AN OVERVIEW OF THE APPLICATION OF CODE DIVISION MULTIPLE ACCESS (CDMA) TO DIGITAL CELLULAR SYSTEMS AND PERSONAL CELLULAR NETWORKS

May 21, 1992

Notice: This document is an updated and retitled version of "Introduction to CDMA and the Proposed Common Air Interface Specification (CAI) for a Spread Spectrum Digital Cellular Standard: An Overview of the Application of Code Division Multiple Access (CDMA) to Digital Cellular Systems and Personal Cellular Networks" that was submitted to TIA TR45.5 Subcommittee on March 28, 1992.

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FIGURES

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1.0 INTRODUCTION

1.1 Document Objectives and Scope

This document provides an overall understanding of the Code Division Multiple Access (CDMA) system design that QUALCOMM has developed for digital cellular applications and facilitates comprehension of the governing proposed "Wideband Spread Spectrum Digital Cellular System Dual-Mode Mobile Station – Base Station Compatibility Standard."

QUALCOMM firmly believes that its CDMA approach is the candidate for the second generation of cellular systems most capable of providing spectrum efficient, economical, and quality digital cellular/PCN services with low cost portable-pocket phones. To verify this belief, QUALCOMM designed, developed, and tested the CDMA system; including as a part of the overall development activities, the VLSI chip sets for the CDMA system subscriber equipment and the base station channel elements. A prototype CDMA digital cellular system consisting of six cell sites (nine sectors) and 70 mobile stations was also developed and tested extensively in San Diego in conjunction with many cellular operators, network manufacturers, and mobile manufacturers.

This document includes different levels of depth to provide a gradual approach into the details of CDMA. Following this introduction, Section 2 provides a conceptual look at CDMA and its application as a multiple access scheme followed by a discussion of the proposed standard, its contents, and format. Section 3 gives a general overview of the CDMA system and its relationship to the cellular frequency allocations in the United States. Attributes of the CDMA system and its features are also highlighted in Section 3.

Section 4 provides a more detailed look at the system structure, layering, signaling, call processing, functional description and generic system design. Section 4 also includes details of the features highlighted in Section 3. Section 5 gives an overview of the extensive CDMA Validation Test that started last year and is still underway in San Diego. This test, which included widespread industry participation, has shown the viability of CDMA in an extensive field trial. Although the tests are still underway, all the major features of CDMA have been demonstrated. The results of these tests are summarized in Section 5.

1.2 CTIA Requirements and TIA Standards

In September 1988, the Cellular Telecommunications Industry Association (CTIA) released the *Users' Performance Requirements* (UPR) document which specified the cellular carriers' requirements for the next generation cellular technology. These requirements for digital technology include:

- 10-fold increase over analog system capacity
- Long life and adequate growth of second generation technology
- Ability to introduce new features
- Quality improvements
- Privacy
- Ease of transition and compatibility with existing analog system
- Early availability and reasonable costs for dual mode radios and cells
- Cellular Open Network Architecture (CONA)

During 1989, the TIA TR-45.3 Subcommittee on Digital Cellular Systems, a committee of the Telecommunications Industry Association (TIA), formulated the EIA/TIA/IS-54, *Dual-Mode Subscriber Equipment - Network Equipment Compatibility Specification*. The TR-45.3 Subcommittee adopted Time Division Multiple Access, or TDMA, as the air interface radio channel access scheme for traffic channel transmissions. This decision was made prior to QUALCOMM's introduction of CDMA digital cellular technology.

With extensive cellular industry support, QUALCOMM has developed a CDMA system completely compliant with the CTIA requirements. On December 5, 1991, at the CTIA's "Presentations of the Results of the Next Generation Cellular Field Trials," QUALCOMM, along with a number of participating carriers and manufacturers, presented the results of the successful field trials of the CDMA digital cellular validation system. The field trials were conducted publicly with the support and the participation of a large number of major cellular carriers and manufacturers. The infrastructure equipment manufacturers involved in the CDMA development activities include AT&T, MOTOROLA, and most recently Northern Telecom. The subscriber equipment manufacturers include MOTOROLA, OKI Telecom, Clarion, Sony, Alps Electric, Nokia, and most recently Matsushita-Panasonic. The carriers that are taking part in the CDMA digital cellular validation efforts are PacTel Cellular, Ameritech Mobile, NYNEX Mobile, GTE Mobile Communications, Bell Atlantic Mobile Systems, US West NewVector Group, and Bell Cellular of Canada.

Following the CTIA presentations made on December 5, 1991, on January 6, 1992, the CTIA Board of Directors unanimously adopted a resolution that among other things includes the following: "CTIA further requests that Telecommunications Industry Association (TIA) prepare 'structurally' to accept contributions regarding wideband (cellular systems). This should be a separate effort not diluting the IS-54 revision process." On February 11, 1992, the TIA's Cellular and Common Carrier Radio Section, unanimously adopted a motion that recommends that the TR45 Committee address standardization activities regarding wideband spread spectrum digital technologies. It further recommended that the TR45 Committee consider a subcommittee structure that would not dilute the IS-54 revision process. Based on the above recommendations from CTIA and TIA, and more specifically in responding to the needs of the user and service provider communities, at a March 5, 1992, meeting of Committee TR 45, a new subcommittee, namely TR45.5, was formed to develop spread spectrum digital cellular standards.

This system was extensively tested and as a result, the system interface specification is being submitted as a candidate for the Wideband Spread Spectrum Digital Cellular System Dual-Mode Mobile Station- Base Station Compatibility Standard.

2.0 THE CDMA CONCEPT

CDMA is a modulation and multiple access scheme based on spread spectrum communication, a well-established technology that has been applied only recently to digital cellular radio communications and advanced wireless technologies. The approach will solve the near-term capacity concerns of major markets and the industry's long-term need for an economic, efficient, and truly portable communications.

Ever since the second pair of wireless telegraphs came into existence, we have been confronted with the problem of multiple access to the frequency spectrum without mutual interference. In the early days of wireless telegraphy, both frequency division in the form of resonant antennas, time division in the form of schedules, and netted operations were employed. As the number of wireless radios in operation increased and as the technology allowed, it became necessary to impose some discipline on the process in the form of frequency allocations. This has grown over the years to the complex process we have today for world-wide frequency allocations and licensing by service type.

The multiple access problem can be thought of as a filtering problem. There are as many simultaneous users that want to use the same electromagnetic spectrum and there is a choice of an array of filtering and processing techniques which allow the different signals to be separately received and demodulated without excessive mutual interference. The techniques that have long been used include: propagation mode selection, spatial filtering with directive antennas, frequency filtering, and time sharing. Over the last 40 years, techniques involving spread spectrum modulation have evolved in which more complex waveforms and filtering processes are employed.

Propagation mode selection involves a proper choice of operating frequency and antenna so that signals propagate between the intended communicators but not between (very many) other communicators. Frequency reuse in cellular mobile telephone systems is an example of this technique carried to a great degree of sophistication.

Spatial filtering uses the properties of directive antenna arrays to maximize response in the direction of desired signals and to minimize response in the direction of interfering signals. The current analog cellular system uses sectorization to a good advantage to reduce interference from co-channel users in nearby cells.

With FDMA, a channel is a relatively narrow band in the frequency domain into which a signal's transmission power is concentrated. Different signals are assigned different frequency channels. Interference to and from adjacent channels is limited by the use of bandpass filters which pass signal energy within the specified narrow frequency band while reject signals at other frequencies. The analog FM cellular system uses FDMA.

FDMA spectral efficiency in a cellular system is determined by the modulation spectral efficiency (the information bit rate per Hertz of bandwidth) and the frequency reuse factor. The U.S. analog cellular system, divides the allocated spectrum into 30 kHz bandwidth channels; narrowband FM modulation is employed, resulting in a modulation efficiency of 1 call per 30 kHz of spectrum. Because of interference, the same frequency cannot be used in every cell. The frequency reuse factor is a number representing how often the same frequency can be reused. To provide acceptable call quality, a Carrier-to-Interference ratio

(C/I) of 18 dB or greater is needed. Empirical results have shown that in most cases this level of C/I requires a reuse factor of seven. The resulting capacity is one call per 210 kHz of spectrum in each cell. Note that by increasing the number of cells, an arbitrarily high capacity can be obtained, but with increased equipment costs. In addition, there also is a cost of increasing handoff rates as mobile stations move through smaller coverage areas.

With TDMA, a channel consists of a time slot in a periodic train of time intervals making up a frame. A given signal's energy is confined to one of these time slots. Adjacent channel interference is limited by the use of a time gate that only passes signal energy which is received at the proper time. Some systems use a combination of FDMA and TDMA. The TIA proposed EIA/TIA/IS-54-B digital cellular standard uses 30 kHz FDMA channels which are subdivided into six time slots for TDMA transmissions. Two time slots are required for each call when employing 8 kbps vocoders.

TDMA spectral efficiency is determined in a manner similar to that used for FDMA. The EIA/TIA/IS-54-B TDMA standard provides a basic modulation efficiency of three voice calls per 30 kHz of bandwidth. The currently accepted frequency reuse criteria is similar to the analog design. The resulting capacity is one call per 70 kHz of spectrum or three times that of the analog FM system.

With CDMA, (see Figure 2-1) each signal consists of a different pseudorandom binary sequence that modulates the carrier, spreading the spectrum of the waveform. A large number of CDMA signals share the same frequency spectrum. If CDMA is viewed in either the frequency or time domain, the multiple access signals appear to be on top of each other. The signals are separated in the receivers by using a correlator which accepts only signal energy from the selected binary sequence and despreads its spectrum. The other users' signals, whose codes do not match, are not despread in bandwidth and as a result, contribute only to the noise and represent a self-interference generated by the system.

The increased signal-to-noise ratio for the desired signal is shown in Figure 2-2. The signal-to-interference ratio is determined by the ratio of desired signal power to the sum of the power of all the other signals, and is enhanced by the system processing gain or the ratio of spread bandwidth to baseband data rate. As discussed in Section 3, the major parameters that determine the CDMA digital cellular system capacity are processing gain, required E_b/N_0, voice duty cycle, frequency reuse efficiency, and the number of sectors in the cell.[1] The CDMA cellular telephone system achieves a spectral efficiency of up to 20 times the analog FM system efficiency when serving the same area with the same antenna system. This is a capacity of up to one call per 10 kHz of spectrum.

In the cellular radio frequency reuse concept, interference is accepted but controlled with the goal of increasing system capacity. CDMA does this effectively because it is inherently an excellent anti-interference waveform. Since all calls use the same frequencies, CDMA

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[1] E_b/N_0 is defined as the bit energy to noise power spectral density: comparable to C/I.

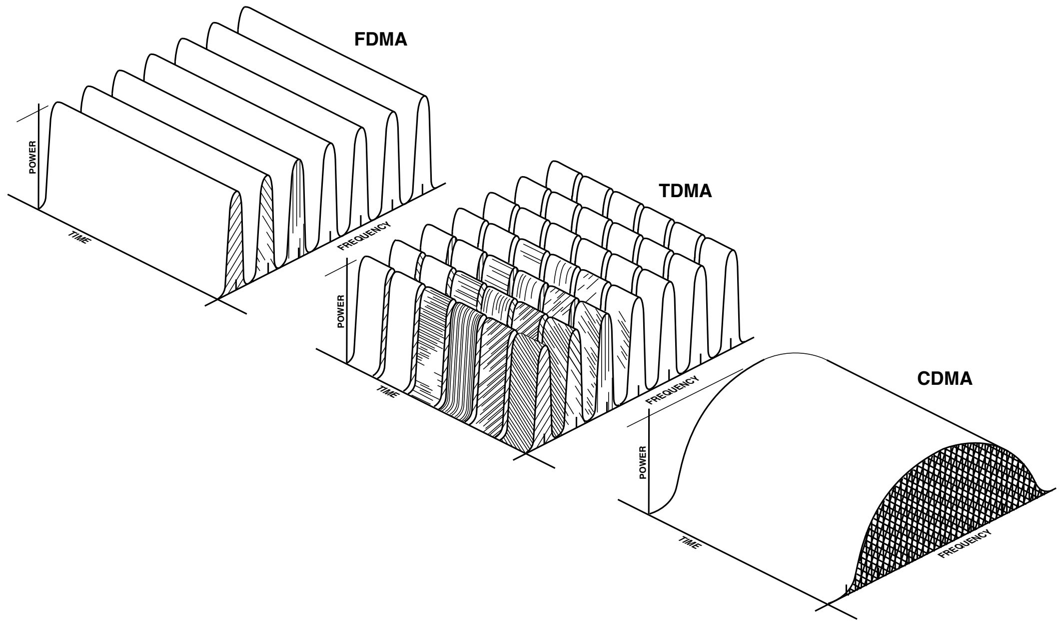

Figure 2-1. Frequency and Time Domain Representations of FDMA, TDMA, and CDMA*. Unlike FDMA or TDMA, CDMA has multiple users simultaneously sharing the same wide band channel. Individual users are selected by correlation processing of the pseudonoise waveform.*

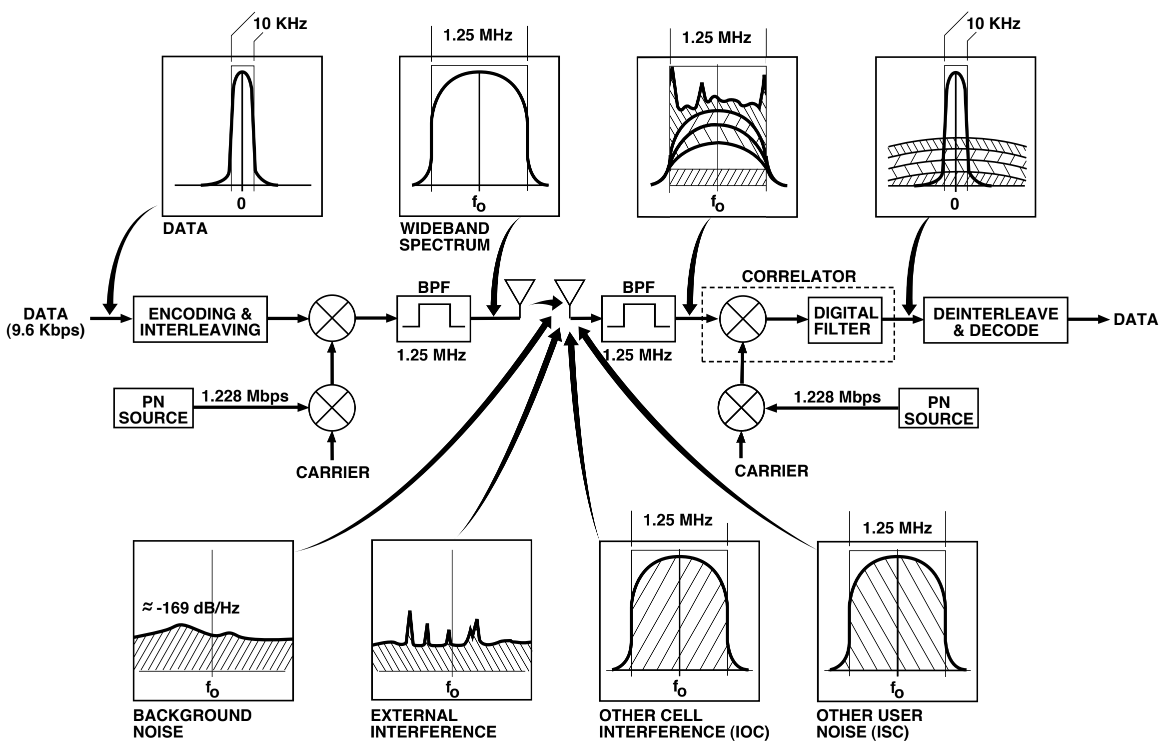

Figure 2-2. A View of the CDMA Concept. *The desired signal is selected from four different sources of interference. The dominant source is system self-interference produced by other users of the same cell. This source is controlled by closed loop power control.*

frequency reuse efficiency is determined by a small reduction in the signal-to-noise ratio caused by system users in neighboring cells. CDMA frequency reuse efficiency is approximately 2/3 compared to 1/7 for narrowband FDMA systems. The CDMA system can also be a hybrid of FDMA and CDMA techniques where the total system bandwidth is divided into a set of wideband channels, each of which contains a large number of CDMA signals.

2.1 CDMA System Overview

The multiple access scheme exploits isolation provided by the antenna system, geometric spacing, power gating of transmissions by voice activity, power control, and very efficient modem and a signal design which uses error correction coding.

A combination of open loop and closed loop power control (through measurements of the received power at the mobile station and the base station) commands the mobile station to make power adjustments in order to maintain only the power level required for adequate performance. This minimizes interference to other users, helps to overcome fading, and conserves battery power in the mobile station.

The CDMA digital cellular waveform design uses a Pseudorandom Noise (PN) spread spectrum carrier. The chip rate of the PN spreading sequence was chosen so that the resulting bandwidth is about 1.25 MHz after filtering or approximately one-tenth of the total bandwidth allocated to one cellular service carrier.

The Federal Communications Commission (FCC) has allocated a total of 25 MHz for mobile station to cell site and 25 MHz for cell site to mobile station for the provision of cellular services. The FCC has divided this allocation equally between two service providers, the A and the B carriers, in each service area. The channel number denotes the FM (30 kHz) channels. Because the FCC increased the cellular frequency allocations, the 12.5 MHz allocated to each carrier for each direction of the link is further subdivided into two subbands. For the B carriers, the subbands are 10 MHz and 2.5 MHz each. For the A carriers, the subbands are 11 MHz and 1.5 MHz each. A signal bandwidth of less than 1.5 MHz fits into any of the subbands, while a bandwidth of less than 2.5 MHz fits into all but one subband.

A set of ten 1.25 MHz bandwidth CDMA channels can be used by each operator if the entire allocation is converted to CDMA. Initially, only one or a small number of 1.25 MHz channels need to be removed from the present FM analog service to provide digital service. This facilitates the deployment by introducing a more gradual reduction in analog capacity. Each 1.25 MHz CDMA segment can provide about twice the capacity of the entire 12.5 MHz allocation using the present FM system. Some frequency guard band is necessary if there are adjacent high power cellular (or other) frequencies in use and the maximum capacity of the CDMA cell is required. Capacity can be sacrificed for decreased guard band if desired. Adjacent CDMA channels need not employ a guard band.

2.2 The CDMA Proposed Standard

The *Wideband Spread Spectrum Digital Cellular System Dual-Mode Mobile Station–Base Station Compatibility Standard*, produced by QUALCOMM is a comprehensive document that specifies the common air interface for a system which uses CDMA technology to provide a very high capacity digital cellular telephone system. The document is structured after the existing EIA/TIA standard documents and has a similar section format and terminology.

Following a July 31, 1990 release, the first draft of the proposed standard was reviewed by many major cellular carriers and network and subscriber equipment manufacturers. On the basis of comments received from the participants actively involved in the development of CDMA, Draft Revision 0.1 of the proposed standard was released on September 11, 1990. Revision 1.0 of the proposed standard, a significant interim release, was released on October 1, 1990. Four subsequent revisions that were each widely reviewed by the cellular industry preceded the document submitted for TIA review. The fundamental system design approach was field tested both before and during the development of the CDMA proposed standard specification. Testing continues today to complete validation of the proposed standard.

A mobile station that complies with the defined specifications can obtain service by communicating with either an analog (FM) base station or with a CDMA base station. The type of system the mobile station operates with depends on the availability of either system in the geographic area of the mobile station as well as the preference of the mobile station. The minimum compatibility requirements for CDMA base stations are specified in the proposed standard. A CDMA-only mobile or base station can be implemented by applying only those specifications that apply to CDMA operation. Minimum performance requirements for dual-mode mobile stations and base stations will be provided in future specifications.

Although the proposed standard includes features only planned for other systems, provisions for future service additions and expansions of system capabilities are included. The flexible architecture defined by the specification permits such expansion without the loss of backward compatibility with older mobile stations.

An inherent characteristic of an analog/digital dual-mode document is the specification of two separate modes of operation that co-exist (or can co-exist) as one functional unit. Though the individual modes can exist alone, the goal is to provide compatibility to the existing analog mode and the new digital mode. This facilitates transition from one technology to the other and will continue to allow roaming with existing systems that have not deployed newer digital technologies. The CDMA architecture is not a forced extension of the analog architecture but is an innovative design that substantially increases spectral efficiency while providing many other benefits. Due to CDMA's autonomous nature, each mode operates virtually independent of the other. For this reason, the proposed standard document structure separates the analog (FM) and digital (CDMA) sections.

The proposed standard specifies that mobile stations operating with analog base stations meet the analog compatibility provisions for mobile stations as specified in EIA/TIA/IS-54-B, *Dual-Mode Mobile Station – Base Station Compatibility Specification,* January 1992. The incorporation of the analog portions of EIA/TIA/IS-54-B instead of EIA/TIA-553 (*Mobile Station – Land Station Compatibility Specification*, September 1989) accommodates all the changes to analog operation imposed by the new EIA/TIA/IS-54-B dual-mode standard.

In the event of conflict between the requirements of EIA/TIA/IS-54-B and the proposed standard, the requirements of the proposed standard take precedence. A document equivalent to IS-55, which specifies recommended minimum standards for mobile stations, will be supplied for CDMA-analog dual-mode subscriber units. Furthermore, mobile stations operating with analog base stations also comply with the provisions of EIA/IS-19, *Recommended Minimum Standards for 800 MHz Cellular Subscriber Units*, where applicable.

3.0 CDMA SYSTEM BENEFITS

This section highlights some of the major attributes of the digital cellular system developed by QUALCOMM and briefly describes the features, summarized in Table 3-1, that provide these benefits. While the CDMA system employs dual-mode subscriber units to provide compatibility with the analog system, only the features peculiar to CDMA are discussed here. More detailed descriptions of the system and its functionality are contained in Section 4.

3.1 Multiple Forms of Diversity

In relatively narrowband modulation systems such as analog FM modulation employed by the first generation cellular phone system, the existence of multiple paths causes severe fading. With wideband CDMA modulations, however, the different paths may be independently received greatly reducing the severity of the multipath fading. Multipath fading is not completely eliminated because multipaths which cannot be independently processed by the demodulator occasionally occur. This will result in some fading behavior.

Diversity is the favored approach to mitigate fading. There are three major types of diversity: time, frequency, and space. Time diversity can best be obtained by the use of interleaving and error correction coding. Wideband CDMA offers a form of frequency diversity by spreading the signal energy over a wide bandwidth; frequency selective fading usually affects only a 200-300 kHz portion of the signal bandwidth. Space or path diversity is obtained three different ways by providing the following:

- Multiple signal paths through simultaneous links from the mobile station to two or more cell sites (soft handoff).
- Exploitation of the multipath environment through spread spectrum processing (rake receiver), allowing signals arriving with different propagation delays to be received separately and combined.
- Multiple antennas at the cell site.

The different types of diversity employed in the CDMA system to greatly improve performance are shown in Figure 3-1 and summarized below:

- Time Diversity - symbol interleaving, error detection, and correction coding
- Frequency Diversity - 1.25 MHz wideband signal
- Space (Path) Diversity - dual cell site receive antennas, multipath rake receivers, and multiple cell sites (soft handoff)

Antenna diversity can easily be provided in FDMA and TDMA systems. Time diversity can be provided in all digital systems that can tolerate the required higher transmitted symbol rate needed to make the required error correction process effective. However, the other methods can only be provided easily with CDMA. A unique feature of direct sequence CDMA is the ability to provide extensive path diversity; the greater the order of diversity in a system, the better the performance in this difficult propagation environment.

Multipath processing takes the form of parallel correlators for the PN waveform. The mobile and cell receivers employ three and four parallel correlators respectively. Receivers using parallel correlators (sometimes called rake receivers) allow individual path arrivals to be tracked independently and the sum of their received signal strengths is then used to demodulate the signal. While there is fading on each arrival, the fades are independent. Demodulation based on the sum of the signals is then, much more reliable.

The multiplicity of correlators is also the basis for the simultaneous tracking of signals from two different cells and allows the subscriber unit to control the soft handoff described in 3.6.

3.2 Power Control in CDMA

To achieve high capacity, quality, and other benefits, the CDMA mobile telephone system employs forward (cell-to-mobile) and reverse link (mobile-to-cell) power control. The objective of the mobile station transmitter power control process is to produce a nominal received signal power from each mobile station transmitter operating within the cell at the cell site receiver. Regardless of a mobile station's position or propagation loss, each mobile station's signal will be received at the cell at the same level. If all the mobile station transmitters within a cell site's area of coverage are so controlled, then the total signal power received at the cell site from all mobile stations is equal to the nominal received power times the number of mobile stations.

Each CDMA receiver at the cell site operates by converting a selected CDMA signal from one of the mobile station transmitters into a signal that carries narrowband digital information. At the same time, the other signals that are not selected remain wide bandwidth noise signals (see Figure 3-1). The bandwidth reduction processing, commonly called processing gain, increases the signal-to-interference ratio (in dB) from a negative value to a level that allows operation with an acceptable bit error rate.

It is very desirable to maximize the capacity of the CDMA system in terms of the number of simultaneous telephone calls that can be handled in a given system bandwidth. The system capacity is maximized if the transmit power of each mobile station is controlled so that its signal arrives at the cell site with the minimum required signal-to-interference ratio.

If a mobile station's signal arrives at the cell site with too low a value of received power, the bit error rate is too high to permit high quality communications. If the received power is too high, the performance of this mobile station is acceptable, but interference to all the other mobile station transmitters that are sharing the channel is increased, and may result in unacceptable performance to other users unless the capacity is reduced.

Reverse link open loop power control, reverse link closed loop power control, and forward link power control are employed in the CDMA system as shown in Figure 3-2. Reverse link open loop power control is primarily a function of the mobile stations. The goal of the open loop portion of reverse link power control is for the mobile station to rapidly adjust transmit power according to changes in received power from the cell. The mobile stations measure the received power level from the cell sites and adjust their transmitter power in an in

Table 3-1. CDMA Features Supporting CTIA's User Performance Requirements

Feature - Description
High Capacity. Field tests in diverse environments have verified the predictions for CDMA in that capacities averaging 15 times greater than analog were achieved under stressed conditions. In terms of Erlangs offered at any grade of service, the advantage is even greater. Finally, if the existing half rate vocoder is used, the capacity increases by a factor of 1.7. Additional sectorization (beyond 3) also increases capacity.
High Quality Service. A variable rate vocoder provides digital voice and highly rated voice reproduction. Background levels are muted even under heavy load. The system independently tracks individual multipath arrivals to greatly reduce the susceptibility to fading. The CDMA soft handoff technique provides a totally transparent handoff of calls. This robust handoff technique virtually eliminates dropped calls and reduces switching loads.
System Evolution. Digital data traffic and paging services are included in the current system. FAX protocols are supported by the existing control structure. Higher data rates can be provided (9.6 kbps is the current level). CDMA-only portables that are compatible with both cellular and PBX operations can meet localized needs.
Ability to Introduce New Features. If desired, a common instrument can access private wireless PBXs, residential cordless, public digital cordless, PCN, and cellular systems; simple interface to ISDN, PBX and PSTN is provided. The digital control signaling provided allows a variety of data services that can be added as the carrier expands the scope of services offered. The variable rate vocoder and data service allow multiple grades of service. Range measurements inherent with the waveform will allow mobile position determination.
Privacy. The digital format, wideband signaling, and addressee-specific traffic protection features provide an unmatched combination of privacy features.
Ease of Transition (and Compatibility with Analog). The initial service using a single CDMA channel and the transfer of the high usage customers to CDMA nearly triples current capacity and provides better service quality for both CDMA and analog users. Capacity and coverage characteristics allow CDMA introduction with far fewer cells than used in current networks. Antenna coverage and sectorization are independent from cell to cell, and not closely dependent as in narrowband systems. Subsequent growth is incremental and can be localized (to provide hot spot coverage) or global. CDMA subscriber units are dual-mode so they can access either CDMA or analog channels.
Availability and Cost. Current estimates of CDMA system costs in terms of network equipment as well as subscriber equipment show them to be equivalent to current analog costs. Capacity improvement allows service with far fewer cell sites than analog/TDMA, reducing installation and operating costs. Proven ASIC technology has reduced the sophisticated signaling technology to very simple manufacturing technology. Mobile subscriber equipment will be available in the third quarter of 92; handheld portables in the first quarter of 93; and infra-structure equipment in the second quarter of 93.
Cellular Open Network Architecture (CONA). Base Station/MTSO interfaces are being addressed that would allow independent development of switch and Base Station equipment.

indirectly proportional manner. Open loop power control attempts to have all mobile station transmitted signals arrive at the cell site with the same nominal power level. The cell site supports the open loop control function by providing a calibration constant to the served mobile stations. The calibration constant is determined primarily by the cell site ERP. Cells that transmit at a higher than nominal ERP must inform their subscribers so the mobile stations will not transmit lower than nominal required power and conversely for low ERP cell sites.

The cell site takes an active role in the reverse link closed loop power control functions. The goal of the closed loop portion is for the cell to provide rapid corrections to the mobile station's open loop estimate to maintain the optimum transmit power. The cell measures the relative received power level of each of the associated mobile station's signals and compares it to an adjustable threshold. A determination is made every 1.25 ms to either transmit a power-up command or a power-down command to the mobile station. This closed loop correction to any variation required in the open loop estimate accommodates gain tolerances and unequal propagation losses between the forward and reverse links.

The cell supports forward link power control by adjusting the forward link power for each subscriber link signal in response to measurements provided by the mobile station. The purpose is to reduce power for units that are either stationary, relatively close to the cell site, impacted little by multipath fading and shadowing effects, or experiencing minimal other cell interference. Thus, extra power can be given to units that are either in a more difficult environment or far away from the cell and experiencing high error rates.

3.3 Low Transmit Power

Besides directly improving capacity, one of the more important results of reducing the required E_b/N_0 (signal-to-interference level) is the reduction of transmitter power required to overcome noise and interference. This reduction means that mobile stations also have reduced transmitter output requirements which reduces cost and allows lower power units to operate at larger ranges than the similarly powered analog or TDMA units. Furthermore, a reduced transmitter output requirement increases coverage and penetration and may also allow a reduction in cells required for coverage.

An even greater gain is the reduction of average (rather than peak) transmitted power that is realized because of the power control used in CDMA. Most of the time propagation conditions are benign. Narrrow band systems must always transmit with enough power to override the occasional fades. CDMA uses power control to provide only the power required at the time, and thus reduces the average power by transmitting at high levels only during fades.

3.4 Vocoder and Variable Data Rates

The vocoder (voice encoder/decoder) in the CDMA system is an 8 kbps variable rate design. The variable data rate two-way voice service option, Service Option 1, provides two-way voice communications between the base station and the mobile station by using a dynamically variable data rate vocoder algorithm. The transmitting vocoder takes voice samples and generates an encoded speech packet for transmission to the receiving vocoder,

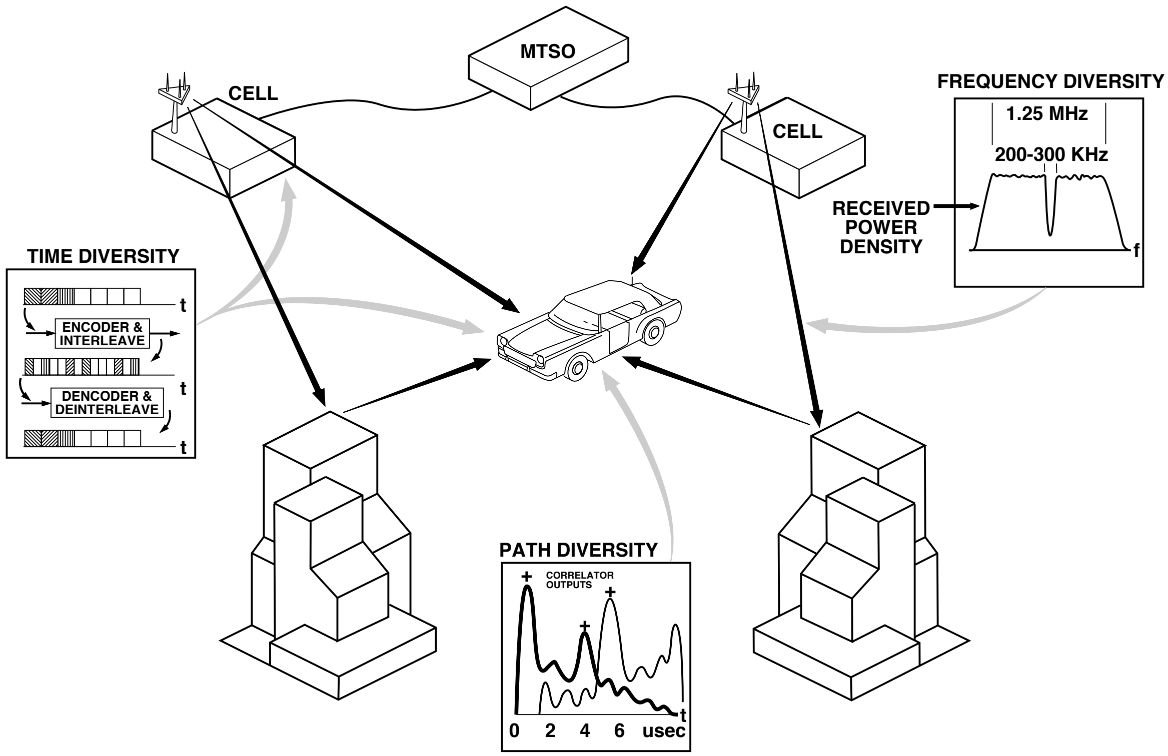

Figure 3-1. Diversity Processes in CDMA. *The reception from two different cells, wide band, signal structure, along with the capabilities of the rake receiver allow CDMA three forms of diversity in addition to the time diversity available in other digital systems.*

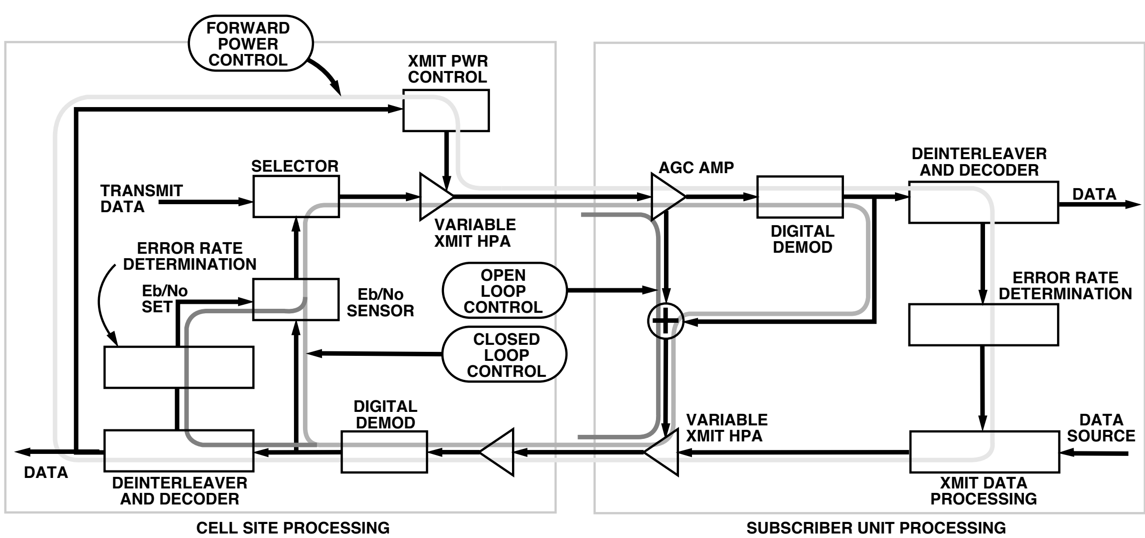

Figure 3-2. Power Control in CDMA. *Fast open loop and closed loop control maintains the reverse link transmit power at a selectable level. A slower loop limits the forward link to only that power required.*

then the receiving vocoder decodes the received speech packet into voice samples. The two vocoders communicate at one of four rates corresponding to the 9600 bps, 4800 bps, 2400 bps, and 1200 bps frame rates. The rates are determined by the input, messaging, or data. The vocoder algorithm uses Code Excited Linear Prediction (CELP) and the CDMA-specific algorithm is termed QCELP.

An important feature of the variable rate vocoder is the use of adaptive thresholds to determine the required data rate. The thresholds are changed according to the background noise level activating the higher vocoder rates only on the local voice. The result is suppression of the background and good voice transmission even in a noisy environment.

3.5 Privacy

The scrambled form of CDMA signals provides for a very high degree of privacy and makes this digital cellular system inherently more immune to cross-talk, inexpensive scanning receivers, and air-time fraud. The proposed standard includes the authentication and voice privacy features specified in EIA/TIA/IS-54-B even though the CDMA architecture inherently provides voice privacy and provisions for extended protection. The digital voice channel is, of course, amenable to direct encryption using DES or other standard encryption techniques.

3.6 Mobile Station Assisted Soft Handoff

As shown in Figure 3-3, soft handoff allows both the original cell and a new cell to temporarily serve the call during the handoff transition. The transition is from the original cell to both cells and then to the new cell. Not only does this greatly minimize the probability of a dropped call, but it also makes the handoff virtually undetectable by the user. In this regard, the analog system (and the digital TDMA-based systems) provides a break-before-make switching function whereas the CDMA-based soft handoff system provides a make-before-break switching function.

After a call is initiated, the mobile station continues to scan the neighboring cells to determine if the signal from another cell becomes comparable to that of the original cell. When this happens, it indicates to the mobile station that the call has entered a new cell's coverage area and that a handoff can be initiated. The mobile station transmits a control message to the MTSO which states that the new cell site is now strong and identifies the new cell site. The MTSO initiates the handoff by establishing a link to the mobile station through the new cell while maintaining the old link. While the mobile station is located in the transition region between the two cell sites, the call is supported by communication through both cells; thereby eliminating the ping-ponging effect, or repeated requests to hand the call back and forth between two cell sites. The original cell site will only discontinue handling the call when the mobile station is firmly established in the new cell.

3.7 Capacity

In the cellular frequency reuse concept, interference is accepted but controlled with the goal of increasing system capacity. CDMA does this effectively because it is inherently a better anti-interference waveform than FDMA or TDMA. Indeed, its genesis was in military anti-jamming systems. Narrowband modulations are limited in frequency reuse efficiency by the

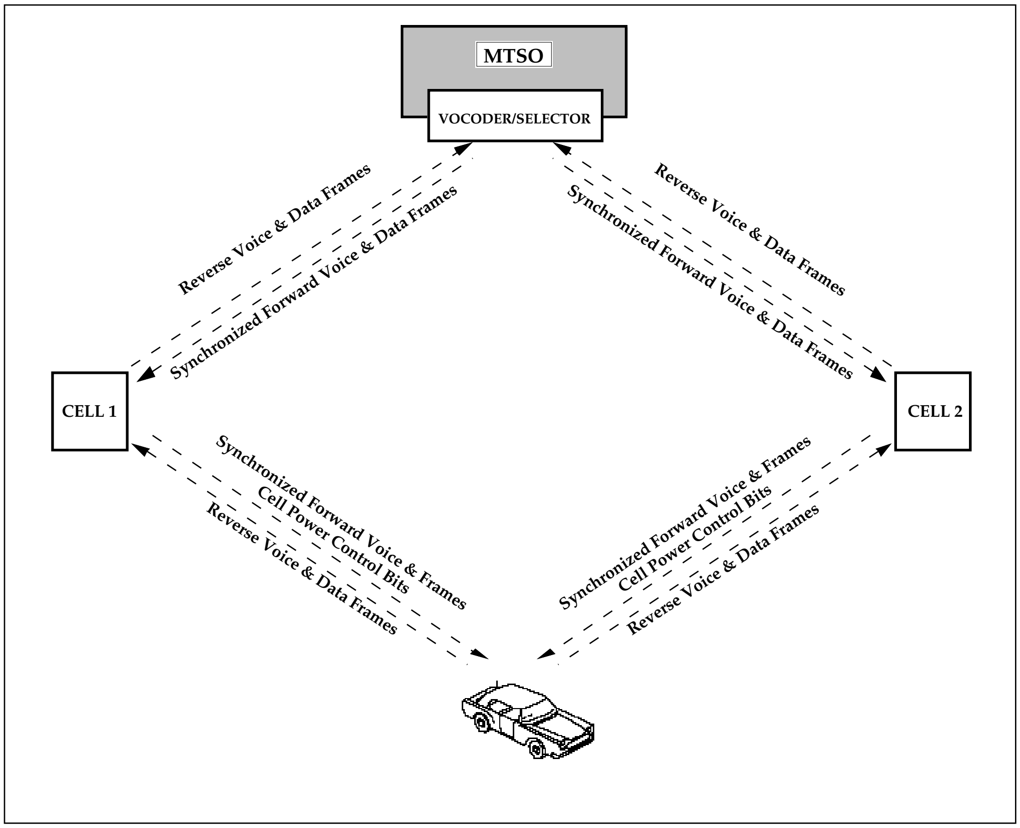

Figure 3-3. Active Links During Handoff. *Following notification by the subscriber which identifies the desired new cell , the MTSO activates the new cell and communication is supported through both cells until the subscriber notifies the MTSO that one of the links is no longer useful.*

requirement to achieve a Carrier-to-Interference (C/I) ratio of about 18 dB. This requires that a channel used in one cell is not reused in a nearby cell. In CDMA, the wideband channel is reused in every cell.

In CDMA, frequency reuse efficiency is determined by the signal-to-interference ratio that results from all the system users within range, instead of the users in any given cell. Since the total capacity becomes quite large, the statistics of all the users are more important than those of a single user. The “law of large numbers” can be said to apply. This means that the net interference to any given signal is the average of all the users’ received power times the number of users. As long as the ratio of received signal power to the average noise power density is greater than a threshold value, the channel will provide an acceptable signal quality. With TDMA and FDMA, interference is governed by a “law of small numbers” in which “worst-case” situations determine the percentage of time in which the desired signal quality will not be achieved.

The primary parameters that determine CDMA digital cellular system capacity are processing gain, E_b/N_0 (with the required margin for fading), voice duty cycle, frequency reuse efficiency, and the number of sectors in the cell site antenna. Additionally, for a given blocking probability, the larger number of voice circuits provided by CDMA results in a significant increase in trunking efficiency, which serves a larger number of subscribers per voice circuit.

For example, if a spread spectrum bandwidth of 1.25 MHz is utilized by mobile stations transmitting continuously at 9600 bps and if the modulation and coding technique utilized requires an E_b/N_0 of 6 dB, then up to 32 mobile stations could transmit simultaneously, as long as they are each power-controlled to provide equal received power at the receiving location. In a CDMA cellular system, this capacity is reduced by interference received from neighboring cells and increased by other factors, as discussed in Section 4.

3.8 Voice Activity Detection

In a typical full duplex two-way voice conversation, the duty cycle of each voice is less than 35%. It is difficult to exploit the voice activity factor in either FDMA or TDMA systems because of the time delay associated with reassigning the channel resource during the speech pauses. With CDMA, it is possible to reduce the transmission rate when there is no speech, and thereby substantially reduce interference to other users. Since the level of other user interference directly determines capacity, the capacity is increased by approximately a factor of two. This also reduces average mobile station transmit power requirements by approximately a factor of two.

3.9 Frequency Reuse and Sectorization

In CDMA, the wideband channel is reused in every cell. The total interference at the cell site to a given inbound mobile station signal is comprised of interference from other mobile stations in the same cell plus interference from mobile stations in neighboring cells. In other words, each mobile station's signal competes with all the other mobile station signals. The contribution of all the neighbor cells is equal to approximately half the interference due to the mobile stations within the same cell. The frequency reuse efficiency of omni-directional cells is shown in Section 4 to be the ratio of interference from mobile stations within a cell to the total interference from all cells, or about 65%. Figure 3-4 shows the percentage of interference contributions from neighboring cells. Each cell in the first tier contributes about 6% of the total interference so the entire first tier contributes an average of 6 times 6% or 36%; cells in the second and greater tiers contribute less than 4%.

When directional cell site antennas are used (e.g., typical 120° sector antennas) the interference is simply divided by three because, on the average, each antenna receives only in the direction of one-third of the mobile stations. The capacity supportable by the total system is therefore increased by nearly a factor of three.[2]

3.10 Low E_b/N_0 (or C/I) and Error Protection

E_b/N_0 is the ratio of energy per bit to the noise power spectral density and is the standard figure-of-merit by which digital modulation and coding schemes are compared. It is directly

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[2] 2.55 actually due to adjacent antenna overlap.

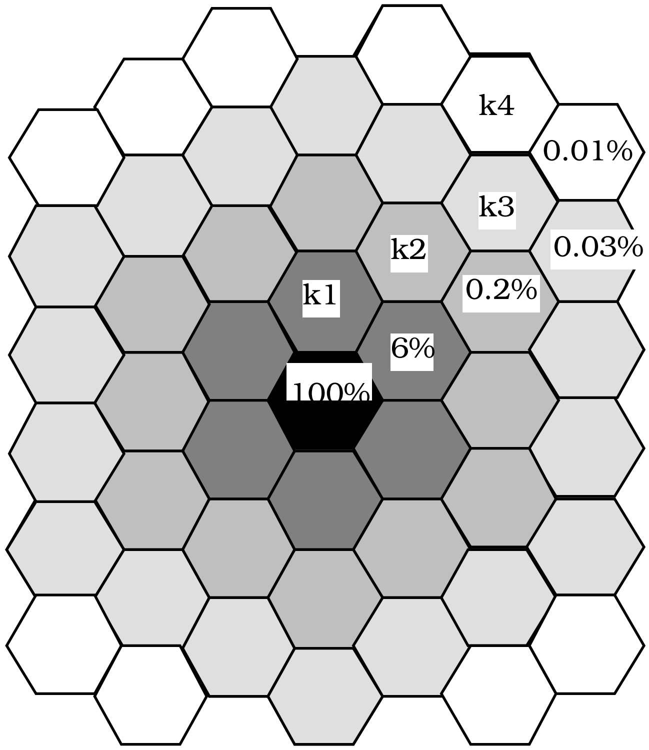

Figure 3-4. Interference Contributions From Neighboring Cells. *Significant contribution to interference seen by a cell as a result of activity in other cells is limited to the first tier of cells surrounding the cell.*

analogous to the C/N (Carrier-to-Noise ratio) for analog FM modulation. Due to the wide channel bandwidth employed in the CDMA system, it is possible to use extremely powerful, high redundancy error correction coding techniques. With narrowband digital modulation techniques, a much higher E_b/N_0 is required compared to CDMA because less powerful, low redundancy error correction codes must be used to conserve channel bandwidth. The CDMA system employs a powerful combination of forward error correction coding together with an extremely efficient digital demodulator in its implementation of the CDMA digital cellular system. The lower E_b/N_0 increases capacity and decreases transmitter output power requirements.

3.11 Soft Capacity

In the present U.S. cellular environment, the FCC has allocated 25 MHz of spectrum which is equally split between two system operators in each service area. The spectrum is further divided between the cells, with a maximum of 57 analog FM channels in a three sector cell site. When demand for service is at a peak, the 58th caller in a given cell must be given a busy signal. There is no way to add even one more signal to a fully occupied system. This call blocking behavior results in about a 35% loss of capacity. With the CDMA system, however, there is a much softer relationship between the number of users and the grade of service. For example, the system operator could decide to allow a small degradation in the bit error rate and increase the number of available channels during peak hours.

This capability is especially important for avoiding dropped calls at handoff because of a lack of channels. In the analog system and in digital TDMA, if a channel is not available, the call must be reassigned to a second candidate or it will be dropped at the handoff. With CDMA, however, the call can be accommodated if it is acceptable to slightly raise the users' bit error rates until another call is completed.

It is also possible to offer a higher grade of service (at a higher cost to the user) where the high-grade user would obtain a larger fraction of the available power (capacity) than the low-grade user. Handoffs for high-grade users can be given priority over those for other users.

3.12 Transition to CDMA

In the initial introduction of CDMA service, a band segment of approximately 1.25 MHz is occupied by the CDMA operation because the spread spectrum modulation requires this minimum bandwidth. This represents only 10% of the present FDMA/FM system capacity, or about two analog FM channels per sector in a three sector cell. In return, however, the introductory 1.25 MHz CDMA system allows up to 40 calls per sector. Some guard band is most likely required for adjacent channels which are not CDMA.

Initially, a set of cells capable of covering the entire geographic area will be identified and equipped with omnidirectional or multi-sectored CDMA cell site equipment. This should be far fewer cells than required by the existing FM system. Although only the selected cells are equipped with CDMA cell site equipment, the 1.25 MHz segment is cleared out in all cells in the local area (i.e., the area of coverage), to prevent mutual interference between the FM and CDMA segments of the system.

As demand for CDMA service grows, additional omnidirectional cell sites are added and existing omnidirectional cells are converted to multi-sectored cells to increase capacity or improve coverage in the more difficult areas. Frequency planning is not necessary to support the change as additional cells are added or converted by sectorization; as demand for CDMA service grows beyond the capacity provided by the initial service, additional 10% of the band segments can be removed from analog service and dedicated to the CDMA service. Each 1.25 MHz band segment requires an additional RF chain and power amplifier per sector. Additional modems are required to support the new channels.

4.0 THE CDMA SYSTEM DESIGN

The following section includes a more detailed description of the features highlighted in Section 3 and an overview of the system structure and functional description. The section concludes with a generic CDMA system design.

4.1 CDMA Capacity Explained

To develop the equation for capacity, we start with the equation for C/I noting that C, the received signal power from a mobile station at the cell is equal to $R \bullet E_b$ where R is the transmission bit rate and E_b is the signal energy per bit; and I is equal to $W \bullet N_0$, where W is the system transmission bandwidth, and N_0 is the interference power spectral density. The C/I ratio is therefore:

$$\frac{C}{I} = \frac{R \bullet E_b}{W \bullet N_0}$$

E_b/N_0 is defined as the ratio of energy per bit to the noise power spectral density that is required by the particular modulation and coding scheme utilized. In the above equation, R/W is commonly called the processing gain of the system.

In a multiple access system using CDMA spread spectrum, we apply the above equation by noticing that the interference power, I, is equal to the C • (N-1) where N is the number of users transmitting in the band, W. Thus C/I is equal to 1/(N-1). This assumes that all the signals are transmitted at a controlled power level to arrive at the receiver with power, C, and that other sources of interference are insignificant. (Modifications to the latter assumption are discussed in Section 4.1.7). This results in the following equation (1) for the capacity of CDMA in a non-cellular environment without additional system features.

$$N - 1 = \frac{W}{R} \bullet \frac{1}{\frac{E_b}{N_0}} \tag{1}$$

Because mobile stations in a cell are at different ranges and experience different path losses, power control of the inbound signals is necessary to normalize the power received at the cell site from all the mobile stations operating in its cell. Each mobile station measures the power level received from the cell site. The larger the power received by a mobile station from the cell site, the smaller the path loss to the cell site and, therefore, the smaller the transmit power required in the inbound path. This power control process eliminates received power variations due to differing mobile station to cell ranges and differing terrain. It does not eliminate Rayleigh fading because the phase relationships that cause this fading are not correlated over the 45 MHz frequency difference between the outbound and inbound frequencies in the U.S. cellular system.

A high-speed closed loop power control measures the power received from each mobile station at the cell site receivers and commands a power adjustment to normalize all received signals within the cell. Thus, the system is capable of compensating for differing multipaths between the two directions of the link. The combination of the open loop and the closed loop power control techniques results in a very wide dynamic range and a very high speed power control that compensates for all known effects. As shown in Section 5, the effect of the power control is to yield capacity results very close to those predicted.

4.1.1 Low E_b/N_0 (or C/I) and Error Protection

E_b/N_0 is the ratio of energy per bit to the noise power spectral density and is the standard figure-of-merit by which digital modulation and coding schemes are compared. It is directly analogous to C/N for analog FM modulation. Due to the wide channel bandwidth employed in the CDMA system, it is possible to use extremely powerful, high redundancy error correction coding techniques. With narrowband digital modulation techniques, a much higher E_b/N_0 is required compared to CDMA because less powerful, low redundancy error correction codes must be used to conserve channel bandwidth.

As mentioned earlier, in the cell site to mobile station direction, or the forward link, the CDMA signal design uses convolutional encoding with a constraint length K = 9 and a code rate 1/2. The optimum decoder for this type of code is the soft decision Viterbi algorithm.

In the mobile station to cell site link, or reverse link, since the modulation scheme employs 64-ary orthogonal signaling that is based on the set of Walsh function sequences, the demodulation is based on the use of the Fast Hadamard Transformers (FHT) as an optimum receive filter for the Walsh function. In the cell site receiver, the correlator output is fed to an FHT processor. This processor produces a set of 64 coefficients for every six symbols. The 64 coefficients are then multiplied by a weighting function and passed to a diversity combiner. The weighted 64 coefficients from each antenna's receiver are added to each other. The resulting set of 64 coefficients is tested to determine the largest coefficient. The magnitude of the result, together with the identity of the largest of the 64, is used to determine a set of decoder weights and symbols for a Viterbi algorithm decoder. The Viterbi decoder, with a constraint length K = 9 and a code rate 1/3 decoder, determines the most likely information bit sequence. For each vocoder data block, nominally 20 ms of data, a signal quality estimate is obtained and transmitted along with the data. The quality estimate is the average signal-to-noise ratio over the frame interval.

Figure 4-1 shows the results of the forward link processing as tested with validation equipment in the Formal Test Laboratory (see Section 5). The plot shows symbol, frame, and bit error rates as a function of E_b/N_0. The specific case shown involves four faded paths (two Rayleigh and two Rician) and vehicle speeds of 10 and 100 mph. Frame error rate and bit error rates are shown. A frame error rate of less than two percent is undetectable in the reproduced voice; both cases are less than this value for an E_b/N_0 of 7 dB or more. Performance varies with the fading environment as well as the velocity but E_b/N_0 values averaged under 7 dB for the cases in the field trials.

4.1.2 Achieving Low E_b/N_0 - Multipath & Diversity

The CDMA system will offer much improved performance in the urban environment because CDMA provides inherent discrimination against multipath. The rake receiver (which provides for individually tracking multiple multipath arrivals) allows the constructive

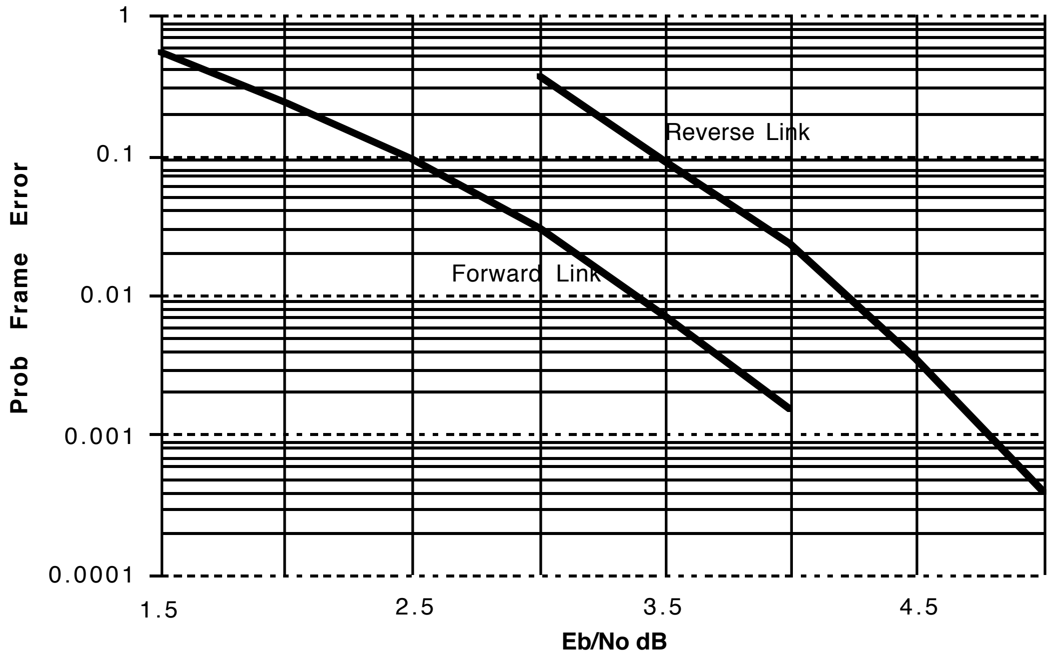

Figure 4-1. Performance of the Forward and Reverse Links on a Gaussian Channel. *Tested E_b/N_0 performance of both links shows the power of the modulation, interleaving, and error processing techniques employed. With power control, this results in a lower subscriber transmit power requirement.*

recombination of arrivals separated by a microsecond or more. This receiver, designed especially for the cellular environment, actually makes use of the multiple arrivals rather than creating destructive interference as in the narrowband systems.

The cellular mobile station channel typically consists of the Rayleigh faded components without a direct line-of-sight component. The Rayleigh fading channel is caused by the reflection of the signal from many different features of the physical environment, and results in copies of the signal arriving simultaneously from many directions with different transmission delays. At the UHF frequency employed for mobile radio communications, this causes significant phase differences between the paths with the possibility for destructive summation of the signals which in turn, results in deep fades. The fading is a very strong function of the physical position of the mobile station. A small change in position, even a few inches, changes the physical delay associated with all of the paths and results in a different phase for each path. Thus, the motion of the mobile station through the environment can result in a rapid fading process. In the 800 MHz cellular radio band, this fading is typically as fast as one fade per second per mile per hour of vehicle speed. Fading is very disruptive to the channel, results in poor communication quality, and requires additional transmitter power to overcome the fades.

The path loss of the UHF mobile station channel can be characterized by two separate phenomena: an average path loss which can be described statistically by a log normal distribution whose mean is proportional to the inverse fourth-power of the path distance and whose standard deviation is approximately equal to 8 dB; and a fading process caused by multipath which is characterized by a Rayleigh distribution. The log-normal distribution can be considered to be the same for both the inbound and the outbound frequency bands (as used in conventional UHF cellular telephone systems). However, Rayleigh fading is an independent process for the inbound and outbound frequency bands. Log-normal distribution is a relatively slow-varying function of position. Rayleigh distribution, on the other hand, is a relatively fast-varying function of position.

In relatively narrowband modulation systems such as the analog FM modulation that was employed by the first generation cellular phone system, the existence of multiple paths causes severe fading. With wideband CDMA modulations, however, the different paths may be discriminated against in the demodulation process, and may greatly reduce the severity of the multipath fading. Multipath fading is not completely eliminated because two or more paths with delay differentials of less than one microsecond (in a 1 MHz PN chip rate system) will occasionally exist which cannot be discriminated against in the demodulator. This will result in fading behavior.

Another unique capability of direct sequence CDMA is the exploitation of multipath to provide path diversity. If two or more paths exist with greater than 1 microsecond differential path delay, then multiple PN receivers can be employed to separately receive the strongest of signals in multiple paths. The number of signals (or paths) is equal to the number of PN receivers provided. Since these signals will typically exhibit independence in fading (i.e., they usually do not fade together) the outputs of the receivers can be diversity combined so that a loss in performance only occurs when all receivers experience fades at the same time. This type of diversity not only mitigates Rayleigh fading but also mitigates fades caused by physical obstructions blocking of the signal path. Signals arriving with larger than a 1 microsecond delay spread probably arrive from different directions. Signals coming from different directions are affected differently by obstructions in the immediate physical environment of the mobile station. This effect is especially pronounced in heavily built-up urban areas.

4.1.3 Voice Activity Detection

In a typical full duplex two-way voice conversation, the duty cycle of each voice is usually less than 35%. Because of the time delay associated with reassigning the channel resource during the speech pauses, it is not cost effective to exploit the voice activity factor in either FDMA or TDMA systems. With CDMA, it is possible to reduce the transmission rate when there is no speech and thus substantially reduce interference to other users. Since the level of other user interference directly determines capacity, the capacity is increased by approximately a factor of two. This also reduces mobile station transmit requirements by a nearly factor of two. If we define the transmit duty cycle as d, then the interference power received is now equal to N • d. Equation (1) becomes:

$$N - 1 = \frac{W}{R} \bullet \frac{1}{\frac{E_b}{N_0}} \bullet \frac{1}{d} \qquad (2)$$

4.1.4 Frequency Reuse

The concept of frequency reuse is the fundamental advance of analog cellular radio systems over its predecessors. This advance has allowed much higher capacity than in previous mobile telephone systems. Frequency reuse introduces the idea of accepting but controlling co-channel interference to increase system capacity. Frequencies allocated to the system are reused by dividing the available spectrum into many sets of frequencies. A given cell uses frequencies from only one of the sets. The cells immediately adjacent to this cell can not use the same frequency set. The system relies on the spatial separation provided by the cell structure and directive cell site antennas to provide adequate isolation between two terminals that use the same frequency. Analog FM voice modulation requires 18 dB C/I isolation to provide acceptable performance. Digital FDMA and TDMA modulation techniques require similar isolation.

Originally, frequency reuse promised nearly infinite system capacity for any given geographic area because the C/I is determined by ratios of distances, instead of absolute distances. This implies that as higher capacity is desired, the cell sizes can be reduced and more cells can be provided to cover the geographic area. There is a practical limit to capacity which is caused by less than ideal cell design in the real world and the need for a very rapid handoff process as cell sizes decrease. Currently, many densely populated areas are approaching saturation and prompting the search for even more efficient frequency reuse techniques. Cell splitting through sectorizing antennas and the use of smaller cells has been carried to the point of diminishing returns. Digital modulation techniques are being proposed to provide increased capacity through improved spectral efficiency.

In equations (1) and (2), only the interference from mobile stations within the boundaries of a cell was considered. The case of a large cellular system is now considered and the interference received in a cell from mobile stations operating in neighboring cells is calculated. Let us assume a large number of equal sized cells, and a uniform density of mobile stations. The path loss is well known to follow a fourth power law of distance if the system exists in an area of uniform flat topography with relatively low antennas. This is fortunate (also for FDMA and TDMA) because without this path loss, an unacceptable level of interference is received from far distant stations in a very large system area.

The analysis for an FDMA cellular system is based on the interference that comes not from the statistical average of received interference from all other users in the system, but rather from particular units in the nearby cells using the same frequency. The interfering cell must be far enough away so that the received interference power results in a C/I of greater than 18 dB. Simple geometric arguments for the seven frequency set case with omni antennas show that an average C/I of 22.3 dB results for mobile stations positioned in the worst case locations within the two cells.[3] However, the log-normal distribution of path loss results in C/I less than 18 dB much of the time. In fact, the C/I exceeds only 16 dB 90% of the time. This illustrates the need for greater than seven frequency sets when omni

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[3] For a detailed description of these arguments, see W.C.Y. Lee, *Mobile Cellular Telecommunications Systems*, McGraw-Hill, 1989.

antennas are used or else the use of directive antennas to provide adequate isolation. Use of 120° sectors improves the C/I situation by about 6 dB for FDMA. With seven frequency sets, FDMA/FM can provide about 57 simultaneous calls per cell (and two control channels) with current cellular frequency allocations.

In CDMA, the total interference at the cell site to a given inbound mobile station signal is comprised of interference from other mobile stations in the same cell plus interference from mobile stations in neighboring cells. The contribution of all the neighbor cells is equal to approximately half the interference due to the mobile stations within the cell. The frequency reuse efficiency of omni-directional cells is the ratio of interference from mobile stations within a cell to the total interference from all cells, or about 65% as discussed in Section 3.2.9.

The following is a derivation of the above result. First, consider only spatial isolation effects in the cellular system (i.e., the cell sites have omni-directional antennas). The results are then augmented to include the effect of directive cell site antennas.

In a cell containing N mobile station transmitters, the number of effective interferers is simply N-1 regardless of how they are distributed within the cell since power control is employed in the mobile stations. In the operation of power control, the incident power at the center of the cell from each mobile station is the same as for every other mobile station in the cell, regardless of the distance from the center of the cell.

In a hexagonal cell structure, six cells are immediate neighbors of the central cell. The mobile stations within these neighboring cells control their power relative to their own cell center. Let us assume that the path losses for mobile stations in the neighboring cells to their own cell centers is also fourth-law. The interference path loss from adjacent cell mobile stations into the center cell is also fourth-law.

The total signal-to-interference ratio received at a cell site is:

$$\frac{C}{I} = \frac{1}{N + 6Nk1 + 12Nk2 + 18Nk3 + \ldots} \tag{3}$$

which can be factored to yield:

$$\frac{C}{I} = \frac{1}{N\,[1 + 6k1 + 12k2 + 18k3 + \ldots\,]} \tag{4}$$

where N is the number of mobile stations per cell, and k1, k2, k3, ... are the interference contribution from individual cells in rings 1, 2, 3, etc. relative to the interference from the center cell. This loss contribution is a function of both the path loss to the center cell and the power reduction due to power control to an interfering mobile station's own cell center.

Let us define a frequency reuse efficiency, F, equal to the following:

$$F = \frac{1}{1 + 6k1 + 12k2 + 18k3 + \ldots}$$

Numerical integration techniques and/or simulation techniques can be used to calculate F. The result is that the frequency reuse efficiency, F, is about 0.65 for this propagation model. Figure 3-4 shows the relative interference contributions of each cell surrounding the center cell.

A similar set of simulations can be used to determine that the outbound half of the CDMA system's capacity is comparable to the inbound or reverse channel. Various software simulations and field tests have verified these results.[4]

4.1.5 Sectorization Capacity Gain

When directional cell site antennas are used (e.g., the typical 120° sector antennas) the interference seen is simply divided by three because, it only receives in the direction of one-third of the mobile stations. The capacity supportable by the total system is therefore increased by a factor of almost three. Accounting for side lobes, this is approximately 85% efficient for an effective gain of 2.55.

4.1.6 Unequal Cell Loading

The discussion of CDMA frequency reuse assumed an equal distribution of mobile stations throughout the service area. However, in reality, unequal cell loading frequently occurs because most cars are on the freeways during rush hour. With FDMA and TDMA-based systems, there are only a fixed number of channels available and they are divided and parceled out to the cells in a neighborhood according to a fixed, inflexible plan. With the CDMA system, the number of channels available in a cell depends upon the loading of the neighboring cells. If neighboring cells are less than fully loaded, then the capacity of a heavily loaded cell can be increased.

With CDMA, the capacity can increase by 10-50%, depending on the actual distribution of mobile stations. If some cells are more heavily loaded than others, then the remaining cells must be more lightly loaded than the average. The lightly loaded cells contribute less interference to their more heavily loaded neighbors and allow more mobile stations to operate in these cells. An example of this is where a line of cells along a freeway has a higher than average demand, while the cells bordering on these cells have only half the demand of the cells along the freeway.

In the example depicted in Figure 4-2, an area of lightly loaded cells, loaded to 30% of normal capacity, surrounds a line of heavily loaded cells. The normal capacity of a cell assumes that all surrounding cells are loaded to that same capacity. When that is not true, as in this case, the interference introduced into the loaded cell by the surrounding cells is reduced. This reduction leads to an increase in capacity for the loaded cell. When the surrounding cells are at 30% normal capacity, the loaded cells are at 120% of capacity.

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[4] A more detailed and precise analysis has been performed and repeated. See in K.S. Gilhausen et al. "On the Capacity of a Cellular CDMA System." *IEEE Transactions on Vehicular Technology*, vol 40, pp. 303-312, May, 1991.

This flexible allocation of capacity is completely transparent to the radios in both the cell site stations and in the mobile stations. The only provision that must be made for such operation is that an adequate number of modems must be provided in the cell sites of the heavily loaded cells. The computer equipment that manages the system must be programmed to coordinate the variable capacity assignment. Note that no other coordination is required to mechanize this function. It happens naturally.

4.1.7 The Complete CDMA Capacity Equation

The complete equation for determination of capacity in QUALCOMM's CDMA cellular system is given by equation (1) and is augmented by the additional system capabilities to provide the following equation for CDMA capacity:

$$N = \frac{W}{R} \bullet \frac{1}{\frac{E_b}{N_0}} \bullet \frac{1}{d} \bullet F \bullet G \tag{5}$$

Where:

N = Calls Per Cell (Assuming Rayleigh Fading on the Reverse Link)
W = Spread Spectrum Bandwidth (Assumed value: 1.25 MHz)
R = Data Rate in kbps (Assumed value: 9600 bps)
E_b/N_0 = Bit Energy ÷ Noise Power Spectral Density (Assumed value: 7.0 dB)
D = Voice Duty Cycle (Assumed value: 40%)
F = Frequency Reuse Efficiency (Assumed value: 60%)
G = Sectorization Gain (Assumed value: 3 (120°) sectors: 2.55)
Radio Capacity Per Cell equals 98 CDMA Channels in 1.25 MHz
Erlang Capacity Per Cell with 2% Blocking equals 72 Erlangs in 1.25 MHz,

The sample Erlang capacity calculation was made using the assumption that the soft capacity limit feature described below is not used (i.e., when the next call comes to a particular sector that already is receiving N calls, it is refused service, and does not try again). The soft capacity limit could allow such a call to proceed with the understanding that slightly higher bit error rates would result for all system users. For the same grade of service, a three-sectored analog cell will offer 36 Erlangs and use the entire operating bandwidth. For this same bandwidth, the above calculation shows CDMA to offer 720 Erlangs; a ratio of 20:1.

4.2 CDMA System Features

The CDMA system has many other features that do not relate directly to capacity, but rather to ease of system operation and to improved link quality. The following sections discuss three of these features: acquisition, mobile station assisted handoff, and variable rate vocoding.

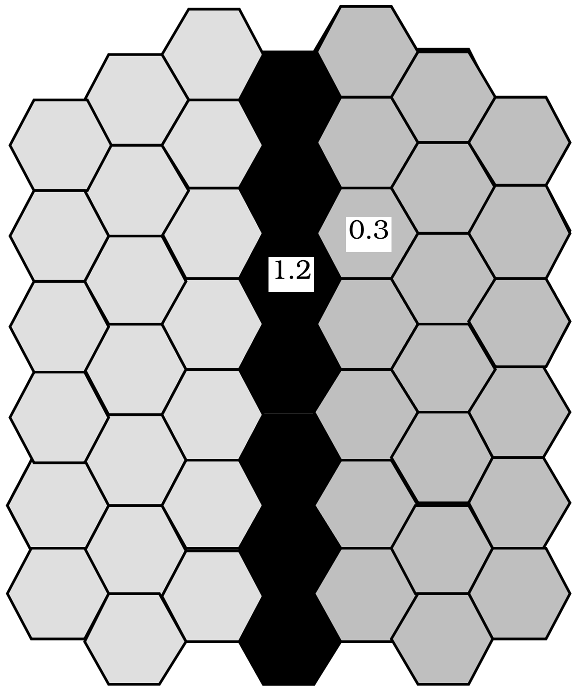

Figure 4-2. Unequal Cell Loading. *When surrounding cells are lightly loaded, the capacity of heavily loaded cells can be increased. For the 30% surrounding capacity shown, the loaded cells are at 120% capacity.*

4.2.1 System Pilot Acquisition

In the CDMA cellular telephone system, each cell site transmits a pilot carrier signal. This pilot carrier is used by the mobile station to obtain initial system synchronization and to provide robust time, frequency, and phase tracking of the signals from the cell site. This signal is tracked continuously by each mobile station. Variations in the transmitted power level of the pilot signal control the coverage area of the cell as is explained in the following section.

The pilot carriers are transmitted by each cell site using the same code but with different spread spectrum code phase offsets, which allow them to be distinguished. The fact that the pilots all use the same code allows the mobile station to find system timing synchronization by a single search through all code phases. The strongest signal found corresponds to the code phase of the best cell site.

Each cell also transmits a setup or sync channel. This channel uses the same PN sequence and phase offset as the pilot channel and can be demodulated whenever the pilot channel is being tracked. This sync channel carries cell site identification, pilot transmit power, and the cell site pilot PN carrier phase offset. With this information, the mobile station is capable of establishing System Time and knows the proper transmit power to initiate calls.

4.2.2 Mobile Station Assisted Soft Handoff

In a cellular telephone system, a handoff mechanism is provided to allow a call to continue when a mobile station crosses the boundary between two cells. In analog cellular telephone systems, the cell site receiver handling a call notices that the received signal strength from a mobile station has fallen below a predetermined threshold value. The cell site receiver then assumes that the mobile station must be near the cell border. When this occurs, the cell site asks the system controller to determine whether a neighboring cell site can receive the mobile station with a better signal strength. The system controller, in turn, sends messages to the neighboring cell sites with the handoff request. These cell sites, employing special scanning receivers, look for the signal from the mobile station on the specified channel. Handoff is attempted if one of the neighboring cell sites reports an adequate signal level. An idle channel from the channel set used at the new cell site is selected and a control message to switch to this new channel is sent to the commanding mobile station. At the same time, the system controller switches the call from the first cell site to the appropriate radio at the second cell site.

In the analog system, handoff can fail if an idle channel is not available to accept the call in the neighboring cell. It can also fail if another cell site reports hearing the mobile station in question when it actually hears a different mobile station using the same channel in a different cell. This results in the call being switched to the wrong cell. Also, the handoff fails if the mobile station fails to hear the command to switch channels. Actual operating experience indicates that handoffs fail frequently and that improvements are necessary. Another common problem is that when the mobile station is near the border between two cells, the signal levels tend to fluctuate at both cell sites and results in a ping-ponging effect. This overloads the system controller and increases the likelihood of a dropped call.

Since TDMA uses the same control structure as the analog system, it suffers from the same problems. In CDMA, soft handoff greatly reduces the link outages in the transition region and in handoff using a technique that allows simultaneous transmission to and from the subscriber through two cells.

At call initiation, the subscriber is supplied a tailored set of handoff thresholds and a list of cells that are most likely to be the candidates for handoff. While tracking the signal from the original cell, the subscriber searches for all the possible pilots (with an emphasis on the candidates) and maintains a list of all pilots whose signals are above a threshold (as shown in Figure 4-3) established in the initial setup. This list is transmitted to the MTSO whenever it is requested, whenever the list changes by having a new pilot appear on the list, or when an existing pilot falls below a level that is useful to support the traffic.

Upon command from the MTSO, via the initial cell, the subscriber unit commences tracking the second cell and uses diversity combining of the two signals (identical data is on each cell's transmission) to enhance the overall received signal. Power control information is received from both cells; both cells have to request a power increase for the subscriber to increase its power. Data from the subscriber unit is received by both cells and is forwarded to the MTSO where the best source is selected on a frame-by-frame (20 ms) basis and is used to represent the data transmitted by the subscriber.

This linkage can be terminated by return to the original cell, dropping of the original cell,

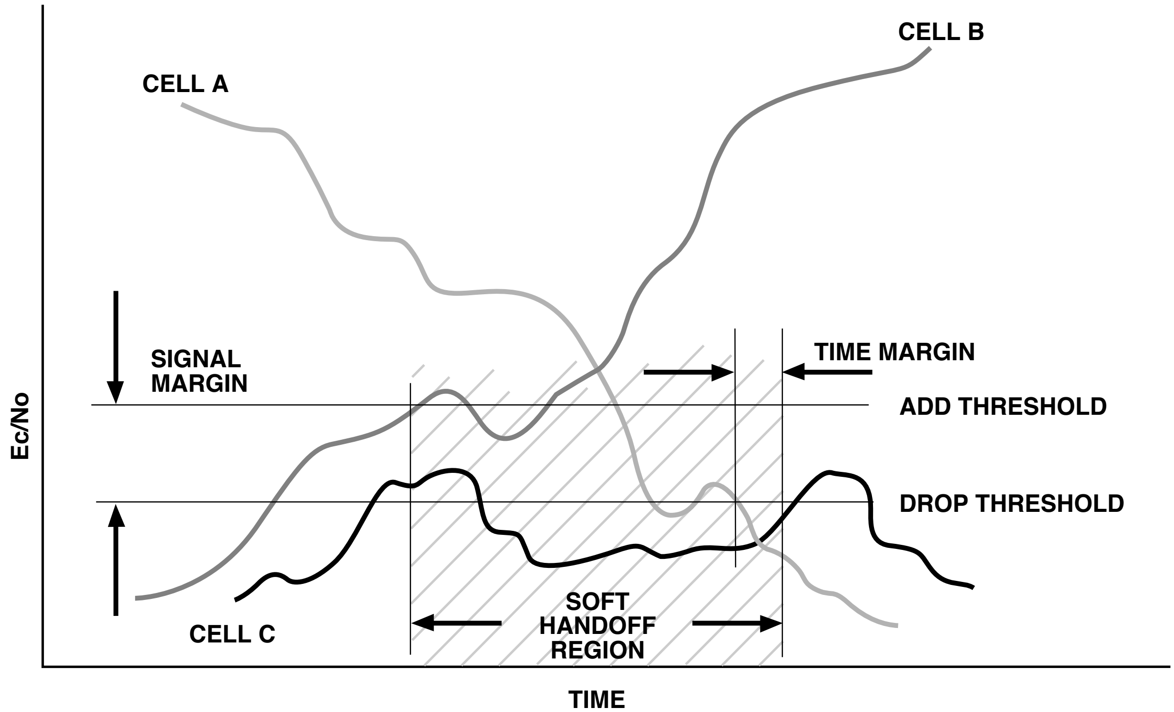

Figure 4-3. Mobile Senses Handoff Requirements. *By measuring signal strength from all pilots, the mobile determines the specific cell for the handoff. Built in margins protect against ping-ponging.*

or initiation of tracking another cell prior to the completion of the handoff. The criteria for these actions are the E_c/N_0 of the pilots; robustness is added to the process by requiring new pilots to exceed old ones by a selectable margin, and by requiring signals crossing thresholds to remain in the new zone for a certain length of time. The combined system of subscriber determination of E_c/N_0, MTSO commanded setup from subscriber identified cell information, continuous monitoring of the pilot signal strengths, and the level and time margins in the decisions, creates a very robust handoff process which field tests have shown to be very reliable.

A similar process takes place when the mobile station moves from one sector to another sector of the same cell. In this process, called softer handoff, the mobile station functions in exactly the same manner as with soft handoff. The cell site, however, intercepts the handoff request, initiates transmissions in the new sector, and thus provides the parallel path as with soft handoff. The cell receiver actually combines signals from the antennas for both sectors and demodulates based on the diversity combining of the signals. The MTSO is notified of the activity, but it does not participate directly. No additional MTSO/cell path is set up for softer handoff, and no additional hardware assets are required. Transparent voice handoff, bit integrity of data, fewer dropped calls, higher quality links in fringe areas, and a reduced load of switching transactions are the effects of soft and softer handoff in the CDMA system.

4.2.3 Variable Data Rate Vocoder

The appearance of the modulated signal does not change if the baseband data rate is changed. This allows considerable data rate flexibility to accommodate differing grades of service. For example, a range of voice coded (or vocoder) rates can easily be introduced over time and offered to subscribers as different grades of voice quality which can be priced accordingly without impact on system operation or costly redesign of the system.

The cellular operator maintains a bank of vocoders that operate at different rates, as a shared resource at the MTSO. A given vocoder's channel data rate is determined by a software parameter changeable from call to call. A wide range of new non-voice services (e.g., data, facsimile, imaging, ISDN, etc.) that require data rates other than the ones employed by the vocoders, can be accommodated simultaneously.

An 8 kbps vocoder, based on a QUALCOMM developed CELP algorithm is the baseline vocoder in the initial implementation and fielding of the CDMA network and subscriber equipment. The 8 kbps vocoder is primarily driven by the capacity considerations for the first generation digital cellular and PCN systems. The capacity of the CDMA system is directly proportional to the basic vocoder data rate. A lower rate vocoder, for example, running at 4 kbps would increase the capacity by a factor of 1.7 times (The full factor of two is not realized because of the requirement to maintain a low rate transmissions during speech blanking).

Based on internal testing, field testing, and MOS testing of the CDMA system utilizing the QCELP, the 8 kbps variable rate vocoder provides better voice quality than the analog system and the TDMA system. The vocoder quality provides the most improvement under adverse propagation environments. The vocoder is a variable rate that supports 8, 4, 2 and 1 kbps operation and corresponds to channel rates of 9.6, 4.8, 2.4, and 1.2 kbps. QUALCOMM is implementing its QCELP 8 kbps vocoder on a VLSI ASIC with an I/O driver module and some additional functions which reside on a general purpose microprocessor that is part of either the mobile station or the channel element at the cell site. At the land end, the vocoder is located at the MTSO. At the mobile station end, the vocoder is located along with the rest of the mobile station digital circuitry.

In the forward link (cell-to-mobile station), the vocoder must signal the cell channel card that a given packet is at a given data rate. The channel card will transmit lower data rate frames by repeating symbols and transmitting them at lower gain levels. The vocoder packet that is sent to the cell will therefore have fewer bits for lower data rates. The transmit waveform will be "ON" continually but the gain level from any given channel will vary throughout the conversation due to voice activity (among other things). At the mobile station, the decoder must process the received vocoder frame four times (multiple decode attempts). The microcontroller must decide what rate was sent using CRC checking results and symbol error rate measurements provided by the decoder.

In the reverse link (mobile station-to-cell) the source vocoder is located in the mobile station and it also must signal when it is changing data rates to the modulation hardware. The transmitted waveform from a given mobile station is based on a Time Division Multiplex (TDM) structure. Lower data rates are produced by pseudorandomly gating-off (punching holes in) the transmit waveform. The remaining signal is still operating at the highest data rate and is organized into groups of six Walsh symbols. Therefore, a 9600 bps operation results in a continuous waveform and a 4800 bps operation has half of the waveform effectively gated-off.

4.3 Link Waveform

4.3.1 CDMA Forward Link Waveform Design

The CDMA proposed standard specifies a forward link CDMA waveform design that uses a combination of frequency division, pseudorandom code division, and orthogonal signal multiple access techniques. Frequency division is employed by dividing the available cellular spectrum into nominal 1.25 MHz bandwidth channels. Normally, a cellular system would be implemented in a service area within a single radio channel until demand requires employment of additional channels.

Pseudorandom noise (PN) binary codes are used to distinguish signals received at a mobile station from different base stations. All CDMA signals in the system share a quadrature pair of PN codes. Signals from different cells and sectors are distinguished by time offsets from the basic code. This relies on the property of PN codes that the auto-correlation, when averaged over a few bit times, has an average which approaches zero for all time offsets greater than a single code chip time (approximately 1 μs). The PN codes used are generated by linear shift registers that produce a code with a period of 32768 chips. The PN chip rate is 1.2288 MHz, or exactly 128 times the 9600 bps information transmission rate. Two codes are generated, one for each quadrature carrier, which results in quadriphase PN modulation.

To avoid confusion between the system bandwidth, the PN chip rate, and the frequency assignment spacing, note that the PN chip rate is exactly 1.2288 MHz. The frequency assignment spacing, in multiples of 30 kHz, for two adjacent CDMA carriers is 1.23 MHz. The 3 dB bandwidth is also 1.23 MHz. The signals are bandlimited by a digital filter that provides a sharp frequency roll-off and results in a nearly square spectral shape that is 1.23 MHz wide at the 3 dB point.

All signals transmitted from a cell in a particular CDMA radio channel share a common PN code phase. They are distinguished at the mobile station receiver by using a binary orthogonal code based on Walsh functions (also known as Hadamard matrices). The Walsh function is 64 PN code chips long and represents 64 different orthogonal codes. Orthogonality provides nearly perfect isolation between the multiple signals transmitted by the base station.

The information to be transmitted is convolutionally encoded to provide the capability of error detection and correction at the receiver. The code used has a constraint length (encoder memory) of nine, K = 9, and a code rate of one-half (two encoded binary symbols are produced per information bit). The encoded symbols are interleaved to combat fast fading. To provide communications privacy, each data channel is scrambled with a user-addressed long code PN sequence.

Thus a channel in the forward link of the specified CDMA system consists of a signal centered on an assigned radio channel frequency, quadriphase modulated by a pair of PN codes with an assigned time offset, biphase modulated by an assigned orthogonal Walsh function, and biphase modulated by the encoded, interleaved, and scrambled digital information signal as shown in Figure 4-4.

An important aspect of the forward link waveform design is the use of the pilot signal that is transmitted by each cell site and is used as a coherent carrier reference for demodulation by all mobile station receivers. The pilot is transmitted at a relatively higher level than other types of signals which allows for extremely accurate tracking. The Pilot Channel signal is unmodulated by information and uses the zero Walsh function (which consists of 64 zeroes). Thus, the signal simply consists of the quadrature pair PN codes. The mobile station can obtain synchronization with the nearest base station without prior knowledge of the identity of the base station by searching out the entire length of the PN code. The strongest signal's time offset corresponds to the time offset of the nearest base station's PN code. After synchronization, the pilot signal is used as a coherent carrier phase reference for demodulation of the other signals from this base station.

Figure 4-5 shows an example of all of the signals transmitted by a base station on a particular sector antenna. Out of the 63 forward code channels available for use, the example shown in the figure depicts seven paging channels (the maximum number allowed) and 55 traffic channels. Other possible configurations could replace the paging channels one for one with traffic channels, up to a maximum of 0 paging channels and 63 traffic channels.

The remaining synchronization details and other system information are communicated to the mobile station by the base station's Synchronization Channel. This channel has a fixed assigned Walsh function. Once the Sync Channel has been received, the mobile station can select one of the paging channels to listen for other system information and pages.

4.3.2 CDMA Reverse Link Waveform Design

The CDMA reverse link also employs PN modulation using the same 32768 length binary sequences that are used for the forward link. Here, however, a fixed code phase offset is used. Signals from different mobile stations are distinguished by the use of a very long (2^{42} - 1) PN sequence with a user address determined time offset. Because every possible time offset is a valid address, an extremely large address space is provided. This also inherently provides a reasonably high level of privacy.

The transmitted digital information is convolutionally encoded using a rate 1/3 code (three encoded binary symbols per information bit) of constraint length nine. The encoded information is then interleaved over a 20 ms interval. The interleaved information is then grouped in six symbol groups (or code words). These code words are used to select one of 64 different orthogonal Walsh functions for transmission. The Walsh function chips are combined with the long and short PN codes. Note that this use of the Walsh function is different than on the forward link. On the forward link, the Walsh function is determined by the mobile station's assigned channel while on the reverse link the Walsh function is determined by the information being transmitted.

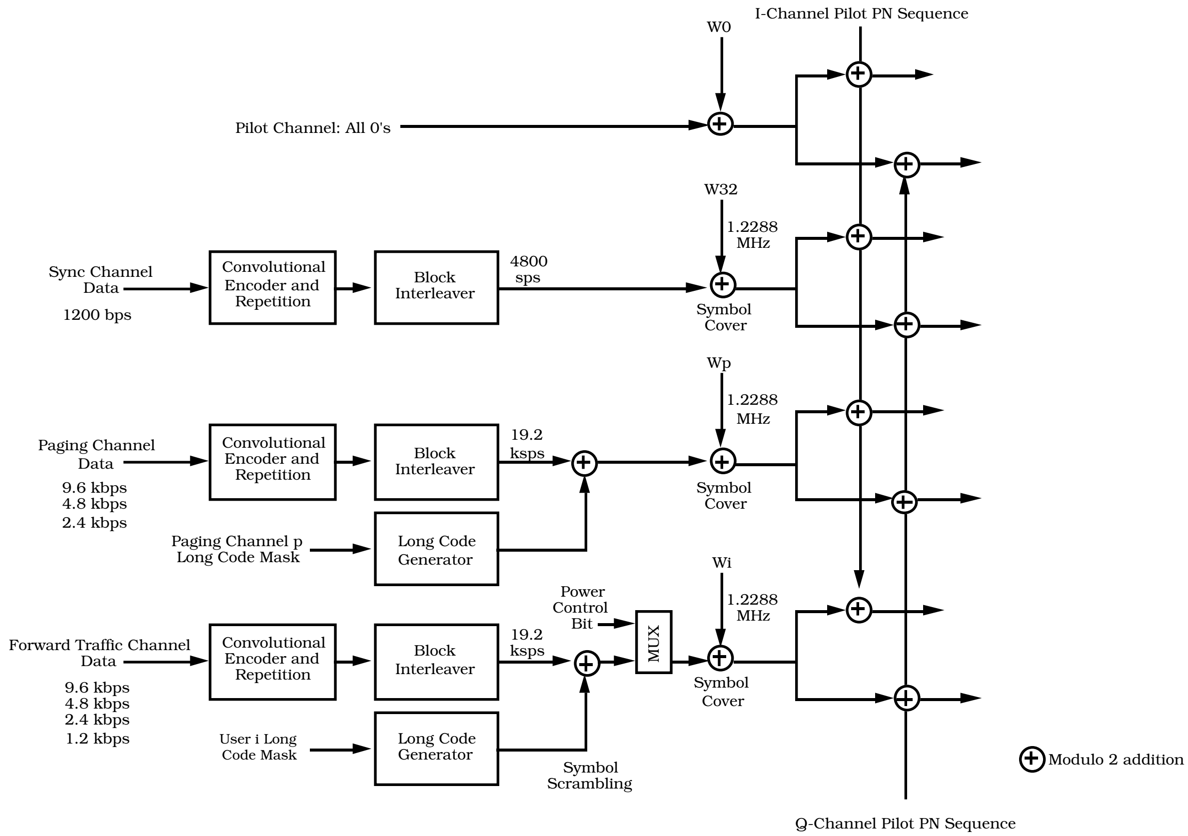

Figure 4-4. Forward Link Channelization. *Forward link channels share a common pseudo-noise modulation, but are individually identified by the assigned Walsh functions (W0-W63). This allows flexible allocation of channels to paging for traffic channels.*

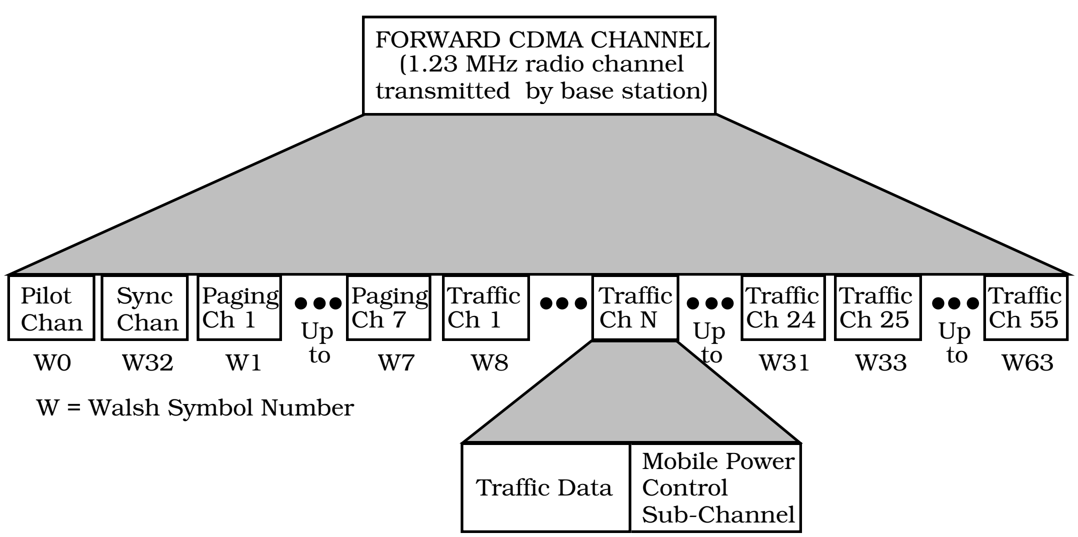

Figure 4-5. Forward CDMA Channels Transmitted by a Base Station. *In addition to the pilot and sync channels, the forward link in each sector supports 62 channels that may be used for paging and traffic. Zero to seven channels are assigned to paging, the remainder are traffic channels.*

The use of the Walsh function modulation on the reverse link is a simple method of obtaining 64-ary modulation with coherence over two information bit times. This is the best way of providing a high quality link in the fading channel with low E_b/N_0 where a pilot phase reference channel cannot be provided. On the forward channel, the Pilot Channel signal is shared among all the users of the forward channel. This is not possible on the reverse channel.

A "channel" on the reverse link of the specified CDMA system consists of a signal centered on an assigned radio channel frequency, offset quadriphase modulated by a pair of PN codes, biphase modulated by a long PN code with address determined code phase, and biphase modulated by the Walsh encoded, interleaved, and convolutionally encoded digital information signal. Figure 4-6 shows an example of all of the signals received by a base station on a particular sector antenna. Each Reverse CDMA Channel can have up to 62 Traffic Channels and up to 32 Access Channels per supported Paging Channel.

4.4 CDMA Power Control

It is very desirable to maximize the capacity of the CDMA system in terms of the number of simultaneous telephone calls that can be handled in a given system bandwidth. The system capacity is maximized if the transmitted power of each mobile station is controlled so that its signal arrives at the cell site with the minimum required signal-to-interference ratio. The bit error rate is too high to permit high quality communications if a mobile station's signal arrives at the cell site with too low a received power value. If the received power is too high, the performance of this mobile station is good; however interference to all the other mobile station transmitters that are sharing the channel is increased, and may result in unacceptable performance to other users unless their number is reduced.

4.4.1 CDMA Reverse Link Open Loop Power Control

Each mobile station attempts to estimate the path loss from the cell site to the mobile station. In the CDMA approach to multiple access, all the cell sites in a region transmit a pilot signal on the same frequency. Those signals used by all mobile stations for initial synchronization. A frequency and time reference for demodulation of digital speech signals is also transmitted by each of the cell site stations. The mobile station measures the power level of both the pilot signal from the cell site to which it is connected and the sum of all the cell site signals receivable at the mobile station.

The outbound link path record signal strength at the mobile station is used by the mobile station to adjust its own transmitter power; the stronger the received signal, the lower the mobile station's transmitter power. Reception of a strong signal from the cell site indicates that the mobile station is either close to the cell site or has an unusually good path to the cell site. This means that relatively less mobile station transmitter power is required to produce a nominal received power at the cell site from this mobile station transmission.

In the case of a sudden improvement in the channel, the open loop power control mechanism, which is analog in nature and has about 85 dB or more dynamic range, provides for a very rapid response over a period of just a few microseconds. It adjusts the mobile station transmit level downward, and thus prevents the mobile station transmitter power from being at too high a level.

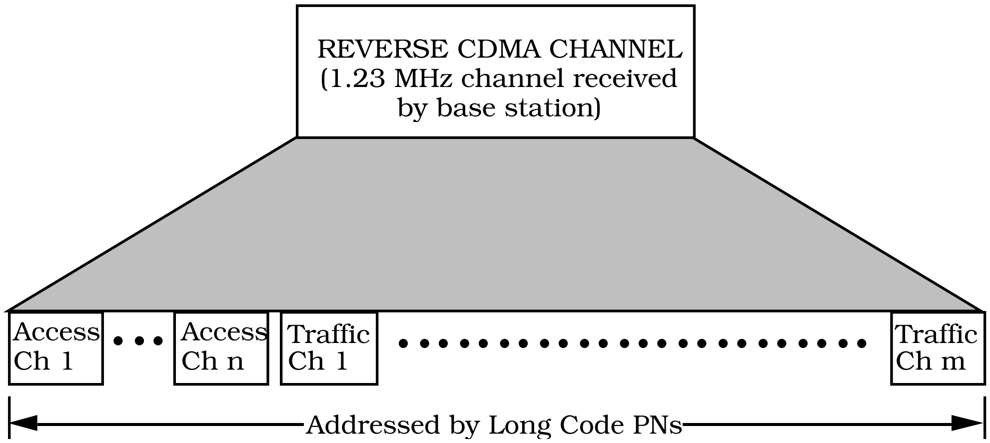

Figure 4-6. Reverse CDMA Channels Received at a Base Station. *Reverse link channels comprise zero to 32 access channels and up to 64 traffic channels per paging channel. The channels can be distinguished by the subscriber unique PN code.*

The rate of increase for mobile station transmit power must generally be limited to the rate at which the closed loop power command from the cell site, described below, can reduce the power. This prevents a sudden degradation which affects only the outbound path from causing a mobile station transmit power to increase to a level significantly higher than required for communication.

The Sync Channel from each cell contains data on the transmitted pilot channel power that the mobile uses to determine the transmitted power. This capability allows the system to have cell sites with differing transmit power levels and antenna gains (ERP levels) corresponding to the size of the cells. For example, a small radius cell need not transmit a high power level as a large radius cell. However, when the mobile station is a certain distance from a low power cell, it receives a weaker signal than it does from a high power cell. It responds with a higher transmit power than is necessary for the short range; hence, each cell site transmits its characteristics for power control.

4.4.2 CDMA Reverse Link Closed Loop Power Control

In a cellular telephone, the full-duplex radio channel is provided by using one frequency band for transmission from the cell site to the mobile stations and a different frequency band for transmission from the mobile stations to the cell sites. The frequency separation allows a mobile station's transmitter and receiver to be active simultaneously without feedback or interference from the transmitter into the receiver. This frequency separation has very important implications for the power control process: it causes multipath fading on the inbound and the outbound channels to be independent processes. This is because the 45 MHz frequency separation greatly exceeds the coherence bandwidth of the channel. This means that a mobile station cannot measure the path loss of the return link directly and, it is assumed that exactly the same path loss is present as on the forward link. This measurement technique usually provides the correct average transmit power, but additional provisions must be made for the effects of independent Rayleigh fading.

To account for the independence of the Rayleigh fading on the forward and the reverse link which the mobile station cannot estimate, the mobile station transmitter power is also controlled by a signal from the cell site. Each cell site demodulator measures the received signal-to-noise ratio from each mobile station. The measured signal-to-noise ratio is compared to the desired signal-to-noise ratio for that mobile station and a power adjustment command is sent to the mobile station in the outbound channel addressed to that mobile station. This power adjustment command is combined with the mobile stations' open loop estimate to obtain the final value of the mobile station's transmit radiated power.

The cell site power adjustment command signals the mobile station to nominally increase or to decrease the mobile station power by a predetermined amount approximately 0.5 dB. The power adjustment command is transmitted at a rate of once every 1.25 ms. The rate of the power adjustment command transmission must be high enough to permit tracking of Rayleigh fading on the inbound path.[1] It is important that the latency in determining the power control signal and the transmission process be kept small so that the channel conditions will not change significantly before the control bit can be received and acted upon.

The system controller residing at the MTSO provides each cell site controller with a value of desired signal-to-noise ratio to be used for each individual mobile station based on the error rate performance of that mobile station. This level is passed to the channel controller where it is used to determine whether to command a particular mobile station as well as to increase or decrease its transmitter power. This mechanism is called the CDMA closed loop power control.

4.4.3 CDMA Forward Link Power Control

The relative power used in each data signal transmitted by the cell site in response to control information is transmitted by each mobile station. In certain locations, the link from cell site to mobile station may be unusually disadvantaged; unless the power being transmitted to this mobile station is increased, the quality may become unacceptable. An example of such a location is a point where the path loss to one or two neighboring cells is nearly the same as the path loss to the cell site communicating with the mobile station. In such a location, the total interference is increased by three times over the interference seen by the mobile station at a point relatively close to its cell site. In addition, the interference coming from these neighboring cell sites does not fade in unison with the desired signal as in the case with interference coming from the desired cell site. This situation may require an additional 3-4 dB of signal power to achieve adequate performance.

At other times, the mobile station may be located where the signal-to-interference ratio is good. In such a case, the cell site could transmit the desired signal using a lower than normal transmitter power, and reduce interference to other signals being transmitted by the system.

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[1] One command every 1.25 ms proved adequate to track fading processes in the field tests.

To accomplish the forward link power control, the cell periodically reduces the power transmitted to the subscriber. This process continues until the subscriber, sensing an increase in received frame error rate, requests additional power. The cell site receives the power adjustment requests from each mobile station and responds by adjusting the power allocated to the corresponding cell site transmitted signal by a predetermined amount. The adjustment is usually small; of approximately 0.5 dB. The rate of change of power is somewhat slower than that used for the mobile station to cell site link, either once per vocoder frame, or nominally once per 15-20 milliseconds. The dynamic range of the adjustment is also limited approximately to a plus or minus 6 dB range around the nominal power.

Figure 4-7 shows the net result of the open and closed loop power control processes. Notice that the return link channel has its own independent Rayleigh fading process.

4.5 Networking and Control

4.5.1 Standard Message Format and System Layering

Signaling on all channels use a synchronized bit-oriented protocol. The messages on all channels have a similar layered format. The highest layer format is the message capsule that consists of a message and padding (padding is used on some channels to make the message fit into a frame). An example of this is with blank-and-burst signaling on the Traffic Channel. If the message is less than a frame, the capsule is the entire frame (less with some overhead bits); the padding bits extend from the end of the message to the end of the frame. The next layer format splits the message into a length field, the message body, and the CRC. The message body consists of a message type field; a fixed set of fields, if present, and a variable number of records, if present. The records then are composed of a fixed set of fields followed by a variable number of fields.

The signaling architecture is divided into the physical, link, and control process layers as shown in Figure 4-8. This is a simplified logical view of the structure of the system. In the mobile station, all of these layers are typically located in one physical piece of hardware. In the base station, these layers are typically distributed between several pieces of hardware which may or may not be located together. Portions of one layer may be implemented in several pieces of hardware which may or may not be located together. Acknowledgments are sent at both the link layer. Responses are sent at the control process layer. To avoid excess signaling, link acknowledgements and control process signaling responses can be bundled into a single message. This is typically done by the mobile station where the processing delay for the control process response is very small. On the base station side, the cell site can respond with a link layer acknowledgment while the MTSO can later respond with a control process response.

The CDMA system layering structure is a useful design approach for ensuring protocol and software structure. Layering creates regularity, orthogonality between functions, and clean interfaces. Thus layering tends to make systems easier to implement and reduces the number of software or other errors.

The physical layer, the multiplex sublayer, the signaling layer 2, the Paging Channel and Access Channel layer 2, the Sync Channel layer 2, and the control process layer 3 serve as the foundation for the CDMA system. These layers provide the basic mobile station services of call setup and tear down, power control, handoff, maintenance, authentication, and registration. In addition, the physical layer and the multiplex sublayer provide the transport of frames (or partial frames) for user applications.

An end-user application, identified by a service option, can be viewed as plugging into sockets provided by the multiplex sublayer. A service option implies a particular layer 2 and all layers on top of the layer 2. For example, Service Option 1, vocoded voice, has a simple layer 2 and a vocoder as a single upper layer. Since there is no retransmission of voice frames due to an error, the layer 2 for Service Option 1 does very little. A service option for a different user application, such as data, may have an entirely different set of upper layers. Some service options may have one or more layers providing identical services. Whether common software is used for these service options is left entirely to the manufacturer.

The multiplex sublayer and frame rate determination mechanisms are specified by the multiplex option. Multiplex Option 1, the default multiplex option, specifies the frame formats given in the proposed standard. This multiplex option allows both primary and secondary traffic as is shown in Figure 4-8. Thus two service options can be simultaneously active and plugged into the multiplex sublayer. Different multiplex options can be defined that are optimized for different service options. A particular multiplex option may allow only a certain set of service options to be plugged into it.

The CDMA cellular system has been designed with a very flexible signaling and control structure. This is to allow extendibility so that additional features and capabilities can be readily added in the future. When a mobile station is not involved in a call, signaling functions must be provided with the base station. For this purpose, the CDMA system has the Sync, Paging, and Access Channels.

4.5.2 The Sync Channel

The Sync Channel is a forward channel that is used during the system acquisition stage. Once the mobile station acquires the system, it will not normally reuse the Sync Channel until it powers on again.

A Sync Channel frame is the length of the pilot PN sequence. The frame is transmitted time-aligned with the pilot PN sequence. Since the pilot PN sequences are offset differently for each base station, the framing of the Sync Channel is different for every base station. Frame alignment with the base station PN allows a mobile station that is initially acquiring the system to easily receive the Sync Channel.

Only one message is sent on the Sync Channel; it is called the *Sync Channel Message*. This message provides the mobile station with certain system parameters. Paramount among these is the time of the base station's pilot PN sequence with respect to the System Time and the Paging Channel data rate.

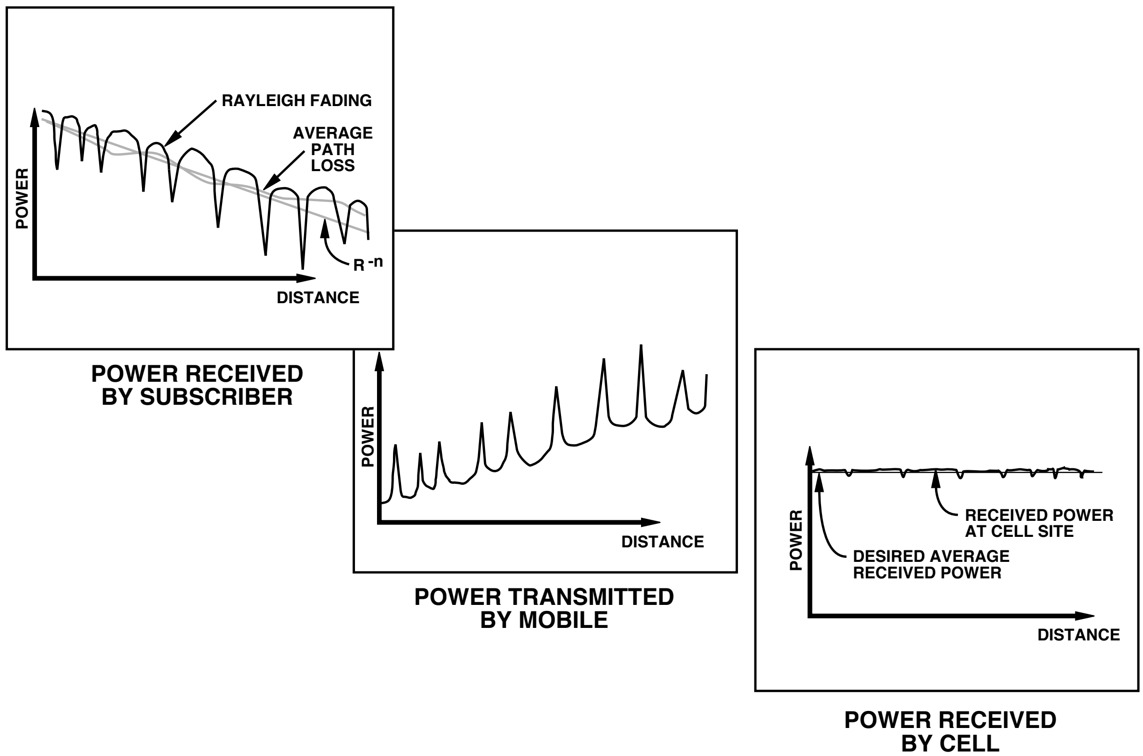

Figure 4-7. Effects of Power Control for the Reverse Link. *The power control modifies the subscriber transmit power to provide nearly constant received power at the cell. The subscriber sees both variable average path loss and possible Rayleigh fading.*

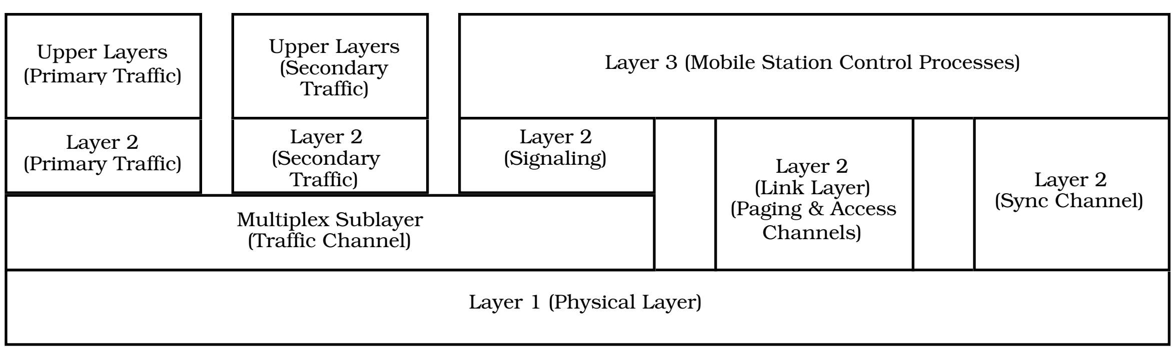

Figure 4-8. Mobile Station and Base Station Layering. *The basic CDMA protocol is supported by the functions shown in Layers 1 through 3 (plus the multiplex layer). Individual services access the system through Level 2 to the multiplex Layer.*

4.5.3 The Paging Channel

Once the mobile station has obtained information from the *Sync Channel Message*, the mobile station adjusts its timing to correspond to normal system timing. The mobile station then determines and begins monitoring its Paging Channel.

The Paging Channel data rates can be either 2400, 4800, or 9600 bps. There can be Paging Channels on different CDMA frequency assignments. On each CDMA frequency assignment, there can be up to seven Paging Channels. Analysis shows that a single 9600 bps Paging Channel can support about 180 pages per second. Using all seven Paging Channels on a single CDMA frequency assignment gives a capacity of about 1260 pages per second. This provides a total paging capacity far in excess of anything anticipated. The mobile station only monitors a single Paging Channel. This Paging Channel is determined by hashing over all the available Paging Channels. The base station may also assign a mobile station to a particular Paging Channel.

Paging Channel messages convey information from the base station to the mobile station. There are four major types of messages: overhead, paging, order, and channel assignment. The CDMA cellular system can be configured in many different ways so that it can be adapted to many different environments. The configuration of the system is conveyed in the four overhead messages: *System Parameter Message*, *Access Parameter Message*, *Neighbor List Message*, and *CDMA Channel List Message*. The *System Parameter Message* contains the configuration of the Paging Channel, registration parameters, parameters to aid pilot acquisition, etc. The *Access Parameter Message* contains information on the configuration of the Access Channel and control parameters. Some of these control parameters provide a dynamic feedback to the mobile stations to control their transmit rate, and thus serve to stabilize the Access Channel. The *Neighbor List Message* contains information to speed handoff to a neighbor base station. This information includes the time offset of the pilot PN and the basic neighbor configuration. The *CDMA Channel List Message* lists CDMA frequency assignments that contain Paging Channels. This allows the mobile station to correctly determine where to find its Paging Channel.

Page Messages contains pages to one or more mobile stations. Pages are usually sent when the base station receives a call for the mobile station and are usually sent by several different base stations. Orders are a broad class of messages which are used to control a particular mobile station. Orders are used for everything from acknowledging registration to locking or preventing an errant mobile station from transmitting. Channel assignment messages allow the base station to assign a mobile station to the traffic channel, change its Paging Channel assignment, or direct the mobile station to use the analog FM system.

The Paging Channel has a special mode called a slotted mode. In this mode, messages for a particular mobile station are only sent in certain pre-defined slots which occur at certain pre-defined times. Through the registration process, the mobile station can specify the slots that it will receive to the base station. These slots can occur from once every 2 seconds to once every 128 seconds. This capability allows a mobile station which is operating in this slotted mode to partially power-down during slots other than its pre-defined slot. The order of messages in a Paging Channel slot is also arranged so that in most cases, a mobile station will only have to receive a portion of the slot. The protocol tells the mobile station when all messages for slotted mobile stations using the slot have been transmitted. These techniques provide a very powerful method by which a battery operated mobile station (portable) can conserve a considerable amount of battery energy when idle.

4.5.4 The Access Channel

The Access Channel provides communications from the mobile station to the base station when the mobile station is not using a Traffic Channel. All Access Channel transmissions use a special 4800 bps mode. Access Channel messages provide for call originations, responses to pages, orders, and registrations.

One or more Access Channels are paired with every Paging Channel. Each Access Channel is distinguished by a different long PN code. The base station responds to transmissions on a particular Access Channel by a message on an associated Paging Channel. Similarly, the mobile station responds to a Paging Channel message by transmitting on one of the associated Access Channels.

The Access Channel is random access CDMA channel. Multiple mobile stations associated with a particular Paging Channel may simultaneously try to use an Access Channel. A transmitting mobile station randomly chooses both an Access Channel from the set of available Access Channels and a PN time alignment from the set of available PN time alignments. Unless two or more mobile stations choose the same Access Channel and the same PN time alignment, the base station is able to receive their simultaneous transmissions. The base station controls the rate of Access Channel transmissions to prevent too many simultaneous transmissions by multiple mobile stations. Simultaneous transmission would invariably, exhaust the available E_b/N_0 on the channel, use the same Access Channel and PN time alignment, and ultimately exhaust the available base station processing resources. Control of Access Channel transmissions is accomplished through the parameters contained in the *Access Parameter Message* which is sent on the Paging Channel. The Access Channel transmission rate can be varied for different types of transmissions and for different classes of mobile stations so that priority can be given to emergency and maintenance mobile stations.

4.5.5 Framing and Signaling on the Traffic Channel

Both the Forward and Reverse Traffic Channels use a similar control structure consisting of 20 ms frames. Frames can be sent at either 9600, 4800, 2400, or 1200 bps. The rate can vary from frame to frame; the receiver detects the rate of the frame and processes it at the correct rate. This technique allows the channel rate to dynamically adapt to the speech of the talker. When a talker pauses, the burst rate is reduced to a low rate; when the talker speaks, the system instantaneously shifts to using a higher burst rate. This technique decreases the interference to other CDMA signals and thus allows an increase in system capacity.

When the mobile station has been assigned to a Traffic Channel, signaling occurs directly on the Traffic Channel. Signaling can be either blank-and-burst or dim-and-burst. Blank-and-burst signaling is sent at 9600 bps and replaces one or more frames of primary traffic data, typically vocoded voice, with signaling data, as in the analog FM system. Dim-and-burst signaling sends both signaling and primary traffic data in a frame using the 9600 bps transmission rate. When the vocoder desires to transmit at its maximum rate (equivalent to 8000 bps), it is permitted to supply data at half of this rate (an equivalent of 4000 bps). The remaining bits are used for signaling and overhead. When the vocoder desires to transmit at other than its maximum rate, its rate is not limited. The 9600 bps transmission rate is used with the vocoder data filling part of the frame and the signaling data filling the remaining part of the frame. Dim-and-burst signaling has an immense advantage over blank-and-burst signaling because degradation in voice quality is essentially undetectable.

There are four types of control messages on the Traffic Channel: messages controlling the call itself, messages controlling handoff, messages controlling forward link power, messages for security and authentication, and messages eliciting or supplying special information from or to the mobile station. The specific uses of these types of messages are discussed in Sections 4.6 and 4.7.

4.5.6 Registration

Registration is the process by which the mobile station notifies the base station of its location. This allows the base station to more efficiently locate the mobile station for mobile station terminated calls. The mobile station also uses registration to inform the base station of the active MINs, Paging Channel slots in use, and other characteristics.

There is a tradeoff between the rate that the network pages mobile stations and the rate at which mobile stations register. By not registering at all, the system does not know whether the mobile station is on or off or where it might be located. The paging rate is high since the system may have to page in every cell and sector of the system. Frequent registrations allow the system to know with great accuracy, the location of the mobile station. Thus very little paging is required. However, frequent registrations place a high load on the Access Channels and a moderate load on the Paging Channels (the base station must acknowledge every registration). Thus there is a tradeoff between the paging and registration rates that results in some optimal use of the base station equipment, Paging Channels, and Access Channels.

The CDMA cellular system supports eight different forms of registration:

1. Power-up registration. The mobile station registers whenever it powers on, switches from using the alternate serving system, or switches from using the analog system.
2. Power-down registration. The mobile station registers whenever it powers off.
3. Timer-based registration. The mobile station registers whenever a timer expires.
4. Distance-based registration. The mobile station registers whenever it moves more than a certain distance from where it registered the last time.
5. Zone-based registration. The mobile station registers whenever it enters a new zone.
6. Parameter-change registration. The mobile station registers whenever one of its parameters changes (such as a MIN or the SLOT_CYCLE_INDEX).
7. Ordered registration. The mobile station registers whenever the base station requests it.

8. Implied registration. Whenever a mobile station successfully uses the Access Channel, the base station can imply the mobile station's location.

The first six forms are called autonomous registration since the mobile station initiates the registration in response to an event, (i.e., without being explicitly directed to register by the base station). The base station can enable or disable any of the various forms of autonomous registration. It is expected that combinations of registration methods will be the most effective. Some forms of autonomous registration have parameters which may be tuned. The base station communicates the forms of registration that are active and the corresponding registration parameters via the *System Parameters Message*.

With distance-based registration, the base station sends its latitude, longitude, and a distance parameter in the *System Parameters Message*. When the mobile station starts receiving a new base station, the mobile station receives the new base station's latitude and longitude. The mobile station then computes a metric using these latitude and longitude values and those from the base station where the mobile station last registered. If this metric exceeds the distance parameter from the base station where the mobile station last registered, the mobile registers. Upon registering, the base station becomes the center of a circle which is typically several cells in radius. The mobile station performs distance registration again only when it exits the circle.

With zone-based registration, a cellular system is divided into zones or location areas. The mobile and the MTSO both keep a list of the zones in which the mobile has recently registered. When the mobile station enters a zone not on its list, it registers. Upon a successful registration, both the mobile station and the MTSO add the new zone to their lists and set expiration timers on all other zones on the list. After the expiration of the timer, the mobile station and MTSO delete the zone from their list. By keeping multiple zones on the list, the system can avoid multiple registrations along the border between zones. By setting timers on old zones, the MTSO can avoid paging in the old zones after the timers expire. Zone-based registration is particularly powerful for defining boundaries between different sections of a cellular system or between systems.

With power-down registration, the mobile station registers whenever it has been directed to turn off. Power-down registration is not expected to be extremely reliable as the mobile station may have driven beyond the range of the cellular system. It is expected to be even more unreliable for a portable as a portable may be in a poor location, may have a poor orientation, or may have its antenna collapsed. Even though power-down registration may be unreliable, a successful power-down registration allows an MTSO to avoid paging the mobile station.

With timer-based registration, the mobile station registers whenever a timer expires. Upon successfully accessing the system, both the base station and the mobile station set timers. The base station timer is typically a little longer in duration that the mobile station's timer. If the mobile station has not registered by the expiration of the base station's timer, the base station may determine that the mobile station is no longer monitoring the system or was unsuccessful in power-down registration.

4.5.7 Service Options

The CDMA cellular system supports different user applications, called service options. As described in Section 4.5.1, a service option plugs into the multiplex sublayer. All service options use the capabilities provided by the physical layer and multiplex sublayer. The variable rate vocoder is called Service Option 1. Other possible service options include data and FAX services. Service options are also a way of introducing new technology into the system. For example, a second or third generation mobile station that supports an advanced technology vocoder could request a service that supports that device.

Two different service options can be simultaneously supported. One service option is for primary traffic and the second is for secondary traffic. Primary traffic and signaling always have precedence over secondary traffic. For example, Service Option 1 (variable rate vocoded voice) could be an active primary traffic service option and a packet data service could be an active secondary traffic service option. Packet data can be transmitted continually; however, when the speaker pauses and the vocoder drops to a lower rate, more of the available bandwidth is allocated to secondary packet data.

The mobile station can specify the desired service option at call origination. At any time during a call (typically at the beginning), the mobile station or base station can request either a primary traffic or a secondary traffic service option. If the request is agreed upon, then the new service option is activated.

4.5.8 Authentication, Message Encryption, and Voice Privacy

The CDMA system uses the authentication procedures developed for EIA/TIA/IS-54-B. The authentication algorithm is identical to the CAVE algorithm defined in Appendix A of IS-54-B. The mobile station maintains one A-key and one set of shared secret data which are used in both the analog and CDMA modes of operation. The mobile station can add the 18-bit authentication signature to origination, page response, registration, or data burst messages on the Access Channel. The mobile station can be challenged and have its shared secret data updated.

The CDMA system supports message encryption on the Traffic Channel using procedures similar to IS-54-B. The message encryption algorithm is identical to the CMEA algorithm defined in Appendix A of IS-54-B. When performing message encryption, the mobile station and the base station only encrypt the layer 3 portions of a message. Thus the message can be acknowledged before the message is decrypted.

The CDMA system also supports privacy using the private long code mask. The generation of the long code mask is identical to the generation of the voice privacy mask defined in Appendix A of IS-54-B.

4.6 Call Flow

The basic call flow for a mobile station originated call is shown in Figure 4-9. The message sequence is as follows. After the user enters the digits and presses the send key, the mobile station sends an origination message to the cell. Upon receipt of the origination message, the cell assigns the mobile station to a Traffic Channel and sends the dialed digits to the MTSO. While the MTSO finishes setting up the call, the mobile station receives the cell on the Forward Traffic Channel and commences transmitting on the Reverse Traffic Channel. When the cell acquires the mobile station on the Reverse Traffic Channel, it issues an acknowledgment stating that the Traffic Channel has been fully initialized. The CDMA system very quickly assigns the mobile station to a Traffic Channel; with the CDMA system this does not impact system capacity as transmissions occur at the lowest rate and at the corresponding lowest transmit power level.

After the Traffic Channel has been fully initialized, the base station may have the mobile station use the private long code for enhanced security. While not shown, the base station may also authenticate the mobile station. Ringback for a voice call may be through the voice channel by sending a vocoded tone, or by generating a tone at the mobile station's vocoder. This generation is controlled by the *Alert With Information Message* and the *Stop Alert Order*.

The call flow for a mobile station terminated voice call is shown in Figure 4-10. Upon receipt of a call, the system pages the mobile station by issuing pages in cells or sectors where it believes the mobile station is located. Upon receipt of a page, the mobile station autonomously responds and is assigned to a Traffic Channel. Traffic Channel initialization is the same as in the mobile station origination case. At this point, the base station sends an *Alert With Information Message* to have the mobile station ring. When the user answers the call, the mobile station uses the *Connect Message* to tell the base station that the call has been answered.

4.7 System Functional Description

4.7.1 Mobile Station Functions

The mobile station antenna is connected to the transmitter and receiver through a diplexer of standard design which allows simultaneous transmissions and reception through a single antenna. The receive signal is translated from the RF frequency in the 850 MHz band to an IF frequency. The translation process includes a frequency synthesizer of standard design which permits the receiver to be tuned to any of the frequencies within the receive portion of the cellular telephone frequency band. The IF signal is then passed through a SAW bandpass filter of approximately 1.25 MHz in bandwidth.

The filtered output of the IF is digitized in an A/D converter. The digitized signal is provided to each of four simple correlator receivers, one of which is called the searcher and the others are called digital data receivers. The digitized IF signal contains the signals of many on-going calls with the pilot carriers transmitted by all the neighboring cell sites. The digital receivers correlate the IF samples with the proper PN sequences. The correlation process provides a processing gain which enhances the signal-to-interference ratio of a signal that matches the proper PN sequence but doesn't enhance the other signals. The correlator output is then coherently demodulated using the pilot carrier from the closest cell site as the carrier phase reference. The result of this demodulation process is a sequence of encoded data symbols.

A property of PN signals is that discrimination is provided against multipath signals. When the signal arrives at the mobile station receiver after passing through more than one path, there is a difference in the reception time which corresponds to the difference in distance divided by the speed of light. If this time difference exceeds one chip time, then the correlation process discriminates against one of the paths. The receiver can chose whether to track and receive the earlier or the later path. If three receivers are provided, three independent paths can be tracked and received in parallel with the outputs diversity combined.

The current CDMA mobile station design includes four demodulator processors. One processor is used for the searcher function, while the others are used as data receivers. During operation in a single cell, the searcher receiver attempts to find multiple paths caused by terrain and building reflections. The three data receivers are assigned to the three strongest such paths, while the searcher receiver continues to evaluate the paths to keep the three data receivers on the three strongest paths as path conditions change.

During soft handoff between two cells, the strongest paths from both cell sites are determined by the searcher receiver, and the three data receivers are assigned to demodulate these paths. The data demodulation process uses information from all three receivers in a diversity combining operation which results in greatly improved fading resistance. The CDMA system employs a form of maximal ratio combining in which the signal-to-noise ratios are determined for all paths being combined and the contributions from the paths are weighted proportionally before summation. The combining is done coherently because the pilot demodulation allows the phase of each path to be determined before combining.

The outputs of the maximal ratio diversity combiner are passed to the decoder function where the resulting combined symbol stream is first de-interleaved and then decoded using a Viterbi algorithm forward error correction decoder. The resulting decoded bits are processed by the vocoder or data user.

The mobile station user voice is passed through a digital vocoder in the direction of mobile station to cell site, is forward error correction encoded using a convolutional encoder, and then interleaved. The resulting symbols modulate a PN carrier signal whose PN sequence is chosen according to the assigned address for the call.

The modulator output is then power-controlled by signals from the digital control processor and the analog receiver, converted to the RF frequency of operation by mixing with a frequency synthesizer which tunes the signal to proper output frequency, and then amplified to the final output level. The transmit signal is then passed on to the diplexer and the antenna.

4.7.2 Cell Site Functions

The cell site uses two or more receive antennas for space diversity reception. The signals from each of the two antennas are processed identically until they are combined in diversity combiner function. The order of space diversity employed can be increased by using more antennas and receiver processors.

The signal from one antenna is amplified, translated to an IF frequency by a synthesizer, filtered, and then digitized in a process identical to that described previously for the mobile

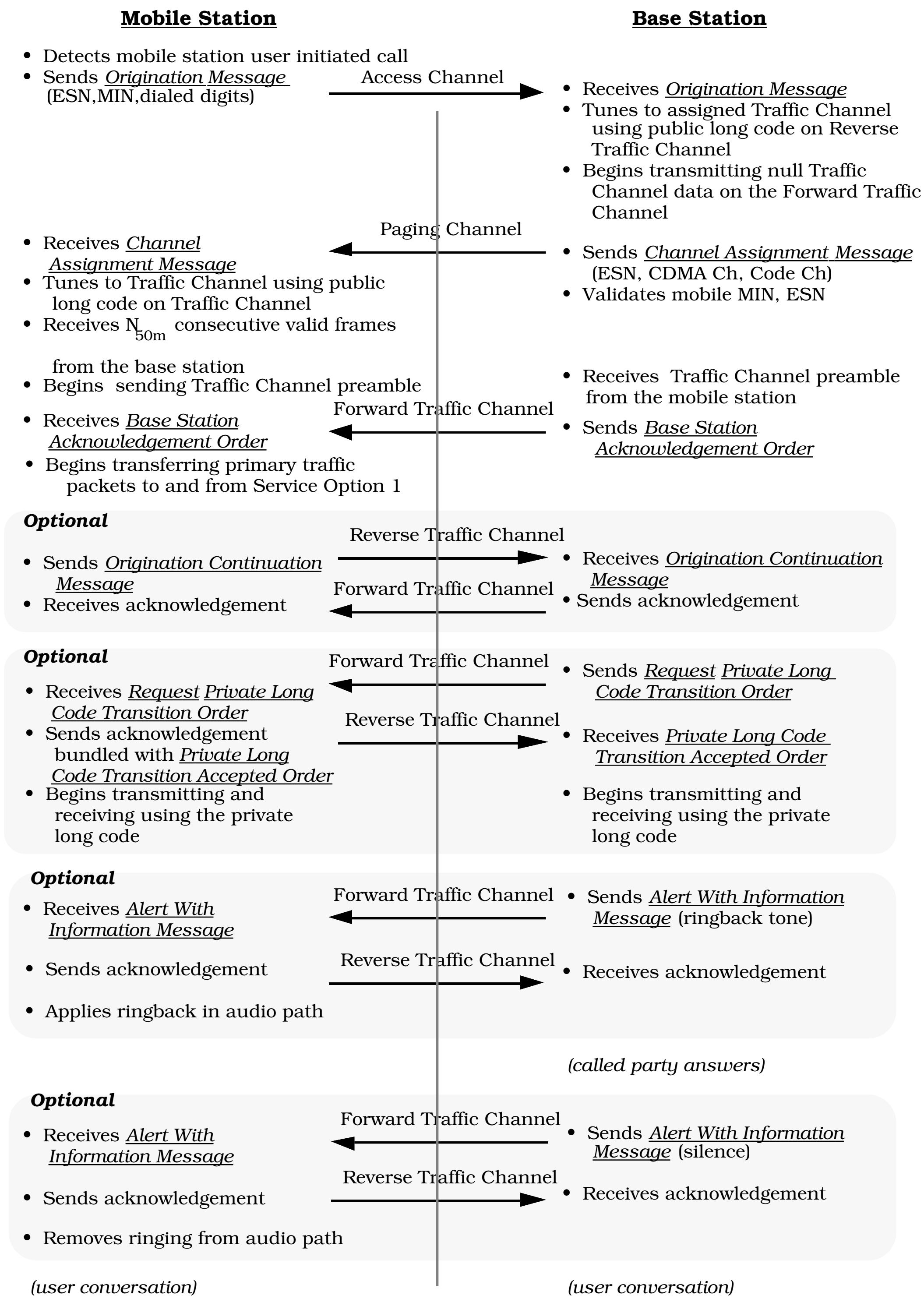

Figure 4-9. Simple Call Flow, Mobile Station Origination Example Using Default Service Option. *A short sequence of messages establishes the subscriber originated call. Options are available for special services.*

station receiver. The digitized IF signals are processed by digital data receivers similar to those used in the mobile station. The mobile station to cell site link also differs from that used in the cell site to mobile station link as mentioned earlier. In particular, a pilot signal is not available for coherent reference purposes so a non-coherent modulation and demodulation scheme is used.

Two searcher receivers are used to scan the time domain to assure that the associated receivers are tracking and processing the strongest available time domain signals. The process is identical to that described previously for the mobile station receiver.

Improved performance is accomplished by the employment of additional digital data receivers. The additional receivers track and receive additional delay paths similar to the method used in the mobile station receiver in order to obtain additional diversity modes. This is probably most useful in cell sites located in dense urban areas where many possibilities for multipath exist.

The cell site controller has responsibility for assignment of digital data receivers and modulators to particular calls. The cell site controller also monitors the progress of the call and the signal quality, and initiates tear down upon the loss of signal. When the cell diversity mode is in use, the mobile station uses its searcher receiver to find and track the strongest multipath signals from up to three cell sites. The digital data receivers are controlled to demodulate the strongest signals.

4.7.3 MTSO Functions

For each vocoder data block, nominally 20 ms long, a signal quality estimate is obtained in the cell site and transmitted along with the data to the Mobile Telephone Switching Office (MTSO). The quality estimate is the average signal-to-noise ratio over the 20 ms interval. The vocoder output is fed to the MTSO using standard telephone wireline or microwave facilities.

Signals may arrive at the MTSO from more than one cell site with the same information if cell site diversity reception is used. However, because of fading and interference on the link from the mobile station to the cell sites, the signals from one cell site may be better than the signals from the other cell site. The MTSO digital switch is used to route the information stream which corresponds to a given mobile station from the one or more cell sites to an individual selector. One selector and a corresponding vocoder is required for each call process.

The selector compares the signal quality indicators that accompany the information bits from two or more cell sites and selects the bits that correspond to the highest quality cell site on a frame-by-frame basis for output to the vocoder. The vocoder then converts the format of the digitized voice signal to either a standard 64 kbps PCM telephone format, analog, or any other standard format. The result is then connected to the PSTN by the switch.

The voice signal from the PSTN to the mobile station first passes through the switch to connect to a vocoder. The resulting information bit stream is routed through a second

Mobile Station		**Base Station**
• Receives *Page Message*	Paging Channel ←	• Sends *Page Message* or *Slotted Page Message* (MIN)
• Sends *Page Response Message* (MIN, ESN)	Access Channel →	• Receives *Page Response Message*
		• Tunes to assigned Traffic Channel using public long code • Begins transmitting null Traffic Channel data on the Forward Traffic Channel
• Receives *Channel Assignment Message*	Paging Channel ←	• Sends *Channel Assignment Message* (ESN, CDMA Ch, Code Ch)
• Tunes to assigned Traffic Channel using public long code • Receives N_{50m} consecutive valid frames from the base station • Begins sending Traffic Channel preamble on the Reverse Traffic Channel		• Receives Traffic Channel preamble from the mobile station
• Receives *Base Station Acknowledgement Order*	Forward Traffic Channel ←	• Sends *Base Station Acknowledgement Order*
• Begins transferring received primary traffic packets to Service Option 1 and sending null Traffic Channel data on Reverse Traffic Channel		
• Receives *Alert With Information Message*	Forward Traffic Channel ←	• Sends *Alert With Information Message* (RING tone, CNI)
• Sends Acknowledgement	Reverse Traffic Channel →	• Receives acknowledgement
• Applies ringing to mobile handset • Displays CNI information on mobile display *(user answers call)* • Removes ringing to mobile handset		
• Sends *Connect Order*	Reverse Traffic Channel →	• Receives *Connect Order*
• Begins transmitting primary traffic packets from Service Option 1		
• Receives acknowledgement *(user conversation)*	Forward Traffic Channel ←	• Sends acknowledgement *(user conversation)*

Figure 4-10. Simple Call Flow, Mobile Station Termination Example. *Call to a subscriber unit can include a phase that establishes the specific service option required.*

switch to one or more cell sites. If the mobile station is not in soft handoff, the signal goes to only a single cell site. If the mobile station is in soft handoff, the switch routes the information bit stream to the appropriate cell sites for transmission to the mobile station.

The MTSO controller determines the assignment of calls to cell sites and to vocoder equipments. This controller also communicates with each cell site controller about the assignment of particular calls to lines between the MTSO and cell site, and the assignment of PN codes for the calls. The functionality depicted as two separate switches could be performed by a single physical switch unit.

4.8 The CDMA Equipment Design

4.8.1 Dual-Mode Mobile Station/Portable

The mobile station design uses existing RF and IF circuitry, power amplifier, and frequency synthesizer functions as shown in Figure 4-11. The mobile station is fully backward-compatible with the existing analog FM system, (better known as “dual-mode” capability), so that new generation digital cellular units can be used in all areas with existing cellular coverage. The major difference between the dual-mode CDMA mobile stations and existing analog cellular mobile stations is the addition of digital signal processing. The signal processing functions (including all FM/FDMA analog functions) of the dual-mode CDMA mobile station/portable unit are currently being implemented on three custom VLSI chips or ASICs. These three chips are currently combined into a single device. The chip designs do not stress the state of the art in speed, size, or power consumption.

4.8.2 The CDMA Cell Site

Figure 4-12 is a block diagram of a single sector CDMA cell. The heart of the system is the digital shelf which holds multiple channel elements. Each channel element can be configured as a traffic channel or an overhead channel. The GPS receiver provides the timing to the system. This includes a 1 Pulse Per Second (PPS) tick and a reference clock. The main function of the transceiver shelf is to upconvert the IF signal out of the digital shelf to UHF and downconvert UHF back to IF. The forward link from the transceiver shelf passes through a high power amplifier and a filter to the Tx antenna. The reverse link starts from the Rx antennas, passes through filters and a low noise amplifier. It is then downconverted to IF in the transceiver shelf and input to the digital shelves. Note that only a single set of RF components is required per antenna; this eliminates the expensive power combiner function.

The digital shelf and the transceiver shelf are controlled through a Cell Controller (CC). The function of the CC is to manage the operation of a cell within a CDMA cellular system. CC maintains the service status of hardware and software entities within the cell, allocates and configures resources for call traffic, collects statistical information about the operation of the cell, monitors subordinate devices for detected faults, and distributes some aspects of timing. It also controls the multiplexing of the channel element ports to the digital backhaul to the MTSO.

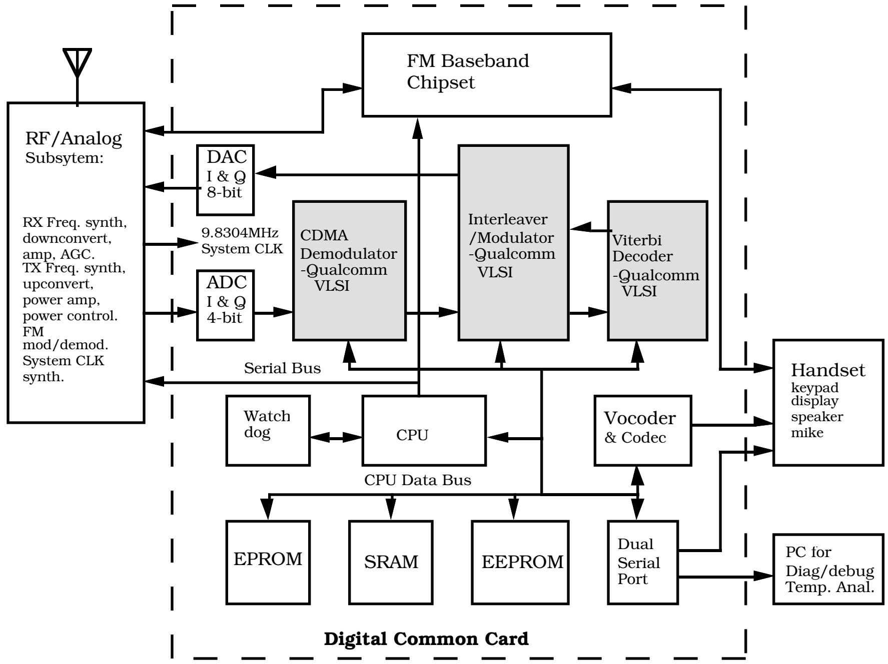

Figure 4-11 Mobile Subsystem. *The subscriber unit comprises an analog section similar to current analog units and a digital processing section. The CDMA functions are contained in three (soon to become one) ASICs and the controller processor.*

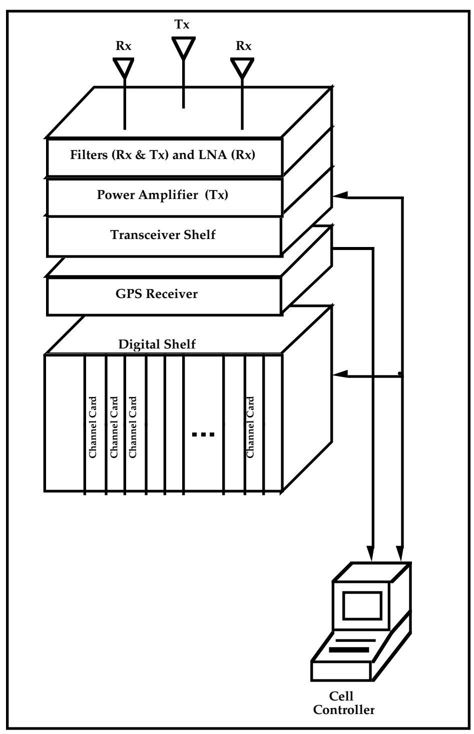

Figure 4-12. A Single Sector CDMA Cell. *A single transmit or receiver channel supports all channels in the sector. Two traffic channels are supported per channel card.*

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5.0 CDMA VALIDATION TESTING

5.1 Overview

Extensive testing has been performed to establish feasibility, functionality, and performance of the CDMA concept and system. Over the past year, many manufacturers and carriers participated in all aspects of the field trials to help evaluate the technology. The testing continues to validate all remaining relevant portions of the proposed standard. The following is a brief summary of the goals, scope, and results of some the testing.

5.2 Testing Goals and Objectives

The goals of the carriers and manufacturers were to validate the Common Air Interface (proposed standard) and to prove the performance of CDMA in actual field conditions. Typical performance areas involved were: capacity, power control, low E_b/N_0, soft handoff, voice quality, low mobile station transmit power, and wideband propagation/coverage.

The carriers and manufacturers developed a test matrix of over a hundred sets of tests necessary to validate CDMA system performance. The matrix was prioritized by the group and the high priority tests were addressed first followed by all the other lower priority tests. A test plan and schedule for the high priority testing was created by QUALCOMM and agreed to by the carriers and manufacturers. Tests were grouped into major categories and a “core test team” was established. This team established the objectives and success criteria for each test category and assisted in creating the procedures. The core test team, representatives of carriers and manufacturers, and many other parties participated in the lab and field testing.

5.3 Laboratory Testing

The CDMA laboratory tests conducted were designed to measure performance under a variety of controlled conditions. The test complement included a mobile, one cell, and one small switch. Calibrated fading simulators were used to simulate fading environments in the lab. The channel parameters were characterized with the channel simulators to include multipath fading, interference, and vehicle speed. The channel simulations were based on extensive field measurements from various cities and areas. A calibrated noise generator was used to simulate the effect of other CDMA users in the form of interference. The results of these tests provided individual evaluation of system parameters and insight into the field testing required to assess system performance.

The laboratory test environment remains as a stable, calibrated test facility to evaluate software upgrades and new mobile implementations.

5.4 Field Trials

The field test configuration included five cells with eight sectors, one small switch connected to the PSTN, and up to seventy mobile stations. The environments varied from urban and suburban to hilly terrain with canyons. A portable unit was used for in-building testing. Calibrated noise generators were used to simulate additional CDMA users. QUALCOMM’s five ASICs (two for the mobile station, two for the cell, and one common) which contain the proposed standard system functionality were used during testing to verify performance.

The results shown here briefly are grouped into the following categories: capacity and voice quality, power control, handoff, and mobile station transmit power.

Capacity and voice quality are linked together to emphasize the requirement for quality under loaded capacity conditions. During the particular field run shown in Figure 5-1, the system was loaded at 20 mobile stations per sector. The acceptable frame error rate to achieve above average voice quality is 2%. The figure shows Frame Error Rate (FER) versus vehicle speed for both links. The average FER is better than acceptable throughout with the expected and noticeable degradation at low speeds. At very low speeds (0-10 mph), the power control reacts to compensate for fading. Between 10 and 20 mph, the power control no longer keeps up with the fades; this causes durations of low received E_b/N_0 that are too long for the interleaver to randomize the errors (a step required for good performance from the error correcting process). However, at 20 mph and above, the fade durations are short enough for the interleaver to restore the full performance of the Viterbi decoder.

The accuracy and response of the power control has been a concern since the inception of the CDMA concept. Not only was the power control put through rigorous testing, but extensive interference and jamming tests were also performed. Figure 5-2 shows the mean and standard deviation for full rate and traffic variable rate. The deviation was similar to expected values even with the E_b/N_0 value set high. Notice that with the full rate frames, the deviation is much less than with the variable rate. A standard deviation of 1.6 dB was predicted for the variable data rate case, so the test results are extremely close to the predicted values.

Figure 5-3 shows test results of the capacity trials in a variety of test environments. The abscissa is the average E_b/N_0 realized in the sector under test; the ordinate is the total received signal power at cell from all mobile stations within the cell, normalized to the total background noise power in the bandwidth. The family of curves represents values predicted by the capacity equation for capacity levels of 30, 40, and 50 users.

The markers represent measured E_b/N_0 and total relative signal power for a set of capacity measurements. The agreement with prediction for these measurements gives confidence in the use of the curves for predicting capacity in different environments. Stability arguments limit the total signal power received at the cell to 10 decibels greater than the total background noise power. Figure 5-3, therefore, shows limits in sector capacity being induced for higher required E_b/N_0. The average required E_b/N_0 during this particular set of tests was 6.8 dB which shows an operating point well within the capacity ranges shown by the curves in Figure 5-3.

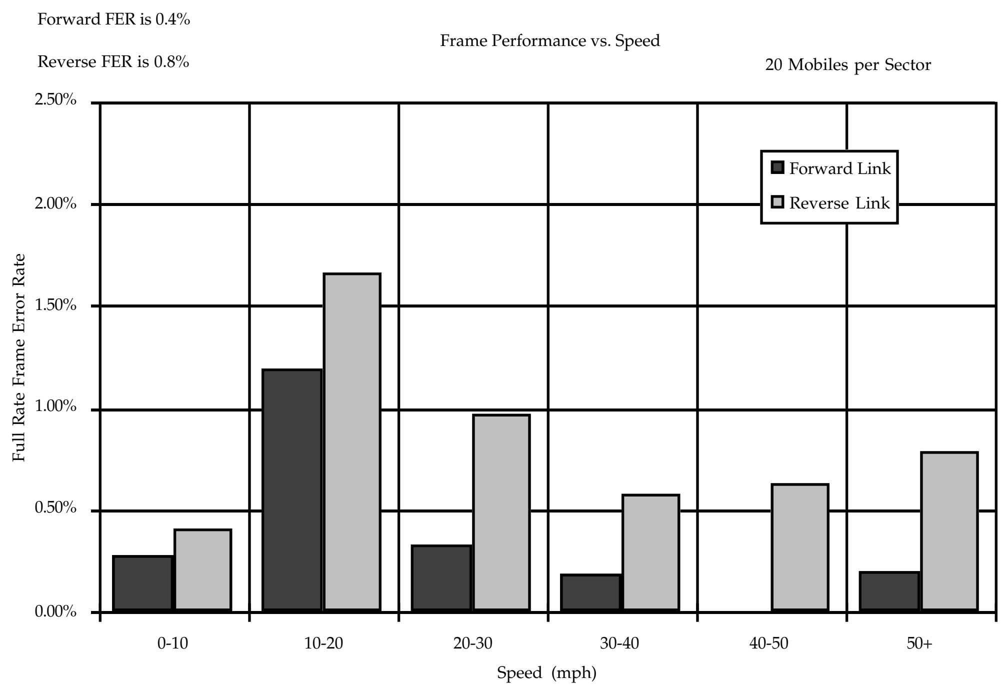

Figure 5-1. Frame Error Rate Performance As a Function of Speed. *Power control, wideband modulation interleaving, and error control combine to limit error rates for all ranges of vehicle velocity.*

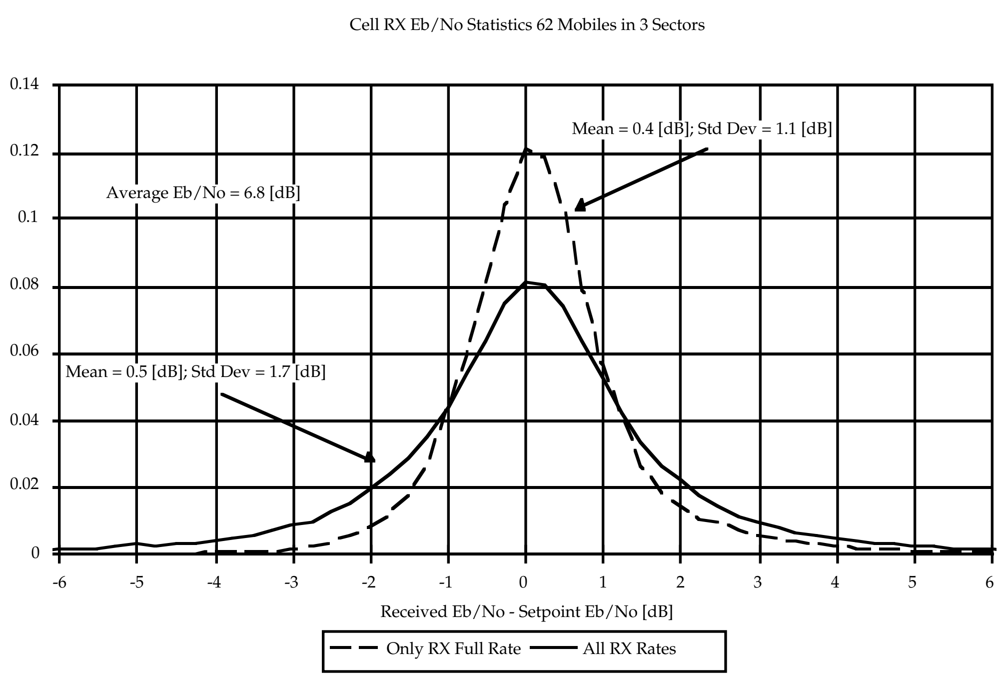

Figure 5-2. Results of Power Control During Field Tests. *Field trials show a 1.7 dB standard deviation for power control of cell site received power in the variable data rate case. The full rate case is even better (1.1 dB).*

One of the primary goals of the testing effort was to determine the system level characteristics of CDMA. To this end, a test was run using six sectors in four cells with 62 active mobiles plus sufficient simulated links to amount to a total system loading of 10 times the analog capacity. A jammer was then inserted into a sector containing active mobiles. The jammer cases were: CW jamming at levels from 6 to 30 decibels greater than the intrinsic noise power in the bandwidth, and a gated interference at four cycle rates (0.1 to 100 Hz) at a level of 15 decibels greater than the intrinsic noise power. The results of these tests are shown in Figure 5-4.

The abscissa of the figure is the running time during the test. The ordinate is read in two ways. For the bar graph, which represents the number of active mobiles in the sector under test, the ordinate is the actual number of calls active at the particular time. For the line graph, the ordinate represents the level of the jammer in decibels above the intrinsic noise power in the total bandwidth. The first 380 seconds of the test involved the CW jammer; the last 320 seconds involved the cycled jammer.

The system adapted to the CW jammer in three ways. First, as the jammer power increased from 0 dB to 20 dB, the mobile stations increased their transmit power (through closed loop power control commands) to overcome the additional interference. As the jammer approached the 20 dB level, the base station recognized the additional interfering power at its receivers and accordingly adjusted its transmit power, (i.e., reduced its transmit power, and thus effectively “shrunk” the cell coverage). In response to received transmit power from the interfered-upon sector, the mobile stations within the sector (usually stations in the boundary regions) recognized the need to handoff to adjacent sectors which were not subjected to interference. The bar graph shows that as the interference increased from 20 dB and then 30 dB, about 15 mobile stations handed-off to adjacent sectors. Notice that the total number of active cells in the system remained constant throughout the test. As soon as the jammer was turned off, the mobile stations that handed-off returned to the original sector and thus restored the initial number of active cells in that sector. Tests for jammer rate sensitivity that were made using the cyclic jammer failed to show any sensitivity.

Dropped calls did occur during the test but they were not caused by the jammer. The investigation of these dropped calls lead to the discovery of a software problem that has since been corrected; another advantage of thorough testing.

Another important parameter verified during the tests was the mobile station transmit power. Figure 5-5 shows the histogram of multiple mobile stations transmit power. The mean transmit power level was only 6.8 mW which was consistent throughout testing. This implies greatly increased battery life for portables or better penetration.

Overall, the feasibility of CDMA technology for cellular was well demonstrated. The results relative to capacity gains of at least ten, and sometimes thirty, are environment specific and may vary significantly with system implementation. The results are very impressive and testing continues to validate the proposed standard requirements and further investigate system performance and design criteria.

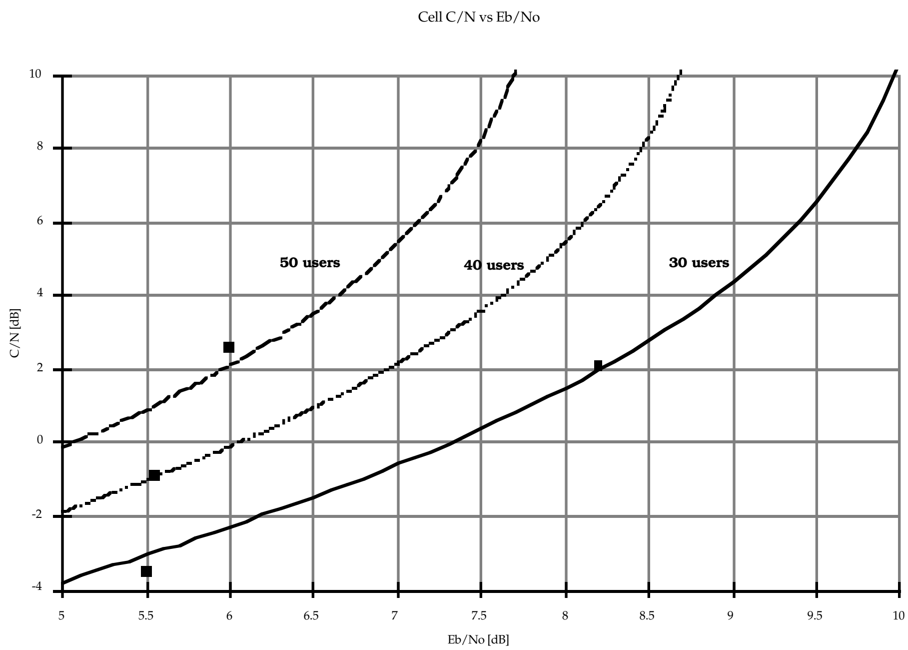

Figure 5-3. Limits in Sector Capacity Induced for Higher Required E_b/N_0. *There has been close agreement between measurements and predicted Carrier--to -Noise ratios for a variety of capacity levels.*

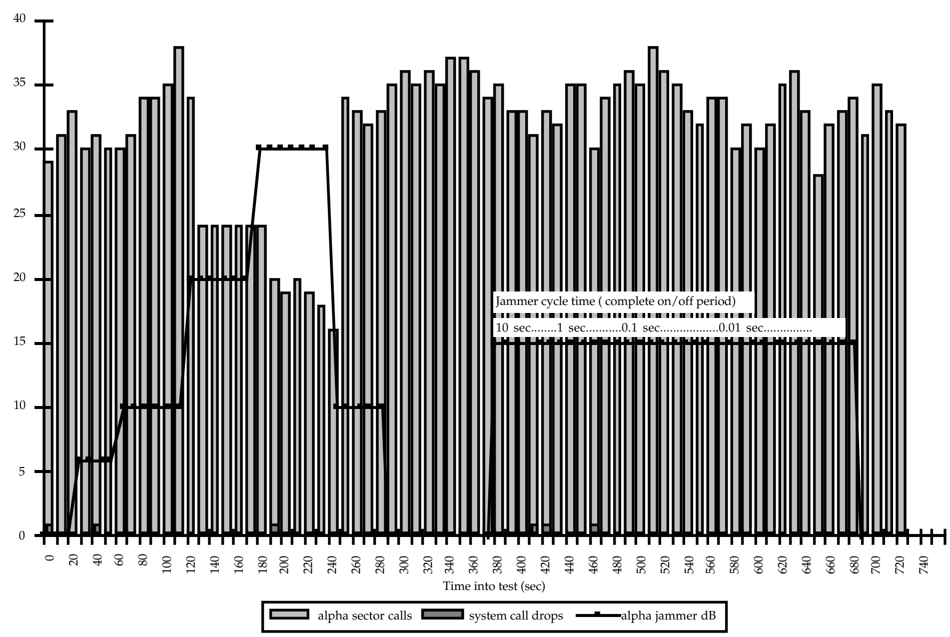

Figure 5-4. The Results of Injected Interference During the Field Tests. *Total system tests showed the effectiveness of power control and handoff in reaction to unanticipated interference. Calls are shifted from cell to cell without losing calls as local conditions change.*

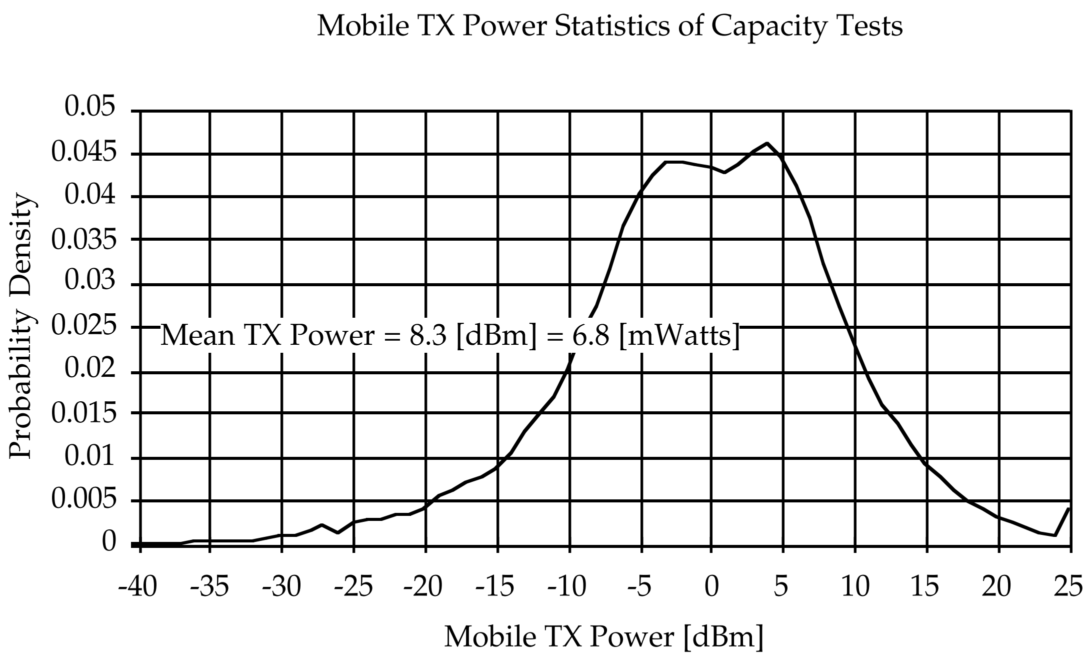

Figure 5-5. Mobile Station Transmitted Power During Field Tests. *An average mobile transmitter power of less than 7 mW means longer portable battery life.*