layers are defined to segment different aspects and needs for communications from each other so that the communications can be conducted in an orderly manner. In this section, we describe the OSI model in sufficient detail so that the protocols and messages in this chapter and in chapters 6 and 7 can be understood.

Each of the seven layers in the protocol communicates with its peer layer at the distant end and with the local layers immediately above and below it. The protocols at each layer define how the peer-to-peer communications takes place by defining message sets and state diagrams. For example, the layer 5 software in one computer communicates with the corresponding layer 5 software in another computer. The software in the two computers might be implemented in two different languages with two different operating systems and two completely different host computers. Thus, the layer 5 software that operates on one computer will not necessarily operate on another computer. But, as long as both layer 5 software packages agree on how they will meet the OSI specification, they will be able to communicate with each other. The model permits computer systems from widely different manufacturers to communicate with each other. For CDMA phones, the messaging is done within the OSI model and allows phones from any manufacturer to communicate with networks from any other manufacturer. In this chapter and chapters 6 and 7, we examine the details of the CDMA and W-CDMA systems and how they use the OSI model.

Figure 5.1 shows the OSI reference model for communications between computer systems. It shows two protocol stacks. One stack is for signaling and the other stack is for voice or data communications. With the reference model, each layer communicates with the layer immediately above and below it and with its peer layer at the other computer. With a properly designed system, the software at one layer can be replaced without affecting the other layers. Similarly, the software/hardware at the physical layer can be replaced without affecting the layers above it. In the following sections, we discuss each layer in more detail.

The seven layers of the model follow:

- **Layer 1. Physical Layer.** This layer describes the voltages or waveforms for a bit (1 and 0), the time duration of a bit, the pin connections and type of connector for baseband systems or the frequencies used for radio systems, the handshaking to start and stop a connection, and whether the connection is one way or two way.
- **Layer 2. Link Layer (Data Link).** This layer converts bits into frames of data. Methods must be determined for obtaining bit sync and frame sync of the frames, preventing the data from causing the false transmission of frame sync, and retransmitting data when errors occur or when frames are lost or duplicated. Buffers must be designed to cope with fast and slow transmitters and receivers.

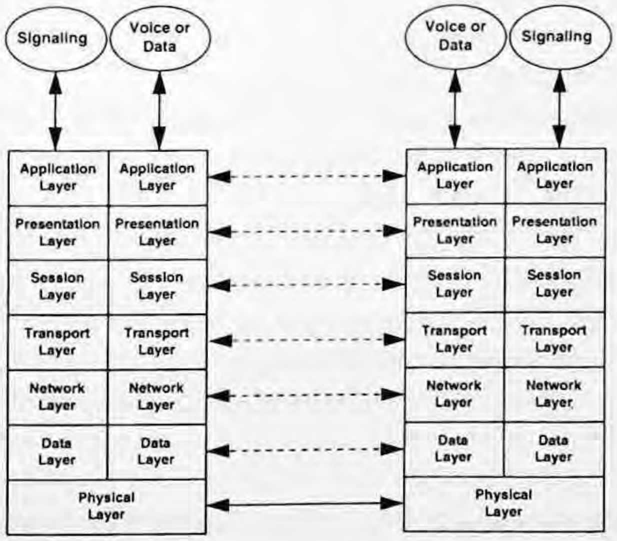


Figure 5.1 ISO Open Systems Interconnection reference model.

- **Layer 3. Network Layer.** This layer passes packets of information between two different end points. This layer often is designed to let layer 4 see an error-free channel. Unfortunately, this is not usually true. Thus, layer 4 must often also cope with errors. At this layer, billing and routing information for packets must be done. Buffering must be done at this layer to prevent too many packets from congesting the network.
- **Layer 4. Transport Layer.** The transport layer is the last layer to do error correction. All higher layers assume that the layer below it provides a perfect connection. Thus, the goal of this layer is to provide an error-free channel for the higher layers. If layer 3 is error-free, this job is easy. If layer 3 has errors, the transport protocol must allow for retransmission of data, error detection, and correction. This layer will set up and tear down calls to another host (addressing information is needed). It will also multiplex data from multiple processes in the host. Like other layers, it too must buffer data.
- **Layer 5. Session Layer.** This layer allows user or presentation layer processes to communicate. Events that occur during the layer are log-on messages and log-on IDs and passwords. Exchange of communications parameters occurs here (e.g., baud rate and full/half duplex). Grouping of messages can occur here. Automatic requests for a new connection can also occur here.
- **Layer 6. Presentation Layer.** This layer copes with things like protocol conversion, terminal type, encryption, definition of primitives, message compression, and file format conversion. Layer 6 software is sometimes combined with the layer 7 software, and sometimes the work done by the application layer is minimal and a null application layer is implemented.
- **Layer 7. Application Layer.** Here the definition of what goes on is up to the end user. Examples are forms entry, record locking, multiple hosts, and data base design.
- **Application.** Even though it is not normally shown in the OSI model protocol flow, the application software is above layer 7. For wireless phones, the application can be voice or data transmission for the user of the phone. The other main application is telephony functions (e.g., the mobility management function for a wireless phone).

In telephony, the signaling system application communicates directly with layer 3, and layers 4–7 are empty. Similarly, the traffic application (i.e., voice or data communications) communicates directly with layer 1, and layers 2–7 are empty. Figure 5.2 shows the CDMA system protocol stack mapped into the OSI reference model.

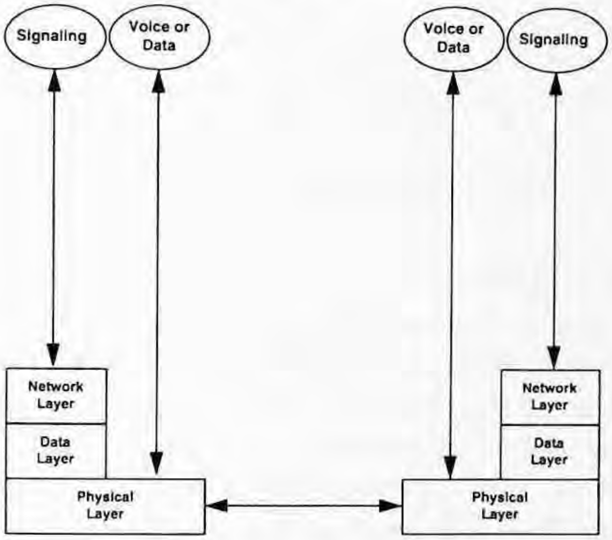


Figure 5.2 CDMA system mapped into the OSI reference model.

5.3 FORWARD CDMA CHANNEL AND W-CDMA CHANNEL

The forward CDMA channel consists of a pilot channel, an optional sync channel, optional (to a maximum of seven) paging channels, and several forward traffic channels. Each of these channels is orthogonally spread by the appropriate orthogonal function and is then spread by a quadrature pair of PN sequences. All the channels are added together and sent to the modulator. Many of the processes for constructing the forward and reverse channels are the similar; therefore, the details will be covered in section 5.6.

When a base station supports multiple forward CDMA channels, frequency division multiplex is used.

5.3.1 Pilot Channel

A pilot signal (fig. 5.3) is sent from the base station to aid in clock recovery at the MS. The pilot signal consists of the all zeros pattern and is modulo-2 added to the Walsh 0 function for the CDMA system. The W-CDMA system uses either Walsh 0 or Hadamard 0 but can use other Walsh codes as described in figure 5.3. The pilot signal is then sent to the modulator.

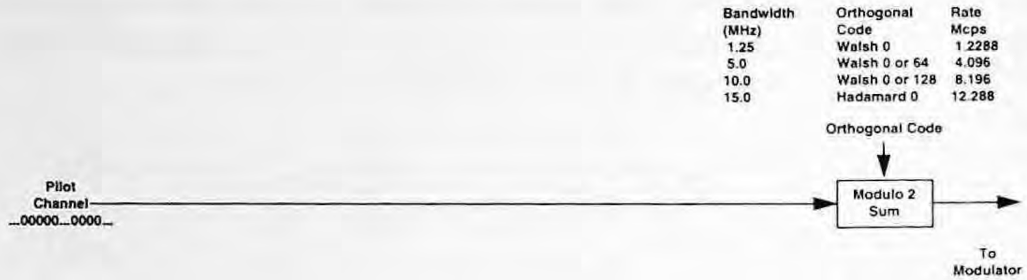


Figure 5.3 Forward CDMA pilot channel (all bandwidths).

5.3.2 Sync Channel

The sync channel is transmitted by a base station to enable the MS to obtain frame synchronization of the CDMA signal. The CDMA system uses a data rate of 1.2 kbps for the sync channel and then convolutionally encodes the data with a rate one-half code (see section 5.6). After encoding, the signal is processed by a symbol repetition stage and a block interleaver stage. The CDMA system repeats the symbol and then interleaves the data. The exact order of these two stages does not matter as long as the appropriate bits are in the correct place after the two stages. After interleaving, the resultant signal is modulo-2 added with the appropriate orthogonal code (see fig. 5.4) and then sent to the modulator.

The W-CDMA system uses a 16-kbps sync rate for all three bandwidths and then convolutionally encodes the data with a rate one-half code (see section 5.6). The W-CDMA system processes the output of the convolutional encoder as two separate data streams. After encoding, the signal is processed by a block interleaver stage and a symbol repetition stage. The exact order of these two stages does not matter as long as the appropriate bits are in the correct place after the two stages. After repetition, the resultant signal is modulo-2 added with the appropriate orthogonal code (see fig. 5.5) and then sent to the modulator.

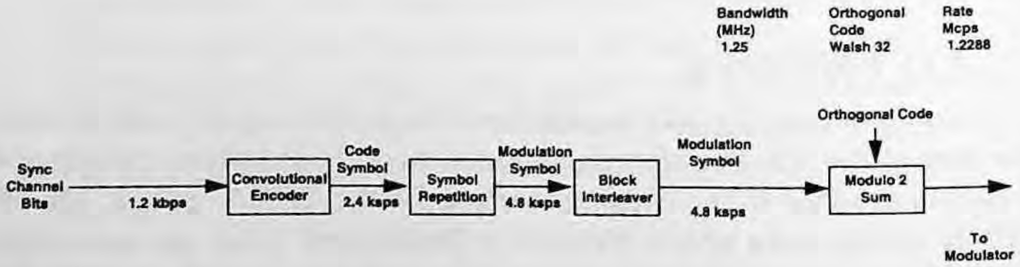


Figure 5.4 Forward CDMA sync channel.

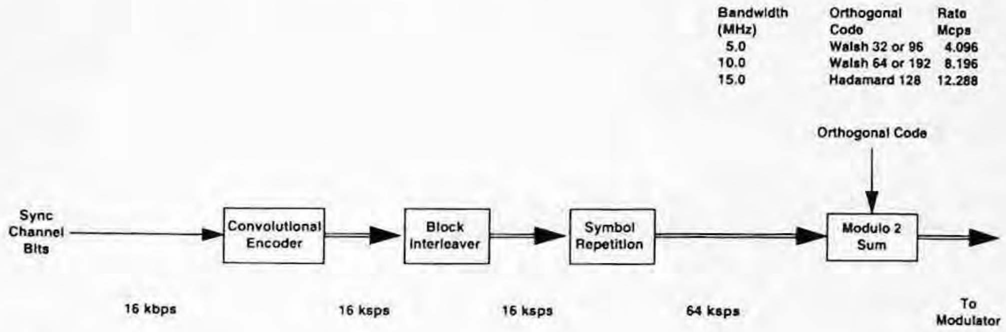


Figure 5.5 Forward W-CDMA sync channel.

5.3.3 Forward Paging Channel

The paging channel is transmitted by a base station to enable the MS to be paged and to process other orders while the MS is powered on and is idle. The CDMA system uses a data rate of either 4.8 or 9.6 kbps for the paging channel (fig. 5.6), and the W-CDMA system uses 16 kbps for the paging channel (fig. 5.7). Several of the modulation steps are similar to the sync channel. Both systems convolutionally encode the data with a rate one-half code (see section 5.6). After encoding, the signal is processed by a symbol repetition stage and a block interleaver stage. The encoding, repetition, and interleaving stages are identical to those used for the sync channel (and the traffic channel). For the CDMA system, the output modulation symbol is passed through a data scrambler. The scrambler prevents long sequences of 0s or 1s from appearing in the data stream. The scrambler is constructed using every 64th bit from a long code generator (see section 5.6) and modulo-2 summing it with the modu-

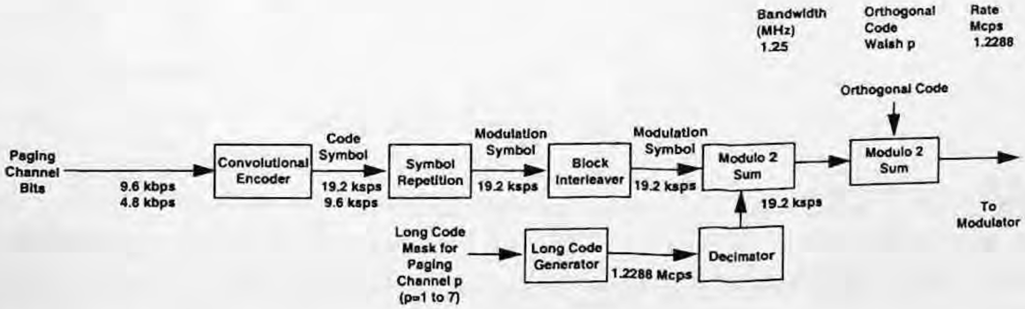


Figure 5.6 Forward CDMA paging channel.

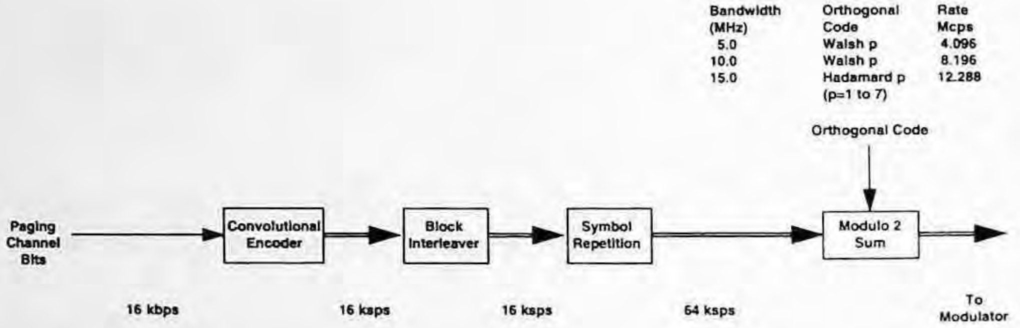


Figure 5.7 Forward W-CDMA paging channel.

lation symbol. The use of 1 out of 64 bits is called *decimation*. The W-CDMA system does not use a data scrambler. Finally, the resultant signal is modulo-2 added with the Walsh (or Hadamard) code. There are from 0 to 7 paging channels using codes 1 to 7, respectively and in sequence. Thus, for a base station with five paging channels, codes 1, 2, 3, 4, and 5 are used. The paging signal is then sent to the modulator.

5.3.4 Forward Traffic Channel

The traffic channel is transmitted by a base station to the MS (figs. 5.8 and 5.9) to carry voice or data traffic. The traffic channel is multiplexed and can carry voice or data, power control bits, and signaling channel data. The CDMA system multiplexes the voice, data, and signaling before the convolutional encoder. For CDMA, the data bits can be voice, data, or signaling and are multiplexed together according to the capabilities described in table 5.1. Signaling can be sent only by reducing the number of bits used for voice or data.

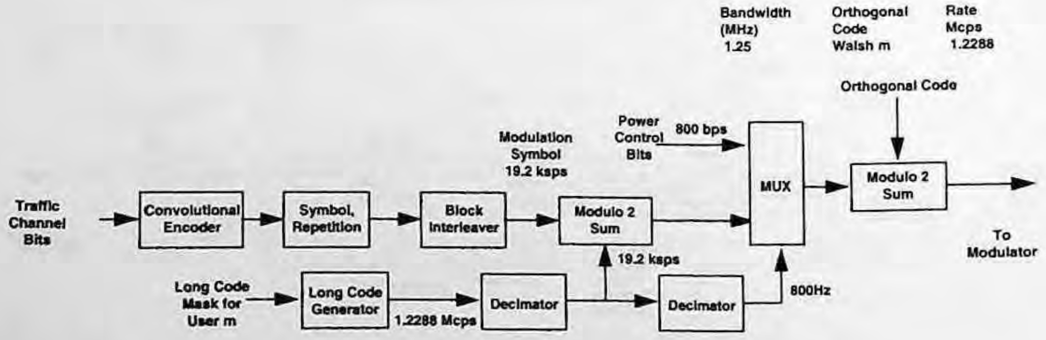


Figure 5.8 Forward CDMA traffic channel.

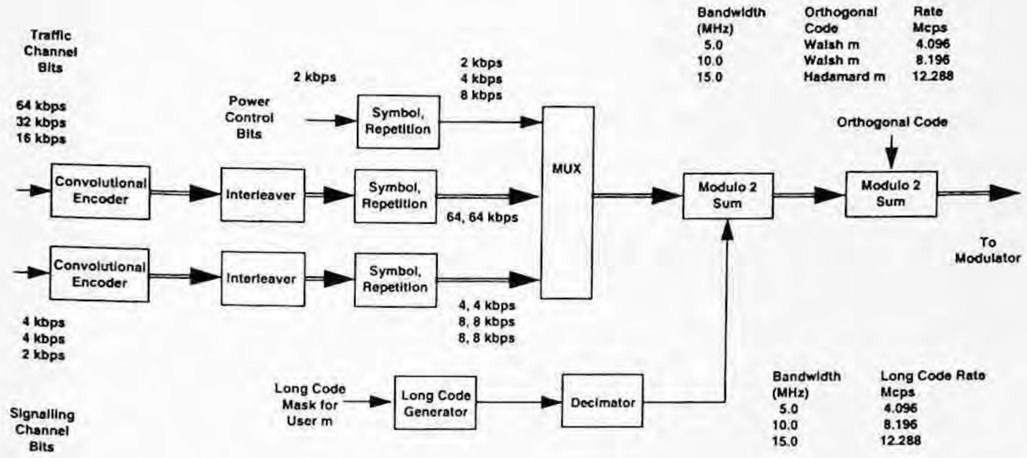


Figure 5.9 Forward W-CDMA traffic channel.

Table 5.1 Multiplexing Options for Forward CDMA Traffic Channel

Transmit Rate	Primary Traffic (voice or data), bits/frame	Signaling Traffic, bits/frame	Secondary Traffic (data), bits/frame
9600	171	0	0
	80	88	0
	40	128	0
	16	152	0
	0	168	0
	80	0	88
	40	0	128
	16	0	152
	0	0	168
4800	80	0	0
2400	40	0	0
1200	16	0	0

The W-CDMA multiplexes the channel after the symbol repetition and always processes a separate signaling channel. The CDMA system uses a data rate of 9.6 kbps for the traffic channel and the W-CDMA system uses 16, 32, or 64 kbps, depending on the type of voice encoding chosen. Both systems convolutionally encode the data with a rate one-half code (see section 5.6), repeat the symbols, and interleave the data using the same methods as the sync and paging channels. As is done on the paging channel, the CDMA system scrambles the data using the decimated long code. The power control bits are then multiplexed into the data stream. The resultant multiplexed signal is then further scrambled by the decimated long code, modulo-2 added to the Walsh (or Hadamard) code for the channel being used, and sent to the modulator. The long code mask chosen for each channel establishes the voice (or data) privacy for that channel.

5.3.5 Modulator

For the forward channel, the modulator (figure 5.10) is identical for both the CDMA and W-CDMA system. In the next section, we show that the reverse channel modulators are different. The *I* and *Q* signals from each channel (pilot, sync, paging, and traffic) are modulo-2 added to an *I* and *Q* pseudorandom noise sequence (see section 5.7.8 for the PN codes). For the CDMA system, the *I* and *Q* signals are identical, but the *I* and *Q* PN sequences are different. For the W-CDMA system, the *I* and *Q* signals are different and are derived from the processed data from the convolutionally encoded data; the same PN sequence is used for both the *I* and *Q* channels. The *I* and *Q* spread signals are then baseband filtered and the signals from all channels are sent to a linear adder with gain control. The gain control permits the individual channels to have different power levels assigned to them. The CDMA system assigns power levels to different channels depending on the quality of the received signal at a mobile sta-

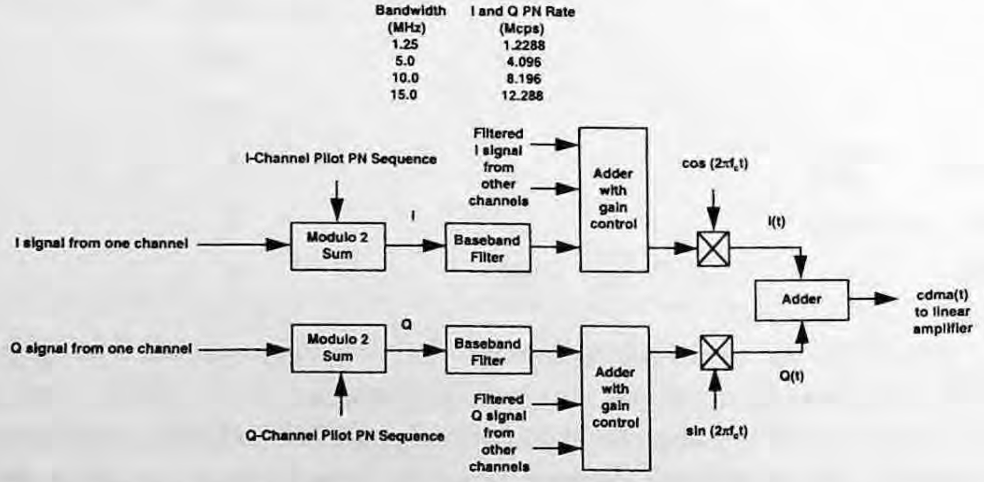


Figure 5.10 Forward CDMA modulator (all bandwidths).

tion. The algorithms for determining the power levels are proprietary to each equipment provider. The *I* and *Q* baseband signals are then modulated by the *I* and *Q* carrier signals, combined together, amplified, and sent to the antenna. The net signal from the CDMA modulator is a quadrature phase shift-signal [5, 6].

The same PN sequence is used on all channels (pilot, sync, paging, and traffic) of the CDMA forward channel. All base stations in a system are synchronized using the global positioning system satellites. Different base stations use time-shifted versions of the PN sequence to permit mobile stations to select the appropriate base station.

5.4 THE REVERSE CDMA CHANNEL

The reverse path from mobile station to base station uses a different frequency band. The reverse CDMA channel is composed of access channels and reverse traffic channels. All mobile stations accessing a base station over an access channel or a traffic channel share the same CDMA frequency assignment using direct sequence CDMA techniques. For CDMA, each traffic channel is identified by a distinct user long code sequence; each access channel is identified by a distinct access channel long code sequence. For W-CDMA, the channel selection is performed using Walsh (or Hadamard) codes similar to the forward channel. Multiple reverse CDMA channels may be used by a base station in a frequency division multiplexed manner.

The designers of the CDMA system assumed that recovery of the pilot signal from the mobiles would be difficult, so an asymmetric channel modulation method is used. On the reverse channel, Walsh functions are not used, but PN functions are used to distinguish the signals from different mobile transmitters. The designers of the W-CDMA system send a pilot signal and believe that they can recover the pilot signal. Therefore, W-CDMA systems uses Walsh (or Hadamard) functions in both directions.

5.4.1 Reverse Access Channel

The reverse access channel (figs. 5.11 and 5.12) is used by the MS to access the CDMA system to respond to pages, make call originations, and process other messages between the MS and the base station. The channel operates at 4.8 kbps for CDMA and 16 kbps for W-CDMA. The information bits are convolutionally encoded (rate 1/3 for CDMA and rate 1/2 for W-CDMA) and processed by symbol repetition and interleav-

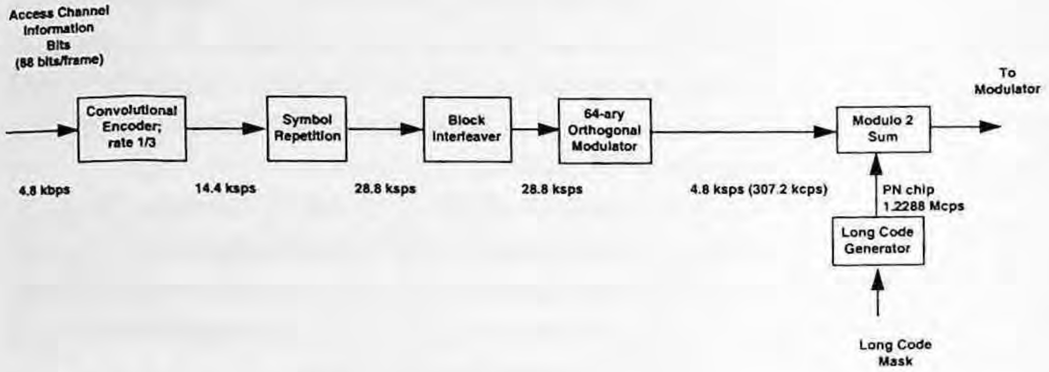
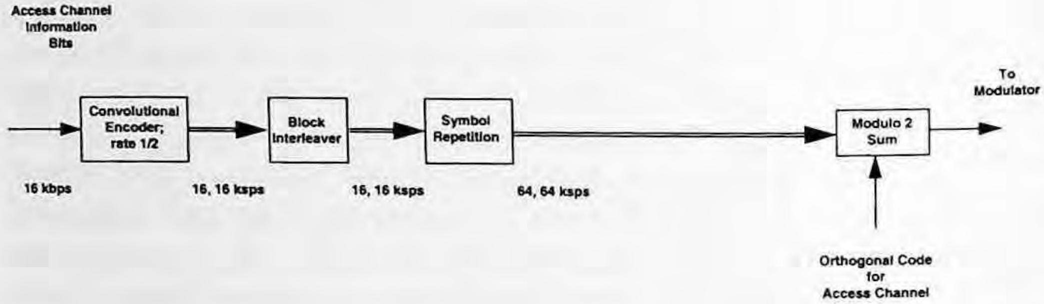


Figure 5.11 Reverse CDMA access channel.



Bandwidth (MHz)	Orthogonal Code Rate Mcps
5.0	4.096
10.0	8.196
15.0	12.288

Figure 5.12 Reverse W-CDMA access channel.

ing functions. As in the forward channel, the order of the repetition and interleaving stages is different for CDMA and W-CDMA. In practice, they could be done in either order as long as the bits are in the correct position after the two stages. The W-CDMA also separately processes the output from each convolutional encoder (as it did on the forward channel). The CDMA and W-CDMA systems operate differently in forming the orthogonal modulation spreading. The CDMA system processes each code symbol through an orthogonal 64-ary modulator generating a Walsh symbol at rate 307.2 kilochips per second (kcps) for each input symbol. It then modulo-2 sums the signal with a PN long code. The long code is chosen by computer simulations to have good orthogonal properties so that the base station can select the MS transmissions. In the W-CDMA system, output of the symbol repetition stage is modulo-2 added to a Walsh (or Hadamard) code for the access channel. The orthogonal properties of the Walsh (or Hadamard) codes is used by the base station to select MS transmissions. The orthogonally spread signal is then sent to the modulator.

5.4.2 Reverse Traffic Channel

For the CDMA system, the primary traffic channel, the secondary traffic channel, and the signaling channel (fig. 5.13) are multiplexed together (see table 5.1 for multiplexing options) and processed by the same covolutional encoder, symbol repetition, interleaver, and 64-ary orthogonal modulator that is used for the access channel. The modulator output is then randomized (to eliminate repetitive 0s and 1s patterns) by blocks of 14 bits taken from the long code. The output of the randomizer is then spread by the long code. The orthogonally spread signal is then sent to the modulator.

For the W-CDMA system, the channel multiplexing is done in the modulator. The output of the traffic channel (encoded speech at 16, 32, or 64 kbps or data at rates up to 64 kbps) is convolutionally encoded, block interleaved, and repeated (if the data rate is less than 64 kbps). The output signal (fig. 5.14) is then modulo-2 summed with the orthogonal code (Walsh or Hadamard) for the traffic channel and sent to the modulator.

For the W-CDMA system, signaling occurs on the traffic channel at either 2 or 4 kbps. The output of the signaling channel (fig. 5.15) is convolutionally encoded, block interleaved, and repeated to generate a symbol rate of 64 kilosymbols per second (ksps). The output signal is then modulo-2 summed with the orthogonal code (Walsh or Hadamard) for the signaling channel and sent to the modulator.

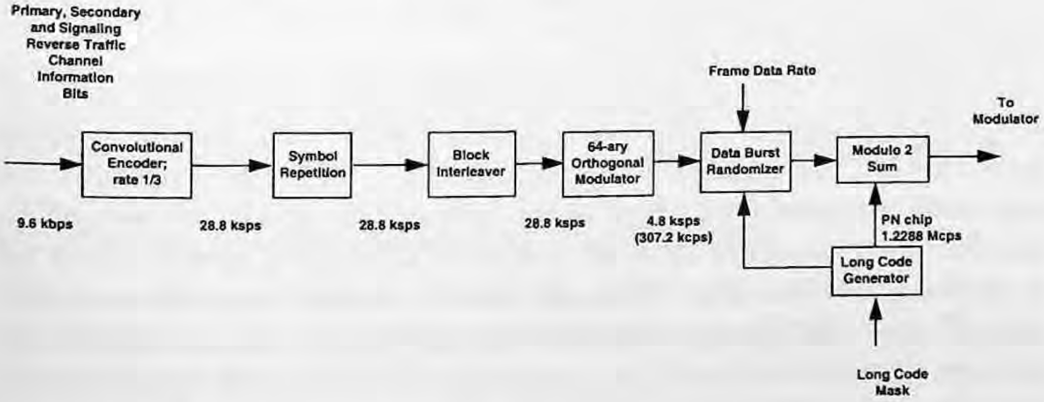


Figure 5.13 Reverse CDMA traffic channel.

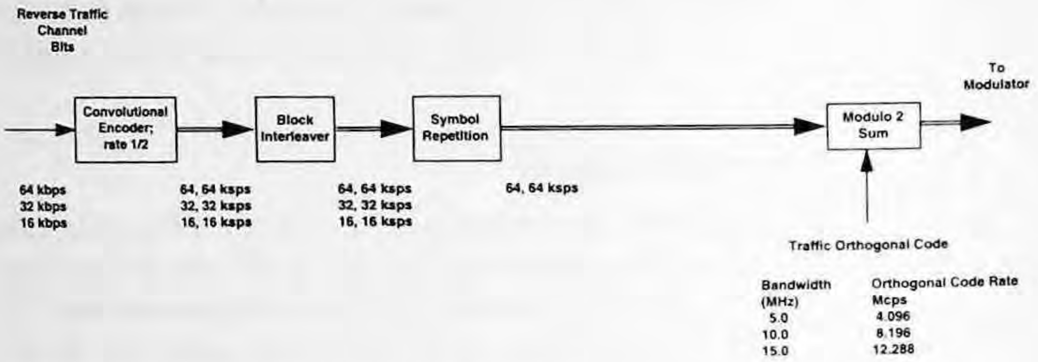


Figure 5.14 Reverse W-CDMA traffic channel.

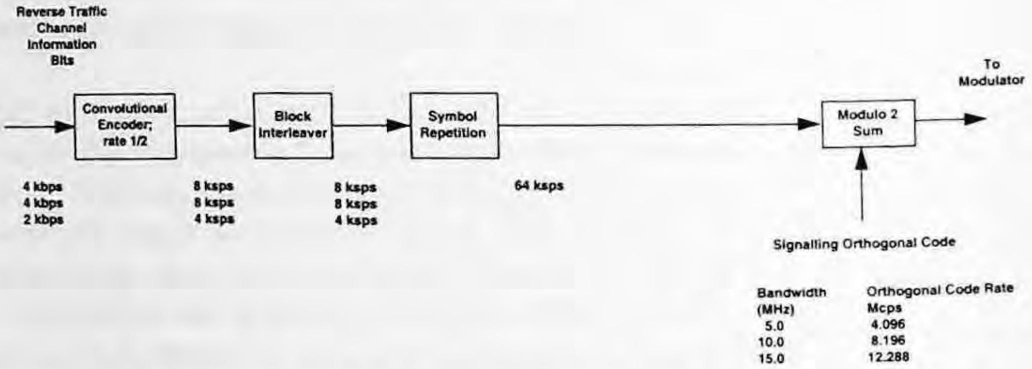


Figure 5.15 Reverse W-CDMA traffic information channel.

5.4.3 Reverse Channel Modulator

Unlike the forward direction, the CDMA and W-CDMA systems use different modulation methods to generate the CDMA signal. The net signal from either CDMA modulator is a four-phase quadrature signal, but the characteristics are different.

For the CDMA system, the output from either the access channel or the traffic channel is sent to two modulo-2 adders, one for the in-phase and one for the quadrature channel (fig. 5.16). Two different PN sequences are modulo-2 added to the data and filtered by a baseband filter. For the quadrature channel, a delay of 1/2 of a PN symbol (406.9 ns) is added before the filter. Thus, the reverse channel uses offset quadrature phase-shift keying (O-QPSK). No pilot signal is transmitted on the reverse channel.

For the W-CDMA system, the in-phase and quadrature signals were separated after convolutional encoding (fig. 5.17). The *I* channel linearly

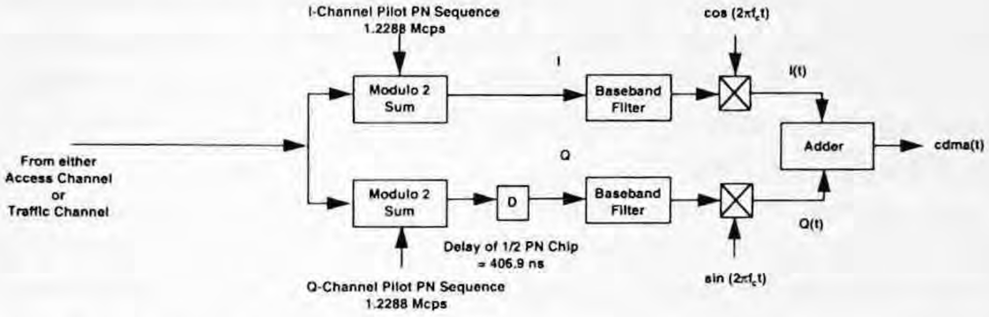


Figure 5.16 Reverse CDMA modulator.

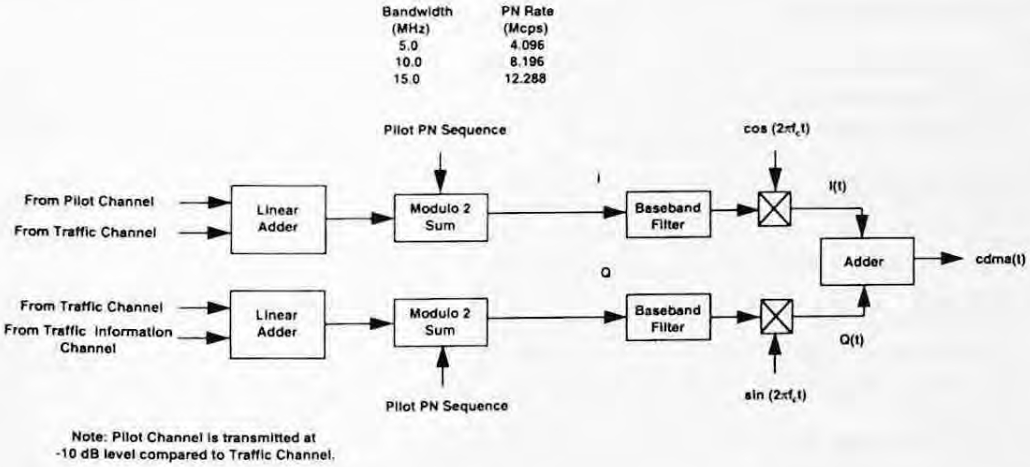


Figure 5.17 Reverse W-CDMA modulator.

adds the traffic channel data and a reduced level pilot channel (–10 dB below the traffic channel). The *Q* channel linearly adds the other traffic channel and the traffic information channel. Both the *I* and the *Q* channels are then modulo-2 summed with the same pilot PN sequence, bandpass filtered, and sent to the modulator. No phase delay is used on the *Q* channel, so the resultant modulation is quadrature phase-shift keying.

5.5 CHANNEL SPACING AND FREQUENCY TOLERANCE

CDMA uses a bandwidth of 1.25 MHz and defines a set of channels on a 50-kHz spacing for J-STD-008 and 30-kHz spacing for IS-95A. Within the assigned cellular and PCS spectrum, any frequencies can be used as long as the signal remains within the assigned spectrum for a service provider. Since mobile stations must know where to listen for base sta-

The base station is the master reference for the CDMA system, and it must maintain its frequency to within ±5 parts per 100 million (±100 Hz at 2000 MHz). The MS must maintain its transmit carrier frequency 80 MHz ± 150 Hz below the base station frequency for PCS frequencies and 45 MHz ± 300 Hz below the base station frequency for cellular frequencies.

For W-CDMA, a 5-MHz band will use a single 5-MHz W-CDMA system. A 15-MHz spectrum will use either one 15-MHz system, one 10-MHz and one 5-MHz system, or three 5-MHz systems.

The W-CDMA base station transmitter must maintain its frequency to within ± 5 parts per 100 million (± 100 Hz at 2000 MHz). The MS transmit carrier frequency will be 80 MHz (± 200 Hz) below the corresponding base station transmit signal.

5.6 POWER CONTROL IN CDMA

The CDMA system defines three power classes at cellular frequencies and five power classes at PCS frequencies (see tables 5.6 and 5.7) for MSs. The MS attempts to control the power output based on received signal strength (open loop control), and the base station sends power control messages to the MS about once every millisecond (closed loop control). The net effect is to control the power received at the base station to within 1 dB for all MSs being received at that base station. The fine level of power control is necessary for proper operation of the CDMA system.

The base station can also vary its transmitted power by ± 4 dB depending on the error rates reported by the mobile station [5]. The mobile station can report frame error rates (as measured on the forward traffic channel) by sending either a power measurement report message (either rate set) or by setting the erasure indicator bit (for rate set 2 only) as described in TSB-74 [7]. Details on how the base station uses reported error rates to control power is proprietary to an equipment vendor's design.

Table 5.6 Maximum Effective Isotropic Radiated Power for a Cellular CDMA MS. (Reproduced under written permission of the copyright holder [TIA].)

Mobile Station Class	EIRP at Maximum Output Shall Exceed	EIRP at Maximum Output Shall Not Exceed
I	+1 dBW (1.25 W)	+8 dBW (6.3 W)
II	–3 dBW (0.5 W)	+4 dBW (2.5 W)
III	–7 dBW (0.2 W)	0 dBW (1.0 W)

Table 5.7 Maximum Effective Isotropic Radiated Power for a PCS CDMA MS. (Reproduced under written permission of the copyright holder [TIA].)

Mobile Station Class	EIRP at Maximum Output Shall Exceed	EIRP at Maximum Output Shall Not Exceed
I	–2 dBW (0.63 W)	3 dBW (2.0 W)
II	–7 dBW (0.20 W)	0 dBW (1.0 W)
III	–12 dBW (63 mW)	–3 dBW (0.5 W)
IV	–17 dBW (20 mW)	–6 dBW (0.25 W)
V	–22 dBW (6.3 mW)	–9 dBW (0.13 W)

The W-CDMA system defines three power classes of PCS mobile stations (see table 5.8).

Table 5.8 Maximum Effective Isotropic Radiated Power for W-CDMA MS. (Reproduced under written permission of the copyright holder [TIA].)

Mobile Station Class	EIRP at Maximum Output Shall Exceed
I	23 dBm (200 mW)
II	13 dBm (20 mW)
III	3 dBm (2 mW)

The CDMA mobile station gates its power on and off depending on the data to be transmitted. This feature is useful for voice-encoded data to improve system performance since the transmitter will not be on during gaps in speech. When the transmitter is gated off, it must reduce its power by 20 dB. If the 20-dB reduction would be below the noise floor of the transmitter, it is permitted to gate the transmitter off to the power level of the noise floor of the transmitter.

When an MS attempts an access on the reverse channel, it must transmit at a power level of

$$P = P_{\text{mean}} + \text{NOM\_PWR} + \text{INT\_PWR} - \text{P\_CNST dBm} \tag{5.1}$$

where P_{mean} = the mean input power of the MS transmitter;
NOM_PWR = the nominal correction factor for the base station, as defined in the overhead message;
INT_PWR = the correction factor for the base station from partial path loss decorrelation between transmit and receive frequencies, as defined in the overhead message;
P_CNST = 73, a constant.

If the access is not successful, the MS will increase its power by PWR_STEP (as defined on the overhead message), remember the total number of unsuccessful accesses it has made (and the sum of all corrections called access probe corrections), and try again, if necessary. It will continue, until it is successful or the process is stopped by the access attempt procedures (see chapter 7). If the maximum power is reached, the MS maintains that maximum power.

When the MS transmits on the reverse traffic channel, it uses a power of

$$\begin{aligned} P = \ & P_{\text{mean}} + \text{NOM\_PWR} + \text{INT\_PWR} - \text{P\_CNST} \\ & + \text{sum of all access probe corrections dBm} \end{aligned} \tag{5.2}$$

Once communication with the base station occurs, the base station will measure the received signal strength and send closed loop power control messages. Then the power output of the MS will be

$$\begin{aligned} P = \ & P_{\text{mean}} + \text{NOM\_PWR} + \text{INT\_PWR} - \text{P\_CNST} \\ & + \text{sum of all access probe corrections} \\ & + \text{sum of all closed loop power control corrections dBm} \end{aligned} \tag{5.3}$$

The ranges and typical values for the power control parameters are

$$-8 < \text{NOM\_PWR} < 7 \text{ dB} \tag{5.4}$$

$$\text{Typical NOM\_PWR} = 0 \text{ dB} \tag{5.5}$$

$$-16 < \text{INIT\_PWR} < 15 \text{ dB} \tag{5.6}$$

$$\text{Typical INIT\_PWR} = 0 \text{ dB} \tag{5.7}$$

$$0 < \text{PWR\_STEP} < 7 \text{ dB} \tag{5.8}$$

The values of these parameters for each base station are transmitted on the forward channel in the Access Parameters message (see chapter 7).

The base station transmits separate power control bits for each of the MS transmitting on the reverse channel. When an MS receives a power control bit, it will increase or decrease its power by 1 dB (bit value of 0 = increase; bit value of 1 = decrease). The MS will maintain a cumulative sum of all received power control bits to determine the correct power output to use. The total range of power control is ±24 dB around the open loop estimated power.

The base station power is limited to 1640 W of effective isotropic radiated power (EIRP) in any direction in a 1.25-MHz band for antenna heights above average terrain (HAAT) less than 300 m. When the base station antenna height exceeds 300 m, the EIRP must be reduced according to current FCC rules.

For PCS frequencies, the base station power output in any direction should not exceed 100 W.

For the W-CDMA system,

$$\text{P\_CNST} = -61 \tag{5.9}$$

$$-47 < \text{INIT\_PWR} < 11\ \text{dB} \tag{5.10}$$

$$\text{Typical INIT\_PWR} = 0\ \text{dB} \tag{5.11}$$

No range for the nominal power (NOM_PWR) is specified. Its value is obtained from the forward overhead channel parameters.

5.7 MODULATION PARAMETERS

In sections 5.2 and 5.3, we discussed the various modulation stages and their order in processing the different bit steams on the forward and reverse channels. In this section, we will describe each of the modulation stages in more detail.

5.7.1 Convolutional Encoding

With convolutional encoding (see fig. 5.18), the encoded output is a function of the input bit stream and delayed versions of the bit stream:

$$c(t) = \sum_{n=0}^{N-1} a_n i(t - n\tau) \tag{5.12}$$

where $i(t)$ = information bit stream,
$c(t)$ = output bit stream,
a_n = coefficient (0 or 1) to specify the addition of the delayed version of $i(t)$,
τ = bit symbol duration, and
N = length of the code.

The coefficients a_n are often written as a generator function

$$g = \left[a_0\ a_1\ \dots\ a_{N-2}\ a_{N-1}\right] \tag{5.13}$$

or generator polynomial

$$g(x) = a_0x^0 + a_1x^1 + a_2x^2 + \dots + a_{N-1}x^{N-1} \tag{5.14}$$

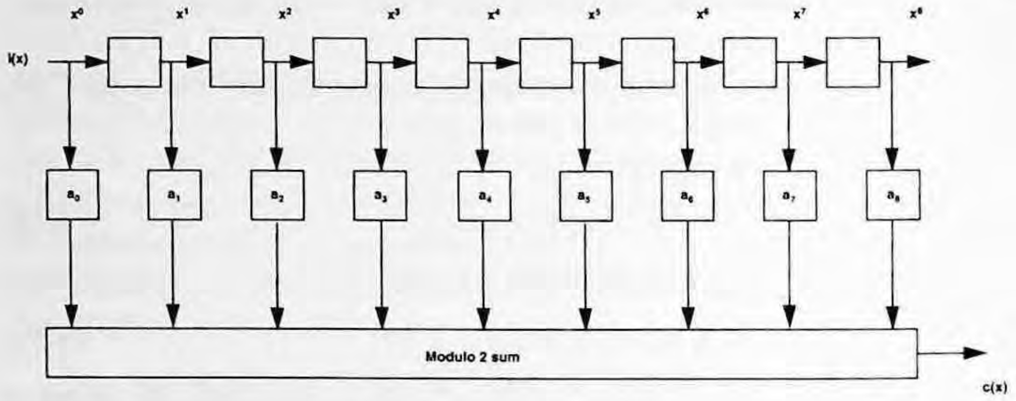


Figure 5.18 Block diagram of convolutional encoder.

For the CDMA MS, a rate one-third convolutional code is used, where three output bits are generated for each input bit. Thus, for an input signal $i(t)$, the output is

$$\begin{aligned} c_0(t) &= g_0(t) \bullet i(t) \\ c_1(t) &= g_1(t) \bullet i(t) \\ c_2(t) &= g_2(t) \bullet i(t) \end{aligned} \tag{5.15}$$

where three bits c_0, c_1, and c_2 are transmitted in sequence, at three times the information rate, for each bit into the encoder.

The generator codes are

$$\begin{aligned} g_0 &= \begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \end{bmatrix} \\ g_1 &= \begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \\ g_2 &= \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{5.16}$$

For the base station, a rate one-half code is used, with generator codes of

$$\begin{aligned} g_0 &= \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \\ g_1 &= \begin{bmatrix} 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{5.17}$$

For the W-CDMA system, a rate one-half code is used in both directions with generator codes specified in equation (5.17). However, the output of the two bit streams is processed in parallel and carried through to further modulation stages as two parallel bit streams.

5.7.2 Bit Repetition

The nominal data rate on the forward and reverse CDMA channels is 9600 bps. If data are being transmitted at a lower rate (4800, 2400, or 1200 bps), then the data bits are repeated *n* times to increase the rate to 9600 bps.

For the W-CDMA system, the nominal data rate is 64 kbps. Therefore any channel-transmitting data at less than 64 kbps are rate multiplied up to a constant 64-kbps rate.

5.7.3 Block Interleaving

The communications over a radio channel are characterized by deep fades that can cause large numbers of consecutive errors. Most coding systems perform better on random data errors rather than on blocks of errors. By interleaving the data, no two adjacent bits are transmitted near to each other, and the data errors are randomized. The specifics of the interleaver are specified in the respective standards and are not reproduced here.

For CDMA, the interleaver spans a 20-ms frame. In the reverse direction, the output of the interleaver is a fixed 28.8 ksps. If the data rate is 9.6 kbps, the resultant signal transmits with a 100 percent duty cycle. If the data rate is lower (4800, 2400, or 1200 bps), the interleaver plus the randomizer (see the next section) deletes redundant bits and transmits with a lower duty cycle (50, 25, 12.5 percent). Thus, bits are not repeated on the reverse CDMA traffic channel. On the access channel, the data bits are repeated. In the forward direction, the nominal data rate is 19.2 kbps, and lower data rates use a lower duty cycle.

For the W-CDMA system (at all three bandwidths), the block interleaver span is 5 ms (the traffic channel spans of 10 and 20 ms are supported as options). Different interleaver matrices are used for different channels. All channels operate at a constant 64-kbps rate.

As noted in sections 5.2 and 5.3, the CDMA and W-CDMA systems differ in the order of repetition and interleaving.

5.7.4 Randomizing

For the CDMA system only, and only on the reverse traffic channel, the output of the interleaver is processed by a data randomizer. The randomizer removes redundant data blocks generated by the code repetition. It uses a masking pattern determined by the data rate and the last 14 bits of the long code. For each 20-ms block (192 bits at 9600 bps), the data randomizer segments the block into 16 blocks of 1.25 ms. At a data rate of 9600 bps, all blocks are filled with data. At a data rate of 4800 bps, 8 of the 16 blocks are filled with data in a random manner. Similarly, for 2400 and 1200 bps, 4 of the 16 and 2 of the 16 blocks, respectively, are randomly filled with data. Thus, no redundant data are sent over the reverse channel.

The W-CDMA system does not use a randomizer in either direction.

5.7.5 Orthogonal Codes

In the forward direction for both CDMA systems and in the reverse direction for the W-CDMA system, the data streams are modulo-2 added to an orthogonal code. The orthogonal code is 1 of 64 Walsh functions for CDMA and 1 of 256 Walsh functions for W-CDMA at 5-MHz bandwidth. At 10-MHz bandwidth, the code is 1 of 512 Walsh codes, and at 15-MHz bandwidth, the code is 1 of 768 Hadamard codes. All codes are orthogonal to each other (see chapter 2 for a more detailed discussion of the orthogonal codes).

For the reverse W-CDMA channel, the orthogonal code is the modulo-2 sum of the Walsh or Hadamard codes and the long code (see fig. 5.19).

5.7.6 64-ary Orthogonal Modulation

For the CDMA system only, and only on the reverse channel, the data stream is modulated by a 64-ary orthogonal modulator. For each six

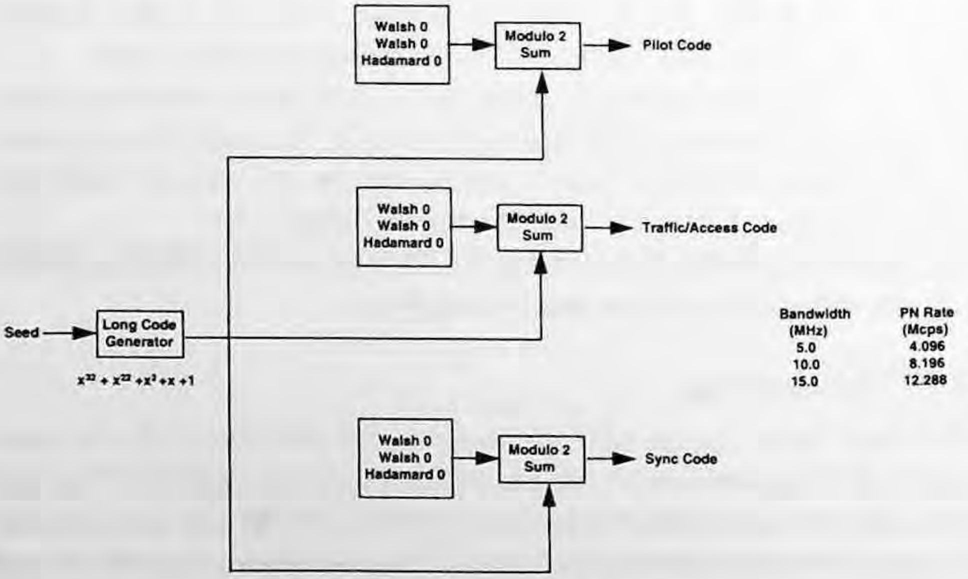


Figure 5.19 Orthogonal code generation for W-CDMA.

input symbols to the modulator, one output Walsh function is generated. The output Walsh function is defined by

$$W_i = c_0 + 2c_1 + 4c_2 + 8c_3 + 16c_4 + 32c_5 \tag{5.18}$$

where c_5 is the most recent and c_0 the oldest of the 6 bits to be transmitted and W_i is chosen from 1 of 64 orthogonal Walsh functions.

The W-CDMA system does not use this step.

5.7.7 Long Codes

Prior to the modulation stage, the reverse CDMA signal is spread by a long code at a rate of 1.2288 Mcps. The long code has a length of $2^{42} - 1$ bits and is generated by the following polynomial:

$$\begin{aligned} l(x) = {} & x^{42} + x^{35} + x^{31} + x^{27} + x^{26} + x^{25} + x^{22} + x^{21} + x^{19} + \\ & x^{18} + x^{17} + x^{16} + x^{10} + x^{7} + x^{6} + x^{5} + x^{3} + x^{2} + x + 1 \end{aligned} \tag{5.19}$$

The output of the long code generator is modulo-2 added with a 42-bit long code mask to generate the long code. The mask depends on the channel used (access or traffic) and the information on the MS transmitting the data. On the traffic channel, either a public or private long code mask is used. The public mask is a function of the electronic serial number of the MS. The private long code mask is generated by a secret algorithm used for voice and data privacy. On the access channel, the long code mask is generated by combinations of data associated with the access channel.

Time alignment of the long code is generated by defining time equal to zero to be January 6, 1980 at 00:00:00 UTC.

5.7.8 Direct PN Spreading

Both the CDMA and W-CDMA systems modulate the processed data stream with a pseudorandom noise spreading sequence at the fundamental rate for the system (1.2288, 4.096, 8.192, or 12.288 Mcps).

For the forward and reverse CDMA system, the following codes are used to generate the PN sequence:

$$g_I(x) = x^{15} + x^{13} + x^{9} + x^{8} + x^{7} + x^{5} + 1 \tag{5.20}$$

$$g_Q(x) = x^{15} + x^{12} + x^{11} + x^{10} + x^{6} + x^{5} + x^{4} + x^{3} + 1 \tag{5.21}$$

For the W-CDMA system, the following code is used for both the *I* and the *Q* channels:

$$g(x) = x^{32} + x^{22} + x^{2} + x + 1 \tag{5.22}$$