WIRELESS DIGITAL POINT TO MULTIPOINT LINK UTILIZING WIDEBAND CDMA

by

Sanjay Ambekar

A half-thesis submitted in partial fulfillment of the
requirements for the degree of

M.Sc.(Eng.) in Communications Engineering

University of Cape Town

1998

Supervised by ______________________________
Chairperson of Supervisory Committee

____
____
____

Program Authorized
to Offer Degree ______________________________

Date ______________________________

University of Cape Town
Department of Electrical Engineering

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

University of Cape Town

Abstract

Wireless Digital Point to Multipoint link utilizing Wideband CDMA

by Sanjay Ambekar

Supervised by: **Dr. R.M. Braun**
Department of Electrical Engineering

One of the proposed techniques for multiple access communications for the third generation is code division multiple access (CDMA). This has been shown to be a viable alternative to both TDMA and FDMA [3],[6]. While there does not appear to be a single multiple accessing technique that is superior to others in all situations, there are characteristics of CDMA that give it a distinct advantage over the other multiple access techniques.

In CDMA each user is provided with an unique, orthogonal code. If these K codes are orthogonal and uncorrelated with each other, than K independent users can transmit at the same time and in the same radio bandwidth. The receivers decorrelate the information and regenerate the original transmitted signal. It must be noted that the term "Wideband CDMA" is used comparitivlely to the only existing commercial CDMA system, IS-95 which uses a spectral bandwidth of only 1.2288 MHz.

This thesis examines and evaluates a good set of orthonormal codes (orthogonal and normalized to have equal power) and their application to providing accessing for a point to multipoint (PMP) stationary system.The correlation properties, design and constellation properties of these codes are investigated. The system model is then simulated using Systemview and then evaluated in terms of it's bit error rate, user capacity and Erlang with addition of users to the system.

TABLE OF CONTENTS

LIST OF FIGURES

Number ***Page***

ACKNOWLEDGMENTS

The author wishes to thank Dr R.M. Braun for all his patience and help during the course of the thesis. Dr Braun was my Supervisor for this thesis and his experience and encouragement are the key factors that made this thesis reach completion. Thanks must also be given to the Electrical Engineering Dept. at UCT for the use of their excellent facilities. Credit must also be given to Plessey who initiated the idea of this project with Dr. Braun.

I also wish to thank my parents for their constant support both financially and mentally. I wish to thank Dr J.G. van de Groenendal for some valuable suggestions made. Last but not least I would like to thank all my Masters colleagues for all their cheer and support.

With submission I hereby declare to the best of my knowledge that all the work and simulations completed in this thesis are the results of my own work and all the literature that was referenced is indicated.

S. Ambekar Date

Signed by candidate

08/02/1999

ABBREVIATIONS

AWGN	Additive White Gaussian Noise
BER	Bit error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
DPSK	Differential Phase Shift Keying
DS	Direct Sequence
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FH	Frequency Hopped
FM	Frequency Modulated
GOS	Grade of service
GPS	Global Positioning System
kbps	kilo bits per second
PMP	Point to Multipoint
PSTN	Public Switched Telephone Network
QPSK	Quadrature Phase Shift Keying

SNR	Signal to Noise ratio
TCDMA	Time Division CDMA
TDMA	Time Division Multiple Access
TH	Time Hopped
UMTS	Universal Mobile Telecommunication System
VAD	Voice Activity Detector
WCDMA	Wideband Code Division Multiple Access

1. INTRODUCTION

1.1 Objectives of the thesis

Chapter 1 introduces the various multiple access schemes that are currently being employed in most communication systems. Code Division Multiple access is also introduced mathematically. Finally all the multiple access schemes are discussed in terms of their respective advantages and disadvantages.

Chapter 2 treats the orthonormal codes to be used in the CDMA system. First some common spreading sequences are introduced with their properties. Hadamard codes which are selected are then described mathematically and their properties of cross-correlation and phase are simulated.

Chapter 3 described the CDMA system simulated and introduces mathematical representations for the transmitter, channel and the receiver models.

Chapter 4 is devoted to the simulations of the systems described in Chapter 3 and evaluates the system performance in terms of error probability, capacity and Erlang capacity of the system.

Chapter 5 summerises all the major findings of the thesis and also introduces the recently selected Wideband CDMA system for third generation mobile communication systems.

1.2 Digital Multiple access schemes

Wireless communication is in the process of revolutionizing telecommunication services and the way in which people use them, exceeding all expectations. There is widespread anticipation that customer demand will continue to expand and this is reflected by the high level of engineering activity and standards development worldwide.

The development of low-rate digital speech coding techniques and the continuous increase in the device density of integrated circuits (transistors per unit area), have made completely digital second-generation systems viable. Digitization allows the use of time division multiple access (TDMA) and code division multiple access (CDMA) as alternatives to frequency division multiple access (FDMA). With TDMA, the usage of each radio channel is partitioned into multiple timeslots, and each user is assigned a particular frequency/timeslot combination. Thus, only a single subscriber in a given cell is using a given frequency at a particular time. With CDMA a frequency channel is used simultaneously by multiple users in a given cell, and the signals are distinguished by spreading them with different orthogonal codes. One obvious advantage of both TDMA and CDMA is the sharing of radio hardware in the base station among multiple users.

Digital systems can support more users per base station per MHz of spectrum, allowing wireless system operators to provide service in high density areas more economically. The use of TDMA and CDMA digital architectures also offers additional advantages [1], [4]:

- A more natural integration with the evolving digital wireline networks.
- Flexibility for mixed voice/data communication and the support of new services.
- A potential for further capacity increases as reduced rate speech coders are implemented.
- Reduced RF transmit power.
- Encryption for communication privacy.
- Reduced system complexity with fewer radio transceivers.

1.3 Introduction to CDMA

As the wireless industry grows at a phenomenal rate, radio planners and subscribers are demanding greater capacity, improved call quality and enhanced services. Hence more and more operators are turning to CDMA for the numerous benefits it offers. These benefits include[1],[3]:

- Spectral efficiency and capacity increases
- Elimination of frequency planning
- Improved call quality
- Enhanced privacy
- Improved coverage characteristics
- Bandwidth on demand

Literally, the CDMA system is one in which the transmitted signal is spread over a wide frequency band, much wider, in fact, than the minimum bandwidth required to transmit the information being sent. The spread spectrum system takes a base band signal of only a few kilohertz and distributes it over a band that may be many megahertz wide.

Four methods of implementing CDMA are available:

1. Direct sequence modulation scheme.
2. Frequency Hopping system.
3. Time Hopping system.
4. Pulsed FM system.
5. Hybrid forms.

These methods are described in the following paragraphs.

1. **Direct sequence(DS) modulation scheme:** This is the modulation of a pre-information modulated carrier by an orthogonal code sequence. The code sequence is information coded before it modulates the carrier. This modulation is generally 180 degrees biphase PSK. Concerning the receiver, the receiver signal after being amplified, is multiplied by a reference with the same code. Assuming the transmitter's and receiver's codes are synchronous, the carrier inversions transmitted are removed and the original carrier is restored. This narrow band restored carrier can flow through a bandpass filter designed to pass only the baseband-modulated carrier.

2. **Frequency Hopping(FH) system:** Frequency hopping is nothing more than FSK except that the set of frequency choices greatly expanded. This system consists basically of a code generator and a frequency synthesizer capable of responding to the coded output from the code generator. Over a period of time, the ideal FH spectrum would be perfectly rectangular, with transmissions distributed evenly in every available frequency channel. The transmitter should also be designed to transmit the same amount of power in every channel. The received FH signal is mixed with a locally generated replica, which is offset a fixed amount such that $\{f_1, f_2 \ldots, f_n\}\ X$ $\{f_1+f_{IF}, f_2+f_{IF}, \ldots f_n+f_{IF}\}$ produces a constant difference frequency f_{IF} when transmitter and receiver codes are in synchronism.

3. **Time Hopping(TH) system:** Time hopping is familiar pulse modulation; i.e. the code sequence is used to key the transmitter on and off. Transmitter on and off times are therefore psedorandom, like the code, which can give an average transmit duty cycle as much as 50%. The difference between FH and TH systems is that in FH systems the transmitted frequency is changed at each code chip time, whereas a TH system may change frequency and/or amplitude only at one/zero transitions.

4. **Pulsed FM systems:** This form has found it's main application in radar systems, but is also applicable to communications. Chirp transmissions are characterized by pulsed RF signals whose frequencies vary in some known way during each pulse period. The receiver used for chirp signals is a matched filter, matched to the angular rate of change of the transmitted frequency swept signal.

5. **Hybrid forms:** In addition to the usual forms of spread spectrum communication there are the hybrid forms of modulation that offer certain advantages over, or at least extend the usefulness of, DS and FH techniques. Common hybrid combinations are simultaneous FH and DS modulation, simultaneous TH and FH modulation and simultaneous TH and DS modulation. The advantage in using these hybrid techniques is that usually characteristics can be provided which don't normally exist with a single type of modulation scheme.

1.4 Mathematical analysis of CDMA:

Consider the following binary data sequence *b(t)* and code *c(t)* of length *L*. Both these sequences are considered to be in their polar form (two levels equal in amplitude and opposite in polarity). We know from Fourier transform theory that multiplication of two unrelated signal in the time domain produces a signal whose spectrum equals the convolution of the spectra of the two component signals [1]. Since the code is of length *L*, each bit of the data sequence will be multiplied by the entire length of the code *c(t)*. Hence in effect the data sequence is spread by a factor equal to the code length *L*.

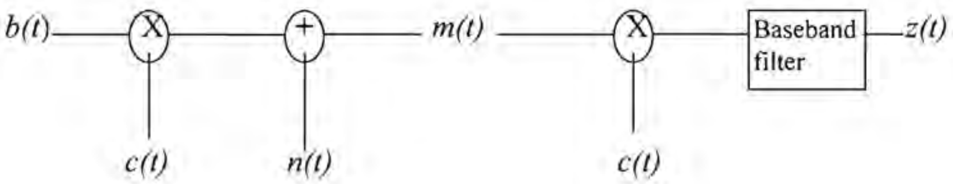
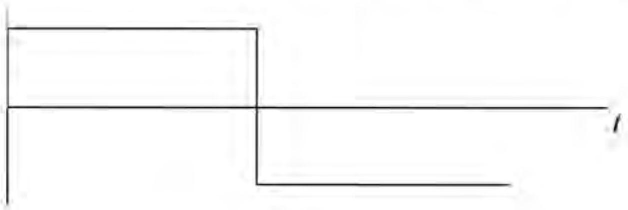


Fig. 1 Model of baseband CDMA system.

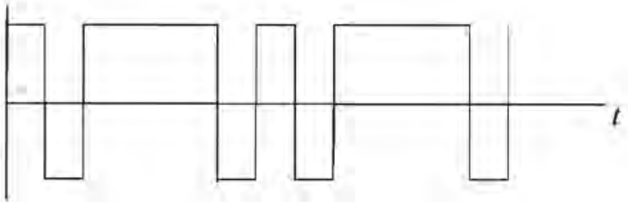
Therefore by multiplying the information-bearing sequence *b(t)* by the code *c(t)* we obtain the transmitted signal as

$$m(t) = b(t).c(t) + n(t) \tag{1.1}$$

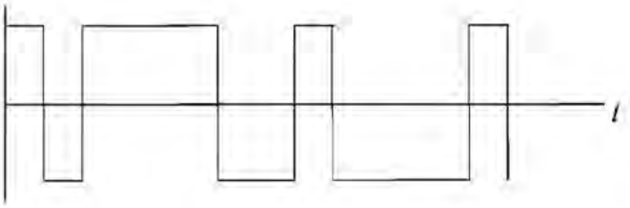
where *n(t)* is the additive noise to the system. This is illustrated graphically as follows:



(a) Data *b(t)*



(b) Orthogonal code *c(t)*



(c) Product signal *m(t)*

Fig. 2 Transmitter waveforms of a CDMA system.

At the receiver the received signal *m(t)* is demodulated by multiplying it with the same code word *c(t)* to recover the original signal:

$$z(t) = c(t).m(t)$$

$$= c^2(t).b(t) + c(t).n(t) \qquad (1.2)$$

Since the codeword *c(t)* alternates between the levels -1 and +1, the alternation is destroyed when the sequence is squared, hence

$$c^2(t) = 1, \qquad \text{for all } t$$

Therefore,

$$z(t) = b(t) + c(t).n(t) \qquad (1.3)$$

The signals are separated at the receiver by using a correlator that accepts only signal energy from the desired binary sequence and despreads its spectrum. The other user's signals whose codes don't match, are not despread in bandwidth and, as a result, contribute only to the noise and represent a self-interference generated by the system. All of the desired signal's energy will pass through a narrow-bandwidth filter following the correlator, while the interfering signals energy is reduced by the ratio of the bandwidth before the correlator to the bandwidth after the correlator, greatly improving the the SNR for the desired signal. This improvement ratio is termed as processing gain [2]. The overall system gain can be defined as [10]:

CDMA gain = Process gain - Process loss due to *k* users

where

Process loss = $10 \log(k)$, *BW* - Bandwidth , R_b - Bit-rate & *k* - number of CDMA users.

$$\therefore\ CDMA\ gain = 10\log\left(\frac{BW}{R_b}\right) - 10\log(k)$$

$$= 10\log\left(\frac{BW}{kR_b}\right) \qquad (1.4)$$

It can be seen from Fig. 3 that the processing gain of the CDMA system decreases with addition of users to the system. We see that the maximum processing gain due to the spreading of the signal is 12.04 dB.

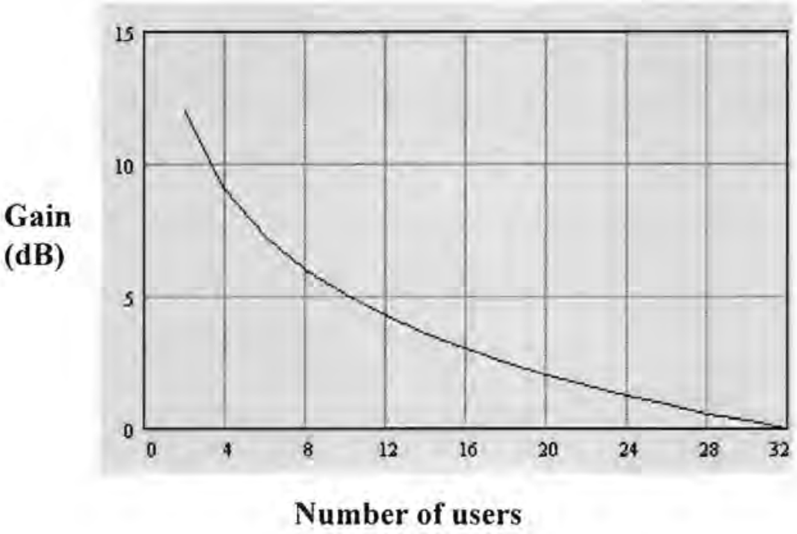


Fig. 3 CDMA gain verses additional number of users.

1.5 Advantages of CDMA over TDMA and FDMA

Code Division Multiple Access as a scheme of accessing various users has numerous advantages over Time Division Multiple Access and Frequency Division Multiple Access [9]. Multiple access schemes are used to allow many users to share simultaneously a finite amount of radio spectrum. This sharing of the spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth to multiple users.

FDMA has it's main advantages in that it requires simple signal processing and has a low cost implementation in a benign environment. Since FDMA is a continuous transmission scheme, fewer bits are needed for overhead purposes (such as synchronization and framing bits) as compared to TDMA [9],[3]. The greatest drawback with FDMA is with channel assignment. It is not reasonable to assign a unique frequency to each user as there are not sufficient frequencies and the spectral resource would be wasted whenever the user is idle. Instead methods that allocate channels on demand can make more efficient use of the spectrum.

TDMA shares a single carrier frequency with several users, where each user makes use of nonoverlapping time slots. The number of time slots per frame is dependent upon factors like modulation technique, available bandwidth, delay of signal and bit rate [3]. Data transmission for users in TDMA is discontinuous and occurs in bursts meaning that the subscriber unit's transmitter is inactive when not in use. TDMA systems require adaptive equalizers, since data rates are high compared to FDMA. Also a high level of synchronization overhead is required as the TDMA transmissions are slotted and this requires the receiver to synchronize on every burst. TDMA has the advantage over FDMA that it is possible to allocate different number of time slots per frame to different users hence bandwidth can be provided on demand to the requirement of the user.

The advantages of using CDMA over FDMA and TDMA are as follows [1],[8],[9]:

- **Voice Activity Cycles**. CDMA is the only technique that succeeds in taking advantage of the nature of human conversation. Human voice activity cycle is only 35%, the rest of the time we are listening. In CDMA all the user are sharing one radio channel and because each channel user is active for 35% of the cycle, all other users benefit with less interference (i.e. mutual interference is reduced by 65%); and thus channel capacity is increased about three times.
- **No Equalizer Needed**. When the transmission rate is much higher than 10 kb/s in both FDMA and TDMA, an equalizer is required. On the other hand, CDMA needs only a correlator, which is cheaper than the equalizer.

- **No Guard Time in CDMA**. TDMA requires the use of guard time between time slots. This guard time occupies the time period for certain bits. This "waste" of bits doesn't exist in CDMA, because guard time isn't required in CDMA technique.
- **Less Fading**. Less fading is observed in wide-band signal while propagating in a mobile radio environment.
- **Capacity Advantage**. Given the correct parameters, CDMA can have four times the TDMA radio capacity; and twenty times FDMA radio capacity per channel per cell.
- **No Frequency Management or Assignment required**. In both, TDMA and FDMA, the frequency management is always a critical task to carry out. Since there is only one channel in CDMA, no or very little frequency management is required.
- **Soft Capacity**. CDMA unlike TDMA and FDMA has a soft capacity limit. Increasing the number of users in a CDMA system raises the noise floor in a linear manner. Thus there is no absolute limit on the number of users in CDMA, the system performance degrades as more users are added and conversely improves as system users are reduced.
- **Coexistence**. Both systems, analog and CDMA can operate in two different spectra's, with no interference at all.
- **For Microcell and In-building Systems**. CDMA is a natural waveform suitable for microcell and in-building.

2. ORTHONORMAL SIGNATURE CODES

2.1 Introduction

Capacity considerations do not say much about orthogonal codes, except that they should possess low cross correlation properties. Essentially they should look like Gaussian noise to all but the intended receiver. They should also have low, ideally zero, autocorrelation between non-adjacent bits of the sequence. Other system considerations, however, dictate many additional properties of the codes [4], [16], [26]:

- Timing in the subscriber stations is to be established, at least in part, by synchronizing with the code radiated by the central base station. The goal is to eliminate any need for accurate timekeeping in the subscriber stations when they are idle.
- The subscriber stations identify the base station, at least in part, by correlating with a priori known base station orthogonal code.
- The process of synchronization in the subscribers should be rapid enough that the placement of a call from a "cold start" takes no more than a few seconds.
- Access to base stations by subscribers should not require any pre-arrangement. That is, it should not be necessary for the base station to have a database of authorized users in order to establish radio communications. The base station, once physical layer access has been achieved, may choose to deny the service for administrative reasons, such as non-payment of bill, but communication through the air interface should be possible no matter what. This is important for emergency messaging.
- In the CDMA forward link the fact that multiple channels are being radiated by each base station can be used to advantage to decrease mutual interference.

- The acquisition search rate for reverse CDMA channel signals in the base stations can be speeded if the receiving stations can pre-correct their timings so that their signal arrives at the base station as close to system time as possible.

Three criteria may be used to evaluate the performance of spreading CDMA codes:

1. The sequence length and family size.
2. The autocorrelation factor.
3. The crosscorrelation factor.

1. **Sequence length and family size:** The length of the spreading sequence is directly linked to the family size of the class of spreading codes. In addition, the correlation characteristics of the spreading sequence also determine the capacity of the system. In a CDMA environment it is desirable to have a code with perfect correlation characteristics. This is because a number of users must each be assigned it's own unique code. A number of unique spreading codes of certain length N are therefore required. The number of codes that can be generated with similar correlation characteristics is called the family size of the class of code sequences. The larger the family size is, the more codes can be generated, causing easier assignment to individual users.

2. **Autocorrelation:** Autocorrelation refers to the degree of correspondence between a code and a phase-shifted replica of itself. Autocorrelation plots show the number of agreements minus disagreements for the overall length of the two codes being compared, as the codes assume every shift in the field of interest. Two kinds of autocorrelation can be distinguished:

   Aperiodic autocorrelation: This is written mathematically as [1]:

   $$R_{xx}(\tau) = \int_{-\infty}^{\infty} x(t)x(t+\tau)dt \tag{2.1}$$

   where *x(t)* is the signal from which the aperiodic autocorrelation is being calculated.

Periodic autocorrelation: The definition of periodic autocorrelation function is similar to that of aperiodic autocorrelation, but calculated only for shift values smaller or equal to the sequence length N. This is expressed as [1]:

$$R_{xx}(l) = \sum_{k=0}^{N-1} x(k)x[(l+k)\,\mathrm{mod}(n)] \tag{2.2}$$

3. **Crosscorrelation:** The crosscorrelation function shows the correspondence between two signals at different phase shifts. Both periodic and aperiodic crosscorrelation functions are defined:

   Periodic crosscorrelation: This is defined as [1]:

$$R_{xy}(l) = \sum_{k=0}^{N-1} x(k)y[(l+k)\,\mathrm{mod}(N)] \tag{2.3}$$

   Aperiodic crosscorrelation: The aperiodic crosscorrelation is defined in a similar way to the aperiodic autocorrelation as given in eqn. (2.1).

   The ideal crosscorrelation function should be zero at all phase shifts. This is not easily obtainable in practice as will be seen subsequently.

A pair of codes is said to be orthogonal if the cross-correlation is zero [3]. For two n-bit codes: $x_1, x_2, \ldots, x_n$ and $y_1, y_2, \ldots, y_n$, this is given by

$$\mathrm{R}_{xy}(0) = \sum_{i=1}^{n} x_i y_i = 0 \tag{2.4}$$

For example, the cross-correlation between two 4-bit codes:

$$\mathrm{x} = 0 \quad 0 \quad 1 \quad 1$$

$$\mathrm{y} = 0 \quad 1 \quad 1 \quad 0$$

will be

$$\begin{array}{rrrr} -1 & -1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ \hline \end{array}$$

$$\mathrm{R}_{xy}(0) = \quad 1 - 1 + 1 - 1 = 0$$

where all 0s are replaced by -1. We also notice that an orthogonal code has an equal number of 1s and 0s. The converse of this is however not true i.e. codes having equal number of 1s and 0s need not be orthogonal. Hence we can conclude that an orthogonal code has two basic properties :

1. An equal number of 1s and 0s;
2. Zero cross-correlation property.

An orthogonal code, which is normalized to have unit energy, is termed as a orthonormal code i.e. it is orthogonal and normalized. We shall see that it is possible to construct orthonormal codes from the rows of Hadamard matrices.

2.2 Different Spreading Sequences

The importance of the code sequence to a CDMA system is difficult to overemphasize, for the type of code used, it's length, and it's chip rate set bounds on the capability of the system that can be changed by only changing the type of code sequence.

Binary spreading sequences are sequences that take on the values {+1,-1}. Amongst these are maximal length sequences, Gold sequences, Kasami sequences and Hadamard sequences. Binary sequences are the most widely used in CDMA applications because of their ease of implementation. I have chosen the Hadamard sequence for my application and the other possible sequences will be described briefly.

Maximal length sequence: The basic definition of a maximal length sequence is "the longest codes that can be generated by a given shift register with a delay element of a given length. When the sequence is generated by a *n* stage shift register, the sequence is constituted by 2^n-1 chips. Properties of maximal length sequences are [1],[6]:

- Number of ones = number of zeros + 1, thus the DC component of the code or the code modulated signal can be neglected.

- The statistical distribution of ones and zeros is well defined and always the same. Relative positions of the runs vary from one code sequence to another, but the number of each run length does not.
- For all values of phase shift, the correlation value equals –1, except for 0 ± 1 chip phase shift area, in which correlation varies from the –1 value to 2^n-1(sequence length), in case the correlation is calculated over the entire sequence length.
- Possess an interesting combinatorial property. When two m-sequences of different length, say 2^n-1 and 2^p-1, are added, the result is a composite sequence which is not maximal but may be a segment of a longer maximal sequence. Thus a pair of sequences of length *r* can generate *r* non-maximal linear codes, each *r* chips long.

Gold sequences: These are a very good type of binary spreading sequences with good correlation properties. Gold codes are created by modulo-2 addition of a pair of maximal linear sequences. The code sequences are added chip by chip by synchronous clocking. Another way of explaining Gold code creation is though the generation by a preferred pair of primitive polynomials of degree *n*, where 4 divides *n*, whose corresponding shift registers generate sequences of period 2^n-1. Gold sequences have the following properties [1],[3]:

- Sequence length: $N = 2^n - 1$
- Family size: $M = 2^n + 1$ where 4 divides n.

One of the main advantages of using Gold sequences is the large family size it provides. This makes it easy to assign different Gold codes to each user operating in the CDMA system. In addition Gold codes may be chosen so that over a set of codes available from the given generator the cross-correlation between the codes is uniform and bounded. The same guarantee of bounded cross-correlation is impossible for maximal sequences of the same length.

Kasami sequences: These sequences were developed at the same time as the Gold sequences. Kasami sequences can be generated by finding a m-sequence that we can call *A* of length $N=2^n-1$ and forming a sequence *B* by decimating *A* by a factor $2^{n/2}+1$. The sequence *B* will then be periodic with period $2^{n/2}-1$. Repeating *B* $2^{n/2}+1$ times, will yield a sequence equal in length to *A*. By adding *A* modulo-2 to *B* and all of it's cyclic shifts and by including *A*, $2^{n/2}$ sequences of length 2^n-1 are obtained. Properties of Kasami sequences are [9],[15]:

- Sequence length: $N = 2^n-1$.
- Family size: $M = 2^{n/2}$.
- Kasami sequences have lower autocorrelation and cross-correlation sidelobes than Gold codes.

2.3 Hadamard Matrices

An $n \times n$ matrix $H = h_{ij}$ is a Hadamard matrix of the order n if the entries of *H* are either +1 or –1 and such that

$$HH' = nI \tag{2.5}$$

where H' is the transpose of *H* and *I* is the order n identity matrix [9]. This can also be stated as, a (+1,-1) matrix is Hadamard if the inner product of two distinct rows is zero and the inner product of a row with itself is *n*.

These matrices were first considered as Hadamard determinants. They were so named because the determinant of a Hadamard matrix satisfies equality in Hadamard's determinant theorem [26], which states that if $X = x_{ij}$ is a matrix of order *n* where $\left|x_{ij}\right| \leq 1$ for all I and j, then

$$|X| \leq n^{(n/2)} \tag{2.6}$$

It is apparent that if the rows and columns of a Hadamard matrix are permuted, the matrix remains Hadamard. It is also true that if any row or column is multiplied by –1, the Hadamard property is retained. Thus, it is always possible to arrange to have the first row and the first column of a Hadamard matrix contain only +1 entries. A Hadamard matrix in this form is said to be normalized. Hadamard matrices have the following properties [10]:

1. The order of a Hadamard matrix is 1,2 or $4n$, where n is an integer.
2. If H is a normalized Hadamard matrix of order $4n$, then every row (column) except the first has $2n$ minus ones and $2n$ plus ones, further n minus ones in any row (column) overlap with n minus ones in each other row (column).

2.4 Hadamard Code Construction

We assume that the spreading code period is equal to the symbol period and consider a rectangular chip pulse. The cross-correlation of the data-modulated code sequences for users i and k is [26]

$$R_{s_i s_k}(\Delta T_c) = T_c \sum_{l=0}^{N-1} c_l^k \left((1-|\Delta|)c_l^i + |\Delta| c_{l\pm1}^i\right) \tag{2.7}$$

Given a specific set of orthogonal sequences, we can assign each sequence as the signature code of a user. The error probability for a given user will depend on the set of active users (up to maximum equal to the number of orthogonal sequences), and on the chip offsets for the interfering users relative to the user of interest.

Previously the main criterion for code set design was based on worst case cross-correlation's [16]. In this case however we would like to design a set of sequences where the average of the square of the cross-correlation's over all pairs of sequences is minimized. If the squared cross-correlation's for the different users vary considerably with respect to the overall average then the performance of the different users can be made equal by cyclically changing the code over the entire set of codes such that no two users utilize the same code simultaneously.

To minimize cross-interference, we seek an orthogonal set that minimizes $E\left\{Rs_i s_k\ (\Delta T_c)\right\}$, where the expectation is taken over the random variable Δ and over all pairs of codes in the set. We write

$$E\left\{Rs_i s_k\ (\Delta T_c)\right\} = T_c E(\Delta^2)\mu_{cor}(N) \tag{2.8}$$

where

$$\mu_{cor}(N) = E\left\{\left(\sum_{l=0}^{N-1} c_l^k c_{l+1}^i\right)^2\right\} \tag{2.9}$$

To maximize (2.5) we need to maximize $\mu_{cor}(N)$. Given a *N x N* Hadamard matrix $C = \left[c_i^j\right]$ with $c_i^j \in \{-1,1\}$, the rows are assigned as code sequences to a maximum of N users. The average of the squared cross-correlation's of the sequences, under a one chip offset, is

$$\mu_{cor}(N) = \frac{1}{2}\left(\mu_{cor+} + \mu_{cor-}\right) \tag{2.10}$$

where

$$\mu_{cor+} = \frac{1}{N(N-1)}\sum_{k=1}^{N}\sum_{\substack{i=1\\ i\neq k}}\left(\sum_{j=0}^{N-1} c_j^k c_{j+1}^i\right)^2 \tag{2.11}$$

and where $c_N^i = c_0^i$. We define μ_{cor-} the same as μ_{cor+} except that we set $c_N^i = -c_0^i$. Our aim is to find the Hadamard matrix C that minimizes (2.7).

For the variance of the multiple-access interference ψ to be minimum, we can see from (2.5) that $\mu_{cor}(N)$ should be minimized. The normalized variance of the multiple access interference γ is related by

$$\gamma = \frac{\Delta_m^{\ 2}\mu_{cor}(N)}{3N^2} \tag{2.12}$$

We wish to find Hadamard matrix C which minimizes $\mu_{cor}(N)$. We restrict the search to the case $N = 2^n$. In all cases of N considered, the best Hadamard matrices found to be equivalent to the conditions required are the $N \, x \, N$ Sylvester-type matrix [26]. This is defined recursively as

$$H_N = \begin{bmatrix} H_{N/2} & H_{N/2} \\ H_{N/2} & -H_{N/2} \end{bmatrix} \tag{2.13}$$

where $H_1 = 1$.

The spread of the distributions decreases, relative to N, as N increases except for an isolated point at a value approximately $\frac{2}{3}N$. The exact value, reproduced here [26], is

$$\mu_{cor}(N) = \frac{2}{3}(N+1) \tag{2.14}$$

Hadamard codes can be created in the following simple manner. The design of the codes has to cater for two provisions [1]:

1. Each code is approximately orthogonal (i.e.. has low cross-correlation) with all the other codes.
2. The CDMA system operates asynchronously, which means that the transition times of a user's data symbols do not have to coincide with those of the other users.

Step 1: Represent the $N \, x \, N$ matrix as four quadrants:

1st Quadrant	2nd Quadrant
3rd Quadrant	4th Quadrant

Step 2: Make the first, second and third quadrants identical and invert the fourth.

A	A
A	$\overline{A}$

where *A* is a bit that can be either 1 or -1. This process generates a *N*, *N*-bit Hadamard codes.

For example, for a 4 x 4 matrix (four 4-bit Hadamard codes), we have

$$\begin{array}{cc|cc} A & A & A & A \\ A & \overline{A} & A & \overline{A} \\ \hline A & A & \overline{A} & \overline{A} \\ A & \overline{A} & \overline{A} & A \end{array}$$

The Sylvester-type Hadamard matrix of length 32 is as follows where + indicates a 1 and - indicates a -1:

```
+ ++ ++ ++  ++ ++ + ++ ++ ++ + ++ + + +++ + ++  +++        code 1
+-+-+-+ -+-+-+-+-+-+ -+-+-+-+ -+-                          code 2
++- -++- -++- -++- -++- -++- -++- -++- -
+- -++- - ++- -++- -++- -++ - -++- -++ - -+
++++- - -  -++++- - - -++++-  - - -++++-  - - -
+-+- -+- ++-+- -+-++-+- - +-++-+- - +-+
++- - - -+ +++- - - -++++- - -  -++++- - -  -++
+- -+-++ -+- -+-++-+- -+- ++-+- -+- ++-
++++++++- - - -  - - - -++++++++- - -  - -  - - -
+-+-+-+- - +-+-+-++-+-+-+- -+ -+- +-+
++- -++- - -  -++- -++++- -++- - - -  ++-  -++
+- -++- -+- ++- -++-+- -++- -+-++- - ++-
++++- - - - -  - - -++++++++- - - - - -  - - ++++
+-+- -+-+- +-++-+ -+-+- -+-+-+ -++-+-
++- - - -++-  -++++-++- - - -++- -+++ +- - -
+- -+-++- - ++-+- -++- -+-++- -++- +- -+
++++++++++++++++- - - - - - - - - - - -  - - - -
+-+-+-+-+ -+-+-+- -+-+-+-+-+ -+ -+-+
++- -++- -++- -++- - - -++- -++- - ++ - -++
+- -++- -++ - -++- -+-++- -++- -++- -++-
++++- - - -+ +++- - - - - - - -++++- -  - - ++++
+-+- -+-++ -+- -+-+-+-++-+- -+ -++-+-
++- - - -+++ +- - - -++- -++++- - - - ++ ++- -
+- -+-++-+ - -+-++- -++-+- -+-++- +- -+
++++++++- - - - - - -  - - - - - - - - - ++++ ++++
+-+-+-+- -+ -+-+- +-+-+-+-++-+- +- +-
```

```
++- -++- - - - ++--++- -++- -++++- - ++ - -
+- -++- -+-++- -++ - -++- -++-+- -++- -+
++++- - - - - -  - -++++- - - -++++++++ - -  - -      code 29
+-+- -+-+-+ -++-+- -+-++-+-+ -+-  -+ -+
++- - - -++- - ++++- - - -++++- -++- -  - - ++        code 31
+- -+-++- -++-+- -+-++-+--++ - -+ -++-                code 32
```

Fig. 4 Sylvester type Hadamard Matrix with rows indicating orthonormal codes.

2.5 Cross-correlation Properties

In order for the CDMA system to have minimal interference between the users and to maximize the number of users the system can accommodate for a certain threshold level, we have to have the minimal cross-correlation values between the codes. For example consider the cross-correlation plot between two of the Hadamard codes of length 32 from Fig. 4.

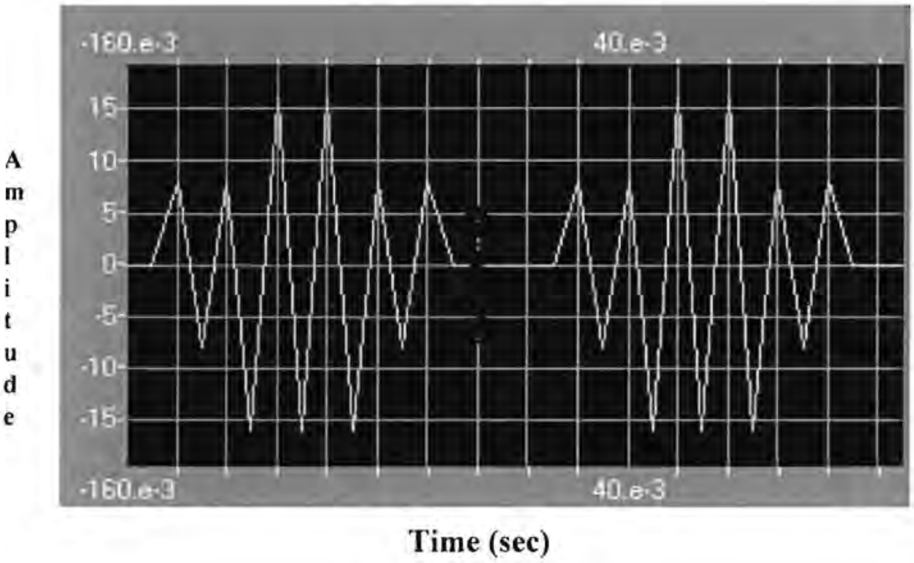
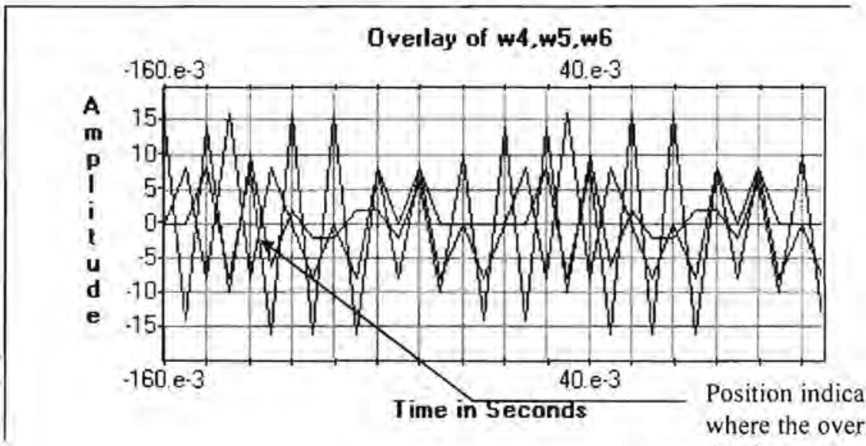


Fig. 5 Cross-correlation plot of two Hadamard codes.

From the above plot we can see that the cross-correlation value is zero at certain intervals. Hence from this computation we can select the times that the two received signals must be sampled in order to yield the lowest interference. In this manner we can compute the cross-correlation's of a single code with all the other codes being allocated to the different users in the system and an overlay of all the plots will indicate the time which will yield the lowest cross-correlation value possible. The figure below shows the overlay of cross-correlation values of a single code with three other codes.

From the point indicated we can observe that this is the best time for sampling of all the three users to yield the lowest cross-correlation value and hence interference value with respect to each other.



Position indicating where the overlap of the three cross-correlations is minimum.

Fig. 6 Overlay of cross-correlation plots of three codes.

From cross-correlation studies done we can also observe that the Hadamard codes of length 32 selected display good cross-correlation properties and hence theoretically should work well for the CDMA system to be simulated.

2.6 Phase constellation of the Hadamard codes

Fig. 7 shows the phase constellation of the Hadamard code sequence. From the simulation it is evident that the modulated signal possesses constant envelop properties. This can be seen from the pattern of the samples forming a unit circle. Constant envelope properties imply a continuous-phase type of modulation scheme where amplitude of the carrier is constant, regardless of the variation in the modulating signal.

The simulations in Fig. 7 were carried out with code length 32 and number of samples equal to 32000 for a single user in the CDMA system. It is possible to linearly interpolate the phase difference between two successive phase samples of the Hadamard sequence on the unit circle, and to use these values to reconstruct the original signal.

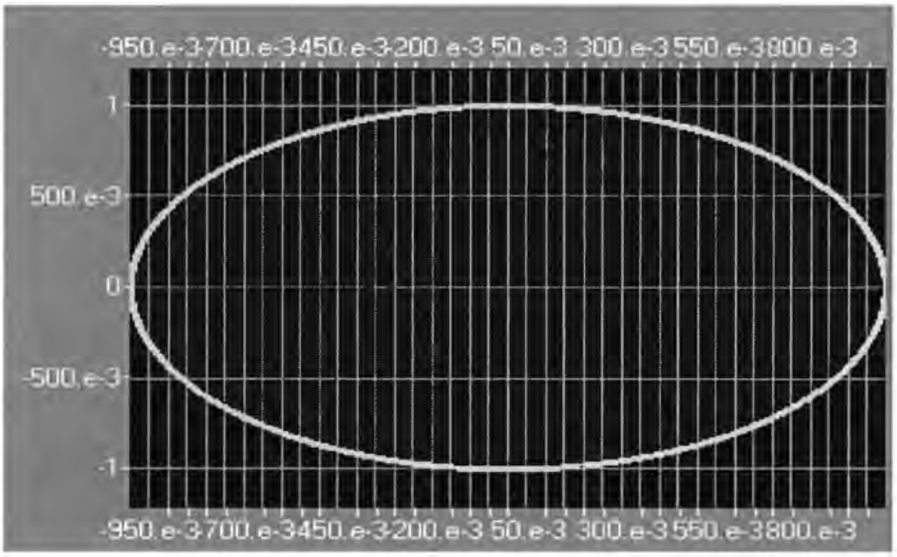


Fig. 7 Phase constellation for a single user modulated by a Hadamard code.

Fig. 8 shows the simulated results for the similar code length 32 but with four users in the CDMA system for 32000 samples.

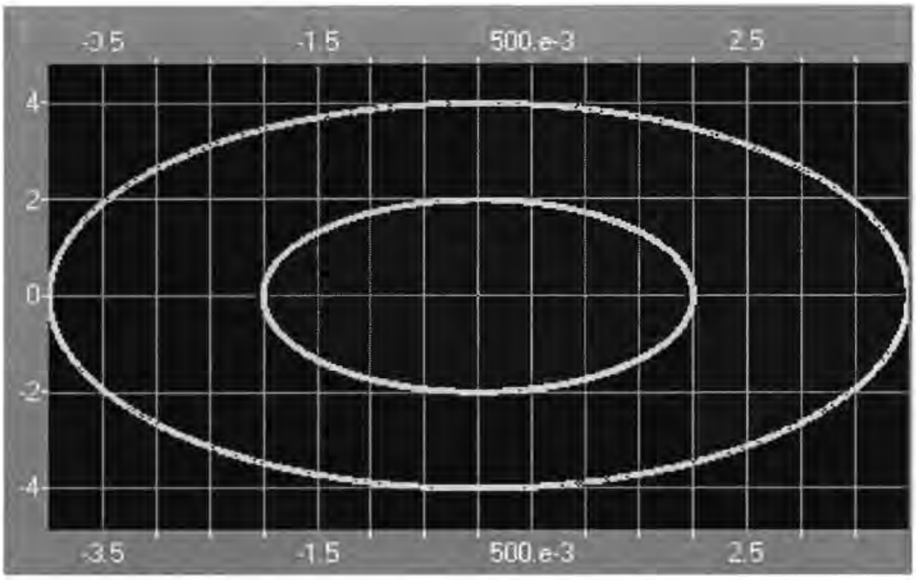


Fig. 8 Phase constellation for 4 users modulated by Hadamard codes.

It is interesting to note the effect of the mapping of the constellation with the addition of more users. In case of four CDMA users, the inner circle is twice unity and the outer one is four times unity circle.

3. SYSTEM SPECIFICATION AND DISCRIPTION

3.1. System Description

The CDMA system to be designed consists of a PMP network with a star topology assumed. This implies that all the multipoint users are communicating via a central base station. The system is designed to accommodate upto 30 multipoint users. Theoretically since a 32 length orthogonal code is being implemented, we can accommodate 32 users, but normally two codes are used for synchronization and overhead purposes.

Each user will be transmitting at a data rate of 64 kbps and when modulated by a code of length 32 gives an effective bandwidth of 2.048 MHz. Hence the channel bandwidth required for the system is 2.048 Mbps. All the multipoint users can transmit simultaneously at 64 kbps and the receiver will separate the users based on their unique orthonormal codes with which they are multiplied.

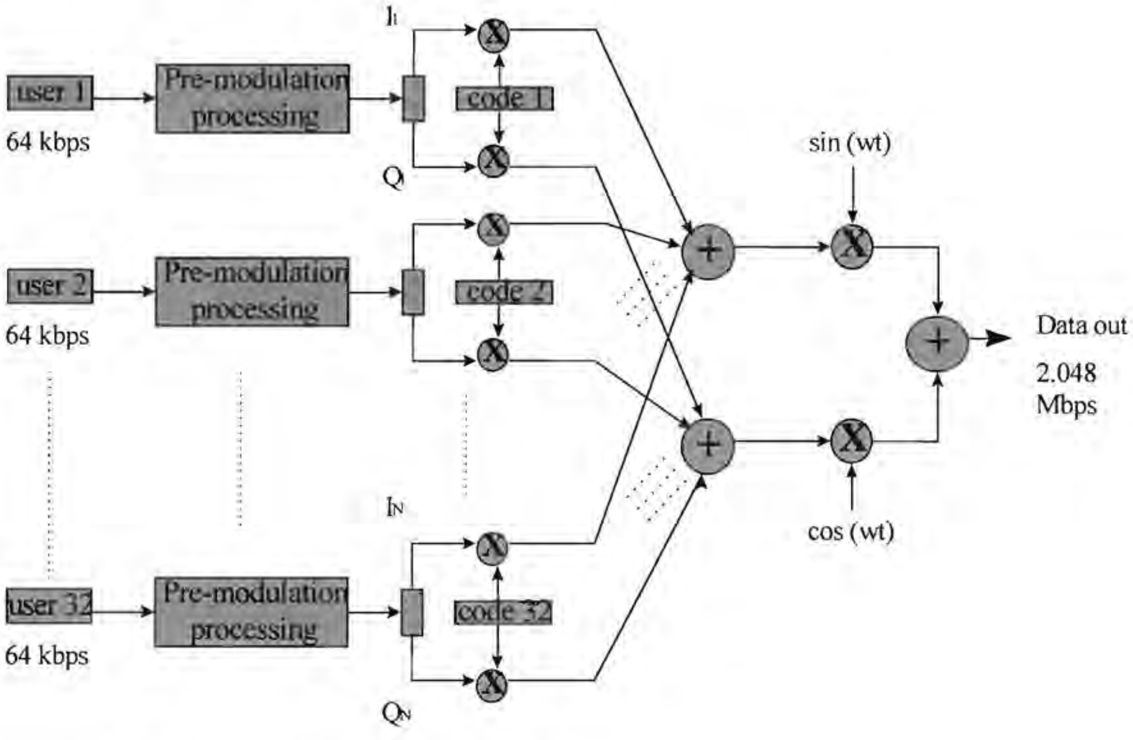


Fig. 9 Up-link system block diagram.

To provide better interference rejection capability and less complex synchronization a unique CDMA and BPSK scheme was adopted which shall be described. The block diagram of the up-link is illustrated in fig. 9.

From the block diagram we can see that each users data is split up first into a in-phase and quadrature channel. Both the in-phase and quadrature channels data is multiplied by the orthonormal code. This same procedure is repeated for all the users. Then the sum of all the in-phase and sum of all the quadrature channels is BPSK modulated as shown and then summed to give a net data output.

The receiver block diagram is as follows:

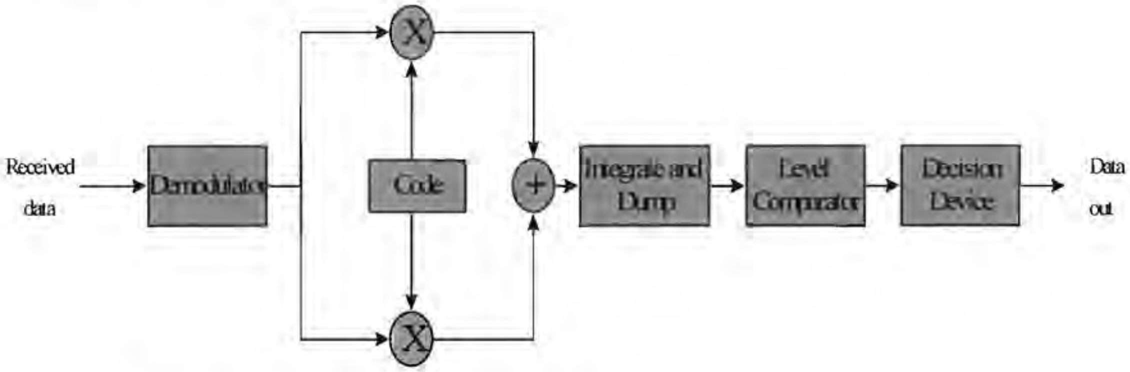


Fig. 10 CDMA receiver block diagram.

At the receiver the modulated and coded data is first demodulated using a Costas loop demodulator. The output of this modulator gives us the data in the in-phase an quadrature format. Both these channels are then multiplied by the same code used at the user's transmitter. This second multiplication causes the signal to be collapsed to it's original format where it is then summed. The data is then integrated and dumped over the pulse-width and then level detected to yield the final output data.

For all our transmitter and receiver descriptions, we shall concentrate on the reverse link. Also since CDMA systems are interference limited it is assumed that all the users provide average power control in the reverse link.

3.2 Transmitter, Channel and Receiver Model

In this section we deal with the mathematical aspects of the CDMA system treating the transmitter, receiver and the channel as different units. For modulation in case of wireless systems two methods are normally employed, Binary Phase Shift Keying (BPSK) and Differential Phase Shift Keying (DPSK). It is known that BPSK gives a better error performance than DPSK but it's only drawback is that it requires coherent detection which is difficult to achieve in a mobile wireless environment but in our case of a fixed PMP system, it is the better choice.

Transmitter

The transmitted signal of the kth user is

$$s_k(t) = Aa_k(t)b_k(t)\cos\left[\omega_c(t) + \theta_k\right] \tag{3.1}$$

where

$$a_k(t) = \sum a_k^i P_{T_c}(t - iT_c) \tag{3.2}$$

$$a_k^i \in \{-1,1\}$$

and $$b_k(t) = \sum_i b_k^i P_{T_b}(t - iT_b) \tag{3.3}$$

$$b_k^i \in \{0,1\}$$

The index k refers to the k^{th} user. The parameter b_k is the user data waveform, b_k^j is the j^{th} bit of the data waveform, a_k^i is the i^{th} chip of the Hadamard orthonormal code, P_T is is a rectangular pulse of unit height and duration T, and T_b and T_c are the bit and chip duration respectively. It is assumed that $T_b/T_c = N$, where N is the length of the Hadamard orthonormal code.

Channel Model

The complex lowpass equivalent of the radio channel's impulse response is given by [8]:

$$h_k(t) = \sum_{l=1}^{L} \beta_{lk} \exp\{ j\gamma_{lk} \} \delta(t - \tau_k) \tag{3.4}$$

where β , τ , and γ are the path gain, time delay and phase of each path, respectively. The subscript *lk* refers to the l^{th} of the k^{th} user and *j* is an imaginary number defined as $j^2 = -1$. It is also assumed that the path phase of the received signal, $\left(\omega_c \tau_{lk} + \gamma_{lk}\right)$, is an independent random variable uniformly distributed over [0, 2π]. The path delay is also an independent random variable and is assumed random over [0, T_b]. The number of paths, *L*, may be fixed or randomly changing. Here fixed values of *L* are assumed since the CDMA system is stationary one, according to

$$L = \left[\frac{T_{\max}}{T_c} \right] + 1 \tag{3.5}$$

where $T_{\max}$ is the delay spread.

Receiver

The actual signal received at a given receiver in the model for an additive, possibly impulsive channel is given as [20], [21]

$$r(t) = n(t) + \sum_{k=1}^{K} \sqrt{2P_k}\, b_k(t - \tau_k) a_k(t - \tau_k) \cos(\omega_c t + \phi_k) \tag{3.6}$$

where *n(t)* represents the channel noise, P_k is the power received from the k^{th} user, ω_c is the carrier frequency common to the *K* signals, and where ϕ_k and τ_k are the phase and delay, respectively, of the k^{th} signal at the receiver. The signal representing the kth user's binary data sequence is $b_k(t)$, which is a sequence of unit amplitude, positive and negative, rectangular pulses of duration *T*. This data signal is modulated onto a phase coded carrier. The code waveform $a_k(t)$ is generated by the Hadamard code sequence assigned to the k^{th} user. This code sequence which spreads the data sequence by a factor N can be written as

$$a_k(t) = \sum_{j=-\infty}^{\infty} a_j^{(k)} P_{T_c}(t - jT_c), \quad k = 1, 2, \ldots, K \tag{3.7}$$

where $a_j^{(k)} \in \{-1,+1\}$ and also $a_j^{(k)} = a_{j+N}^{(k)}$ for all j and k and for some integer N. We are also assuming that N is the least period of the sequences. The parameter T_c is the chip length, and we assume that $T = NT_c$ so that there is one code period

$a_0^{(k)}, a_1^{(k)}, \ldots, a_{N-1}^{(k)}$ per data symbol.

For each signal in (3.6), there is an associated delay τ_k for a given receiver. This time delay accounts for propagation delay and the lack of time synchronization between transmitters. The correlation receivers studied here are assumed to be matched to the first of the K signals in the CDMA system hence we need to only consider time delay and phase angles relative to user 1. We therefore assume $\phi_1 = 0$ and $\tau_1 = 0$ in the analysis of the receiver synchronized to the first user's signal. Furthermore there is no loss of generality in assuming $\phi_k \in [0, 2\pi]$ and $\tau_k \in [0, T]$, $2 \le k \le K$ since we are concerned only with time delays modulo T and phase shifts modulo 2π.

The hard-limiting correlation receiver is depicted in Fig. 11 below:

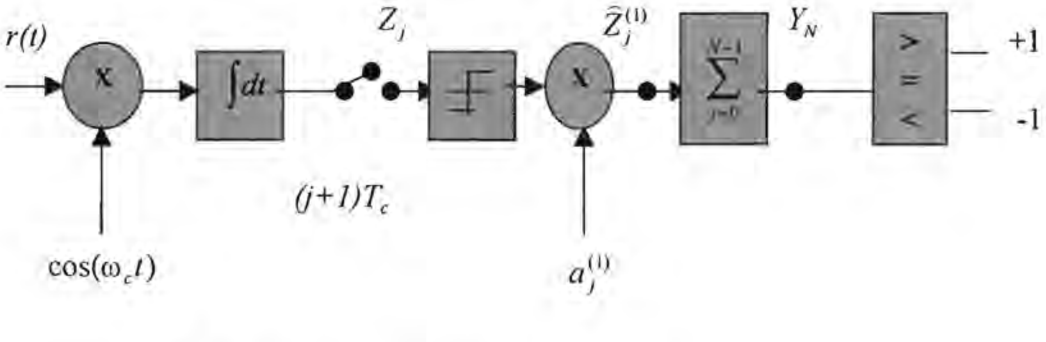


Fig. 11 Hard-limiting correlation receiver

The structure of the non-linear correlator includes a low-pass filter to transform the received signal to the baseband. This low-pass filter is of the integrate-and-dump type, and it's output is sampled every T_c seconds. The sampler is followed by a sign detector and in turn by an accumulator.

The test statistic is thus written as

$$\begin{aligned} Y_N &= \sum_{j=0}^{N-1} \hat{Z}_j^{(1)} \\ &= \sum_{j=0}^{N-1} a_j^{(1)} \operatorname{sgn}(Z_j) \end{aligned} \tag{3.8}$$

where Z_j denotes the input to the hard limiter at the *(j+1)*th sampling instant and where *sgn( )* denotes the usual signum function.

Assuming equally likely bit polarities, the average bit error probability using the statistic of (3.8) can be written as:

$$P_e = \frac{1}{2} P_r\left[Y_N \geq 0 \middle| b_o^{(1)} = -1\right] + \frac{1}{2} P_r\left[Y_N < 0 \middle| b_o^{(1)} = +1\right] \tag{3.9}$$

where $b_m^{(k)}$ denotes the m^{th} data bit of the k^{th} user. Our statistical assumptions of the multiple access interference are identical to those in (3.8). In particular, we assume that the elements $b_k \in \left(b_{-1}^{(k)}, b_0^{(k)}\right), \tau_k, \phi_k | 2 \leq k \leq K$ are mutually independent random variables. It is also assumed that $b_m^{(k)}, -\infty < m < +\infty$ is a sequence of independent data bits for each k and m. The random variables τ_k and ϕ_k, $2 \leq k \leq K$ are assumed to be uniformly distributed over the sets of their possible values. We also assume that these variables are independent of the channel noise and of $b_m^{(1)}$ for all m.

4. EVALUATION OF SYSTEM PERFORMANCE

4.1 Probability of Error

In CDMA systems the exact calculation of error probabilities is computationally difficult so emphasis is placed on approximations and bounds. One attractive approximation is to use a signal-to-noise ratio in a Gaussian approximation, the "standard approximation" [28].

The system model description follows the model outlined in section (3.2) with K users and the k^{th} user's transmitted signal according to eqn. (3.1) reproduced as

$$s_k(t) = Aa_k(t)b_k(t)\cos\left[\omega_c(t) + \theta_k\right]$$

where $a_k(t) = \sum a_k^i P_{T_c}(t - iT_c)$ and $b_k(t) = \sum_i b_k^i P_{T_b}(t - iT_b)$.

The pulse and chip amplitudes are all independent, identically distributed random variables with probability of ½ of being ± 1. During demodulation at the receiver, the composite of all the user's signals is multiplied by a synchronized replica of the original signature sequence.

The decision statistic for the desired signal 1, normalized with respect to the chip duration T_c and with all signals' received power $P = 2$, is

$$Z_1 = N + \sum_{k=2}^{K} W_k \cos\theta_k \tag{4.1}$$

where W_k is given by

$$W_k = P_k S_k + Q_k(1 - S_k) + X_k + Y_k(1 - 2S_k) \tag{4.2}$$

Relative to the desired signal in eqn. (3.2), the k^{th} interfering user has a time offset to the nearest chip given by S_k and carrier phase θ_k. The random variables P_k and Q_k are uniform on $\{0,1\}$. We need to understand that W_k is dependent on S_k, the kth interfering user's time offset relative to the desired signal in eqn. (3.2), and θ_k, the carrier phase.

Another key quantity is B [28] which represents the number of chip boundaries in the desired signal at which a transition to a different value occurs. Consequently B can be interpreted as a measure of "spreading" given to the desired signal. B is obtained from the signature sequence discrete aperiodic autocorrelation C:

$$B = \frac{N-1-C}{2} \tag{4.3}$$

with

$$C = \sum_{j=0}^{N-2} a_j^{(1)} a_{j+1}^{(1)} \tag{4.4}$$

where $a_j^{(k)}$ is the j^{th} chip of the Hadamard code sequence

It is known that for BPSK, under appropriate Gaussian assumptions the probability of a bit error can be calculated as function Q of a signal-to-noise ratio (actually an E_b/N_o) with Q given as [1]:

$$Q[x] = \frac{1}{2\pi} \int_x^{\infty} e^{-\frac{u^2}{2}} du \tag{4.5}$$

The most straightforward application of this is to calculate a signal to noise ratio by evaluating the variance of the second term in eqn. (4.1). That second term is the multiple access interference (MAI) to the desired signal from the other users. This yields for probability of bit error P_e [27]:

$$P_e = Q\left[\sqrt{\frac{3N}{K-1}}\right] \tag{4.6}$$

The results of the theoretical and simulated tests are displayed in a graphical format in fig. 12 as displayed below. Practical simulations were carried out using SystemView in which the system was created component-wise. The BER counter was also created component-wise in SystemView to record the BER's during simulations

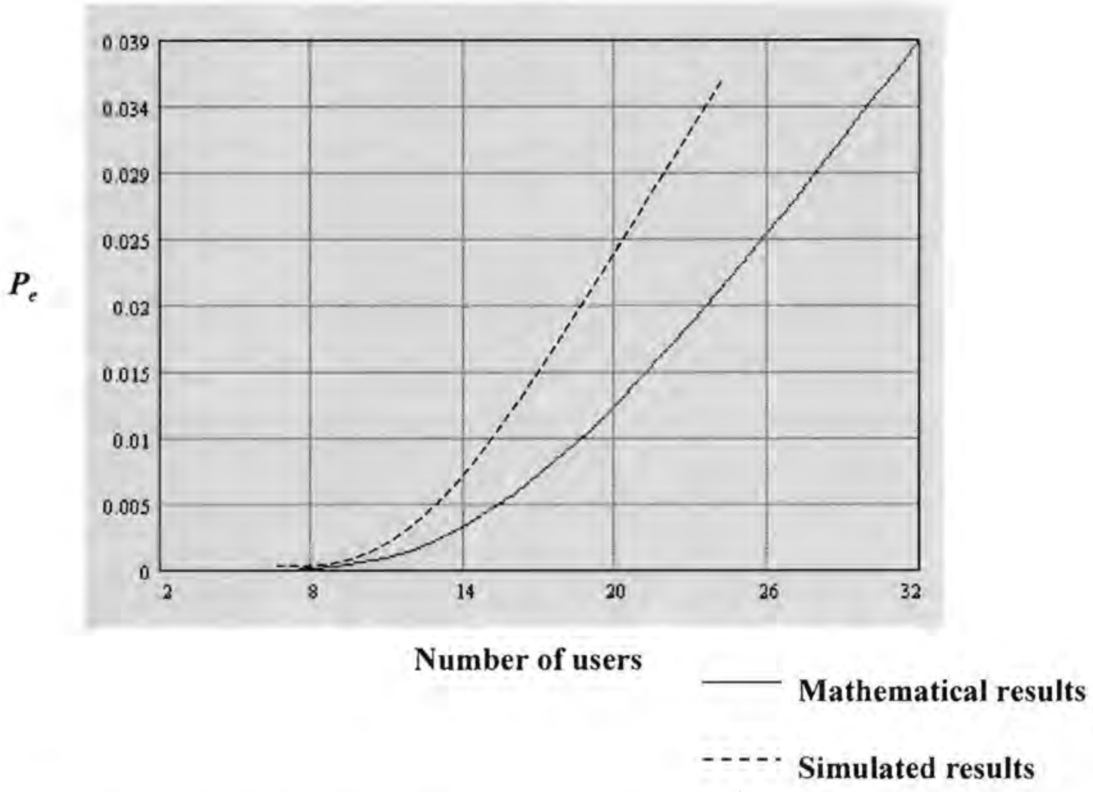


Fig. 12 Results showing Probability of Error (P_e) vs Number of CDMA users.

The small difference between theoretical and simulated results can be attributed to the fact that the theoretical equation does not take into account system losses such as AWGN added and other system component noise. Although the probability of error is very high, one must bear in mind that the simulations were carried out without any coding gain or addition of error detecting and correcting codes which would greatly improve the performance of the system. These simulations were carried out merely to demonstrate the feasibility of the novel CDMA system.

4.2 Improved Probability of Error with AWGN

An improved Gaussian approximation is given in [28] which is based on the observation that the (Multiple Access interference)MAI is approximately Gaussian, conditioned on the delays and phases of all the interfering signals and on *B*. Then an accurate approximation to the bit error probability is given by

$$P_e = \int_0^\infty Q\left[\frac{N}{\sqrt{\psi}}\right] f_\psi(\psi)\,d\psi \tag{4.7}$$

where

$$\psi = Var\left[MAI \middle| S, \theta, B\right] \tag{4.8}$$

with $S = (S_2, \ldots, S_K)$ and $\theta = (\theta_2, \ldots, \theta_K)$. ψ is given by $\psi = \sum_{k=2}^{K} Z_k$.

Note that (4.7) is the expectation of the function $Q\left[N / \sqrt{\psi}\right]$ of the random variable ψ^2. The randomness in ψ is due to the randomness of the Hadamard code sequences, time and phase offsets of the *(K-1)* interfering users and randomness associated with *B*. A considerable computational simplification can be made by using a result from [29]. Let *P* be a real function of ϕ, a random variable with mean μ and variance σ^2. Assuming the existence of derivatives,

$$P(\phi) = P(\mu) + (\phi - \mu)P'(\mu) + \frac{1}{2}(\phi - \mu)^2 P''(\mu) + \ldots\ldots \tag{4.9}$$

Taking expectations one obtains the well know approximation

$$E\left[P(\phi)\right] \approx P(\mu) + \frac{1}{2}P''(\mu)\sigma^2 \tag{4.10}$$

By implementing Stirlings formula (expansion in differences), this will yield significant benefits in both accuracy and computational simplicity. Thus:

$$E\left[P(\phi)\right] \approx P(\mu) + \frac{1}{2}\frac{P(\mu + h) - 2P(\mu) + P(\mu - h)}{h^2}\sigma^2 \tag{4.11}$$

From [29] we can select $h = \sqrt{3}\sigma$ as being an appropriate value. Eqn. (4.11) becomes:

$$E\left[P(\phi)\right] \approx \frac{2}{3}P(\mu) + \frac{1}{6}P(\mu + \sqrt{3}\sigma) + \frac{1}{6}P(\mu - \sqrt{3}\sigma) \tag{4.12}$$

From (4.12), eqn. (4.7) can easily be derived by letting μ and σ be the mean and standard deviation of ψ . We find [29]:

$$\mu = (K-1)E(Z) \tag{4.13}$$

$$\sigma = (K-1)\left[E(Z^2) - E(Z)^2 + (K-2)\operatorname{cov}(Z_j, Z_k)\right] \quad \text{(for any } j \neq k\text{)} \tag{4.14}$$

with

$$E(Z) = \frac{N}{2} - \frac{E(B)}{3} - \frac{1}{6} = \frac{N}{3} \tag{4.15}$$

$$E(Z^2) = \frac{1}{40}\left[8E(B^2) + (8-20N)E(B) + 2 - 10N + 15N^2\right]$$

$$= \frac{7N^2 + 2N - 2}{40} \tag{4.16}$$

$$\operatorname{cov}(Z_j, Z_k) = \operatorname{var}(B)/9 = \frac{N-1}{36} \qquad \text{(for any } j \neq k\text{)} \tag{4.17}$$

$$E(B) = \frac{N-1}{2} \tag{4.18}$$

$$E(B^2) = \frac{N(N-1)}{4} \tag{4.19}$$

This yields the probability of error as:

$$P_e = \frac{2}{3}Q\left[\sqrt{\frac{3N}{(K-1)}}\right] + \frac{1}{6}Q\left[\frac{N}{((K-1)\frac{N}{3} + \sqrt{3}\sigma)^{0.5}}\right] + \frac{1}{6}Q\left[\frac{N}{((K-1)\frac{N}{3} - \sqrt{3}\sigma)^{0.5}}\right] \tag{4.20}$$

with

$$\sigma = (K-1)\left[N^2\frac{23}{360} + N\left(\frac{1}{20} + \frac{K-2}{36}\right) - \frac{1}{20} - \frac{K-2}{36}\right] \tag{4.21}$$

The addition of AWGN is straightforward, we assume that AWGN of two-sided spectral density of $N_0/2$ is added to the sum of the K CDMA signals. Then (4.20) is modified to:

$$P_e = \frac{2}{3}Q\left[\left(\frac{K-1}{3N}+\frac{N_0}{2E_b}\right)^{-0.5}\right]+\frac{1}{6}Q\left[\left(\frac{(K-1)\frac{N}{3}+\sqrt{3}\sigma}{N^2}+\frac{N_0}{2E_b}\right)^{-0.5}\right] \tag{4.22}$$
$$+\frac{1}{6}Q\left[\left(\frac{(K-1)\frac{N}{3}+\sqrt{3}\sigma}{N^2}+\frac{N_0}{2E_b}\right)^{-0.5}\right]$$

where E_b is the energy per bit and σ is given by (4.21).

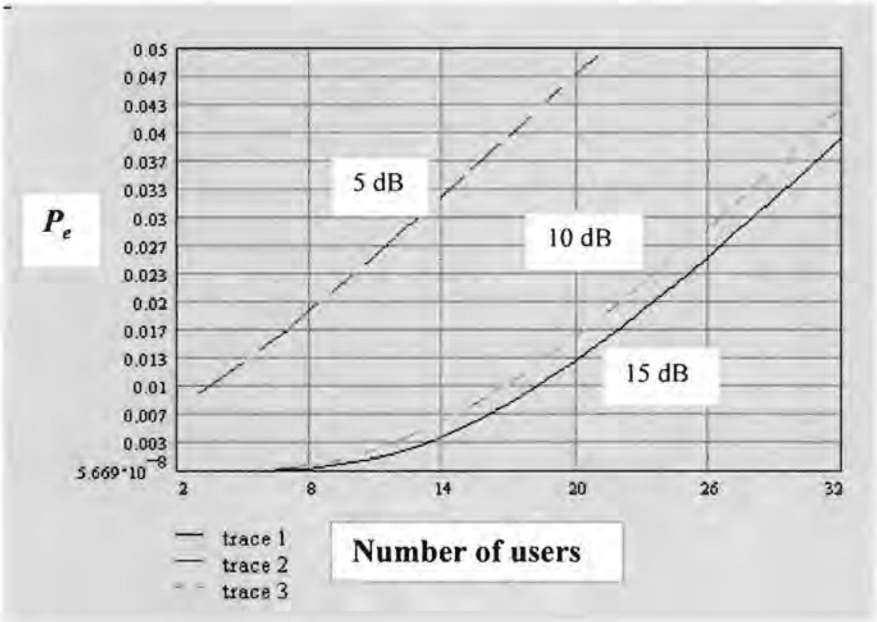


Fig. 13 Probability of error vs Number of users for different E_b/N_0 values.

Fig. 13 above shows that the probability of error decreasing with increasing signal-to-noise ratio (E_b/N_0) based on eqn. (4.22). SNR gives a measure of the strength of the signal over that of the additive noise (AWGN in this case). The system designer must hence make a tradeoff between how much power he will assign to each user to maintain a required probability of bit-error for a number of users in the system.

4.3 Capacity of the CDMA system

One of the problems related to CDMA is the possibility of interference from existing systems. Unlike former techniques like FDMA and TDMA, CDMA has it's capacity solely limited by the amount of interference into the system, which allows any reduction in interference to be converted directly and linearly into an increase in capacity. Therefore because CDMA is interference limited, the number of users that share the spectrum, and still maintain an acceptable performance, is determined by the interference generated by the set of remaining users.

CDMA is a type of non-cooperative channel, which has asynchronous multiplexing , implying that the M information sources transmit through a common medium without any pre-arrangement amongst themselves. In this type of communication system several users transmit simultaneously and concurrently to a common receiver. Therefore all components of the received signal are statistically independent and so, perform as interference in respect to any other given signal [24].

The noise variance σ_i^2 was obtained assuming that that the interuser interference amounts to to a Gaussian distribution, for a CDMA system using orthogonal codes [30].

$$\sigma_i^2 = \frac{(M-1)E_b^2}{3N} + \frac{N_0 E_b}{2} \tag{4.23}$$

Here, M is the number of users in the channel, N is the processing gain, $N_0/2$ is the Gaussian noise power spectral density and T_b is the bit time.

It can be reasonably argued that for the present model, the sum capacity is a one-feature measurement containing most of the needed information about the behavior of the system [15]. CDMA systems, which define a non-cooperative type of channel whose capacity is given by the sum of the individual rates has it's individual capacity defined as [20]:

$$C_i = \frac{1}{\sigma_i \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\left[\frac{(y-E_b)^2}{2\sigma_i^2}\right]} \log\left[\frac{2}{1+\exp(-\frac{2yE_b}{\sigma_i^2})}\right] dy \tag{4.24}$$

The access, or addition of new users to the channel, is governed by a Markovian process and the MAI is assumed proportional to the number of active users.

By evaluation and simplification we can arrive at the final expression for the lower bound on the sum capacity of a CDMA system for a fixed number of users as [31]:

$$C = M - \log_e\left(\frac{2\pi M}{\pi^2 - 8}\right)\left\{\frac{\pi}{\sqrt{2}}\sqrt{\frac{6NE_b/N_0}{2(M-1)E_b/N_0 + 3N}}\exp\left(\frac{8-\pi^2}{2\pi^2}\frac{6NE_b/N_0}{2(M-1)E_b/N_0 + 3N}\right)\right.$$

$$\left. - 2erfc\left(\frac{1}{\sqrt{2}}\sqrt{\frac{6NE_b/N_0}{2(M-1)E_b/N_0 + 3N}}\right)\right\} \qquad (4.25)$$

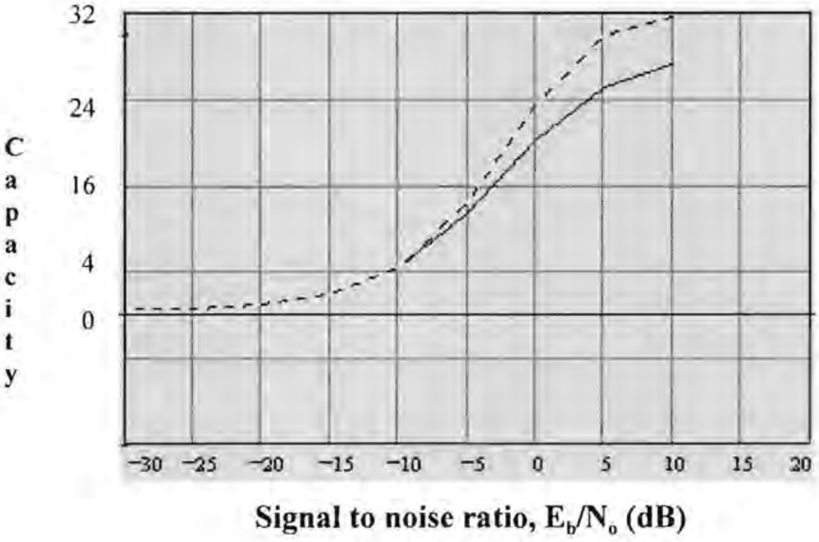


Fig.14 Capacity of the system as a function of SNR (E_b/N_0).

The results of the capacity of the CDMA system are plotted in Fig. 14 as shown above for number of users $M = 32$ and sequence length $N = 32$. The lower curve depicts these simulated values while the upper curve shows the capacity of the same system for a sequence length $N = 320$. From these curves it can be clearly seen that by increasing the processing gain of the system, the capacity can be improved considerably. However it is also recorded that if $N \geq 3M$, there is no significant increase in capacity of the system even if processing gain is increased considerably.

This can be confirmed by Fig. 15 which shows the increase in capacity of the CDMA system with the increase in the code sequence length (N). It is evident that from this graph that a code length sequence of 64 bits would have been ideal to maximize the capacity of the CDMA system, but one must bear in mind the trade-off discussed earlier that an increase in code length increases the bandwidth required for the system to operate in. In this case the required 2.048 MHz required originally would double to 4.096 MHz if the code length sequence was doubled. Hence a tradeoff must be reached taking the system requirements and spectrum constraints into consideration.

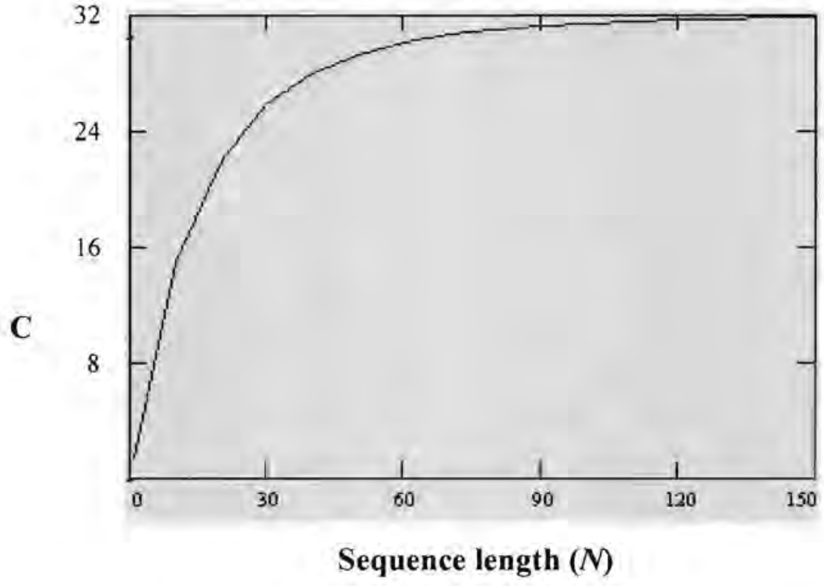


Fig. 15 Capacity (C) of the CDMA system as a function of sequence length (N) for $E_b/N_0 = 15\ dB$.

4.4 Erlang Capacity of the CDMA system

Traffic refers to the usage of channels, and is usually thought of as the holding time per time unit for one or several circuits (trunks or channels). Traffic is measured in the unit Erlang (E), and one subscriber can, if he spends all his time with the telephone, generate one call hour per hour or 1E of traffic. Different assumptions are on subscriber behavior are used to define traffic. The most common method used in wireless communications is the Erlang B-model based on the following assumptions:

- No queues.
- Number of subscribers is much higher than number of traffic channels.
- No dedicated traffic channels.
- Poisson distributed (random) traffic.
- Blocked calls abandon the call attempt immediately.

For any multiuser communication system, the measure of it's usefulness is not the maximum number of users which can be serviced at one time, but rather the peak load that can be supported with a given quality and with the availability of service as measured by the blocking probability (this is the probability that a new user will find all the available channels busy and hence be denied service). Adequate service is usually associated with a blocking probability of two percent. The average traffic load in terms of average number of users requesting service resulting in this blocking probability is called the Erlang capacity of the system [9].

In CDMA systems, users share a common spectral frequency allocation over the time that they are active. Hence new users can be accepted as long as there are receiver-processors to service them, independent of time and frequency allocations. We shall assume that a sufficient number of such processors are available at the common base station such that the probability of a new arrival finding them busy is negligible. Hence blocking in CDMA systems is defined to occur when the interference level, primarily due to other user activity, reaches a pre-determined level above the background level noise of thermal origin. While this interference-to-noise ratio could, in principle, be made arbitrarily large, when the ratio exceeds a certain threshold level (about 10 dB nominally), the interference increase per additional user grows very rapidly [32].

Consequently, we shall establish blocking in CDMA as the event that the total interference-to-background noise level exceeds $1/\eta$ where η corresponds to to 10 dB, and we determine the Erlang capacity which results in a two percent blocking probability. What must be remembered is that this is a "soft-blocking" condition, which can be relaxed. Also unlike conventional systems, where a fraction of the time or frequency slots must be set aside for overhead protocol, CDMA systems incorporate these overheads in the common medium but with greater efficiency (less interference) [33].

It can be shown that the general Erlang capacity formula [33], reproduced here , can be written as:

$$E_c = \frac{(1-\eta)\frac{W}{R}F(B,\sigma)}{\rho(1+f)\left(\frac{E_b}{I_o}\right)} \quad \text{Erlang/cell} \tag{4.26}$$

where,

$$F(B,\sigma) = \exp\left(\frac{-(\beta\sigma)^2}{2}\right)\left\{1+\frac{B}{2}\exp\left(\frac{3(\beta\sigma)^2}{2}\right)\left(1-\sqrt{\frac{1+4\exp\left(\frac{-3(\beta\sigma)^2}{2}\right)}{B}}\right)\right\} \tag{4.27}$$

W is the spread spectrum bandwidth, R is the data rate, E_b is the bit energy, I_o is the maximum total acceptable interference density, f is the ratio of other cell interference to own user interference, ρ is the voice activity factor and $F(B,\sigma)$ is the Erlang reduction factor.

The system was evaluated for the following parameters:

$W = 2.048$ *MHz*, $R = 64$ *kbps*,

$\eta = 0.1$, $F(B,\sigma = 2.5) = 0.695$,

$\rho = 0.4$ & $f = 0.55$.

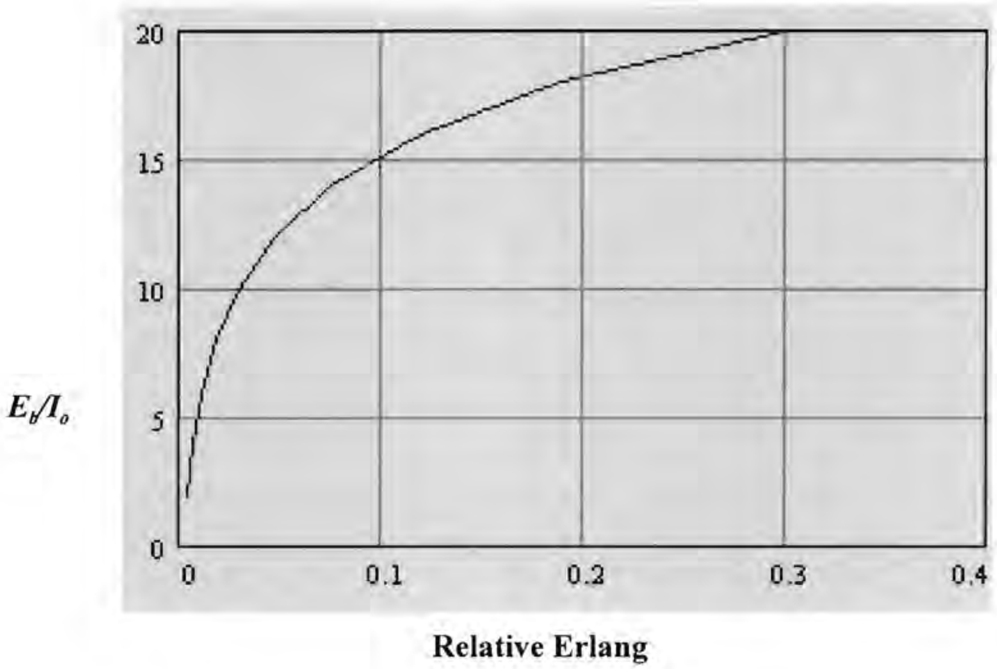


Fig. 16 Relative Erlang plotted against Bit energy to Interference density ratio(E_b/I_o).

In CDMA, in which the allocated resource is energy rather than time or frequency, access requests can share the common channel with ongoing users. The main conclusions established from system tests conducted was that the Erlang capacity of CDMA systems was about twenty times that of FDMA systems [33]. One must remember that this is based on establishing the blocking condition as the event that the total interference-to-noise-ratio exceeds 10 dB.

5. CONCLUSIONS

Hadamard codes

Use of the Sylvester type of Hadamard codes as orthonormal sequences to modulate each user distinctly proved effective. These codes showed good cross-correlation properties as investigated (section 2.4). As an added advantage it was discovered that these codes when simulated yielded constant envelop properties (section 2.5) which have the following advantages [5],[10]:

- Power efficient Class C amplifiers can be used without introducing degradation in the spectrum occupancy of the transmitted signal.
- Low out-of-band radiation of the order of –60 to –70 dB can be achieved.
- Limiter-discriminator detection can be employed which simplifies receiver design.

It was also investigated that a code length of 32 as proposed showed a maximum system capacity of about 28 simultaneous CDMA users (section 4.3).

Propagation considerations

CDMA systems are well suited for wireless environments because of their built-in frequency diversity. The delay spread in typical PMP systems is of the order of several microseconds, and hence, the coherence bandwidth of the channel is smaller than 1 MHz. If, as in our case the spreading bandwidth is selected to be in excess of this value, the channel becomes frequency selective. An estimate of the channel impulse response can be determined by the use of a training sequence, or by means of a pilot signal.

CDMA system performance

It has been simulated that the performance of the system in terms of BER with addition of CDMA users shows a degradation of BER of $2.5x10^{-3}$ for 4 users to $37x10^{-3}$ for 24 users (section 4.1). Although these bit-error-rates are not acceptable practically, it must be noted that no error detecting and correcting codes were implemented, which would dramatically increase the performance of the systems. Also study done with increase in the SNR showed improvement to the probability of error (section 4.2). Another possible solution to improve system performance is the use of multiuser detection [18],[21], in which all users are considered as signals for each other. Then, instead of users interfering with each other, they are all being used for their mutual benefit by joint detection. The main drawback to this optimal multiuser detection is one of complexity and research is currently being undertaken to reach a tradeoff between this complexity and performance. The CDMA system is also shown to be 30% efficient in terms of traffic handling capacity when fully loaded with 32 users. An added advantage with CDMA systems is that the overhead required is handled efficiently and does not affect the Erlang handling capacity of the system.

Further improvements

The system simulated can be enhanced by improvements and research in the following aspects:

- Investigation into the feasibility of using orthonormal codes which possess error detection and/or correction capabilities. This would reduce addition overhead bits required and hence cause the systems to be more spectrally efficient.
- Use of CDMA systems in conjunction with FDD. The arrangement decouples the power control problem on the uplink and downlink respectively
- Exploitation of the property of VAD in CDMA. Speech pauses occupy 65% of the connection time. If no signals are transmitted during such pauses, then the interference level drops and therefore the system can support upto three times the original capacity of the system.

6. THIRD GENERATION CDMA SYSTEMS

In Europe, ETSI is working on the Universal Mobile Telecommunications Systems (UMTS) which will become an International Telecommunications Union (ITU) IMT-2000 specification. It was decided that the solution for the radio interface would be based on CDMA and new frequency has been allocated in the 2 GHz band for the third generation wireless systems. It was also decided that the system should be able to support operation in a frequency spectrum allocation as small as 2x5 MHz (duplex).

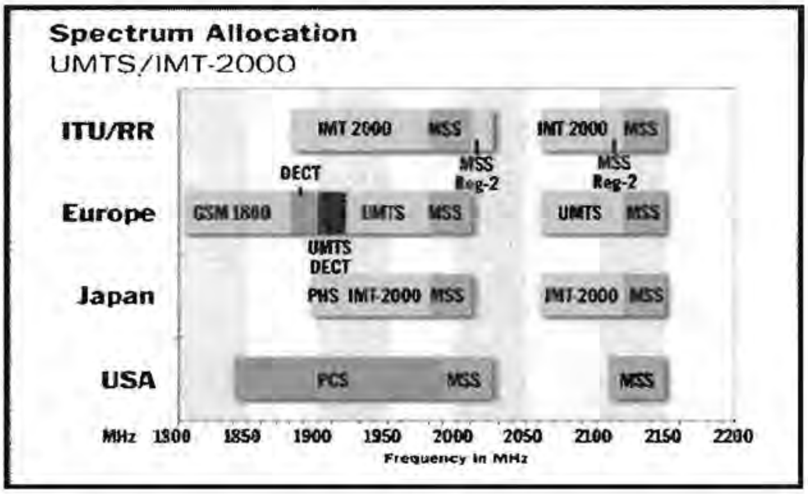


Fig. 17 Spectrum allocation for UMTS/IMT-2000.

Fig. 17 shows the spectrum allocation for the different systems for the different regions of the world. The telecommunication operators, manufacturers, operators, administrations and research bodies agreed on the following technical solution [36]:

- In the paired band (FDD) of UMTS the system adopts the radio access technique formerly proposed by the Wideband CDMA (WCDMA) group.
- In the unpaired band (TDD) the UMTS system adopts the radio access technique proposed formerly by the Time Division/CDMA (TD/CDMA) group.

The next-generation goals; the capabilities of future UMTS/IMT-2000 networks are still in the process of discussion, but the following may be considered the key points:

- High voice quality comparable to wireline services.
- High security comparable to the fixed telecommunications networks.
- A phased approach for data rates up to 2 Mbps for local or indoor/slow-moving access, and 384 kbps for wide-area access.
- Support for several simultaneous connections, so that users can for example browse the Internet at the same time as making a telephone call to a different destination.
- A common infrastructure to support multiple public/private/residential operators in the same locality.
- Interconnection to other mobile or fixed users.
- National and international roaming.
- Capable of handling packet- and circuit-switched services, including internet (IP) and videoconferencing. Also high data rate communication services and asymmetric data transmission.
- High spectral efficiency to make maximum use of limited bandwidth.
- Support for multiple cell layers (hierarchical cell structures).
- Co-existence and interconnection with satellite-based services.
- New charging mechanisms related to data volumes, quality of service and time, rather than distance.

WCDMA is basically CDMA but where the chip rate has been increased drastically to just below that of the spectrum channel bandwidth allocated. In case of WCDMA the chip rate has been set at 4.096 Mbps.

TD/CDMA as the name implies is a time divisioned version of narrowband CDMA. Here there are a number of TDMA slots within a frame. Each slot is in turn allocated a number of orthogonal codes which are individually allocated to separate users to distinguish themselves. Narrowband TD/CDMA has a chip rate of around 1.25 Mbps. Indicative voting in ETSI has revealed that 58% of the voters were in favor of WCDMA whereas only 41% voted for TD/CDMA. I shall hence discuss WCDMA and the advantages it offers.

Wideband CDMA (WCDMA)

Narrowband CDMA (IS-95) was pioneered in the USA and now Europe and Japan have selected WCDMA as their 3rd generation standard. Naturally, the WCDMA standard is a different technology targeting 3rd generation requirements. It has been based on extensive research conducted between 1989 and 1997 [34].

From the start, WCDMA has been designed for high-speed data services and more particularly, Internet based packet-data offering up to 2 Mbps in indoor environments and over 384 kbps for wide-area. In order to achieve these necessary requirements in the 3rd generation mobile communications, including trade-off between maximum capacity and operation in 5 MHz allocations, the so-called chip rate has been set at 4.096 Mbps.

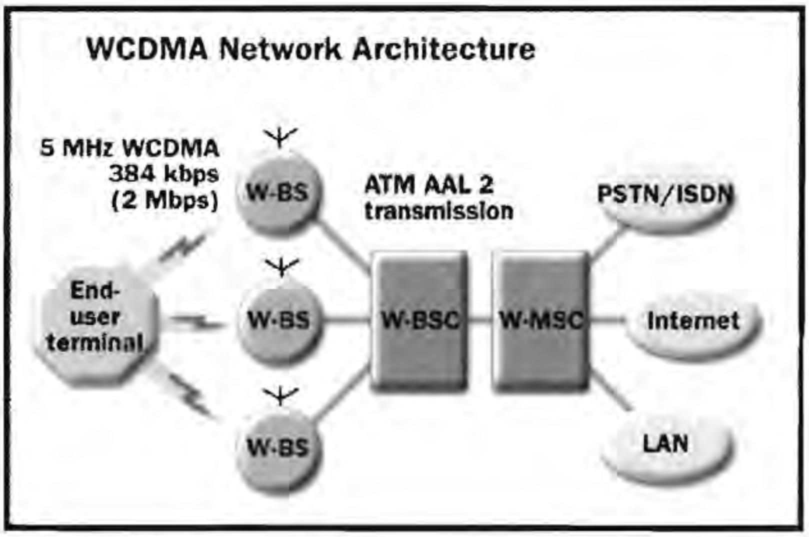


Fig. 18 WCDMA network architecture.

Fig 18 shows the proposed architecture. The user will communicate with the Base Stations (BS) via the wireless CDMA air interface. The Base Stations are in turn controlled by a Base Station Controller (BSC) which in turn is communicating with the

Mobile Switching Centre which would link the cellular network to the PSTN/Internet/LAN.

This new system will offer the following advantages over 2nd generation narrowband CDMA systems [34], [35]:

- *Higher capacity and greater coverage*: WCDMA uses a 4 times wider channel compared to narrowband CDMA providing almost 4 times the capacity. A wider bandwidth improves frequency diversity effects and therefore reduces fading problems. Wider bandwidth, with more users, gives better statistical averaging effects. WCDMA also implements coherent demodulation in the uplink which gives a 2-3 dB demodulation gain which improves coverage. Also due to less fading in a wider channel, power control accuracy will be improved.

  In total, according to tests conducted by Ericsson, a 5 MHz WCDMA carrier can handle up to 8 times more traffic compared to a narrowband 1.25 MHz CDMA channel.
- *WCDMA is built for variable and high speed data rates*: The WCDMA air interface supports both low and high bit rates. Rates up to 384 kbps with full mobility and 2 Mbps in local areas supports users with different communication requirements from voice to multimedia data. Variable data rates are achieved by using variable orthogonal spreading codes and adaptation of the transmitted output power.
- *WCDMA will offer both packet and circuit switched services*: WCDMA supports both fast packet transmission for infrequent packets and on a dedicated channel large or more frequent packets. Packet data services are important for building cost-effective applications for remote LAN and wireless Internet access. High speed circuit switched services are needed for real time applications like video conferencing.
- *WCDMA supports multiple simultaneous services*: Each WCDMA terminal can use several services simultaneously. This allows a user to connect to the corporate LAN and at the same time receive a voice call.
- *WCDMA technology supports other system improvements*: The next generation systems will also introduce other improved system functionality, which will increase capacity. The improvements are as follows:

1. Support for Adaptive Array Antennas (AAA), which is a technique used to optimize the antenna pattern for each individual mobile. It gives possibility to use the spectrum more effectively and increase the capacity.
2. No need for GPS synchronization of radio base stations. WCDMA has an internal system for synchronization of radio base stations which makes installation of these stations in subways and indoor areas possible and easier.
3. Support for Hierarchical Cell Structures (HCS). WCDMA supports HCS by introducing a new hand-off method called Mobile Assisted Inter-Frequency Hand-off (MAIFHO). The mobile stations scan on numerous CDMA carriers.
4. Multi user detection will significantly reduce interference within a cell and improve the capacity.

With the selection of CDMA as the multiple access scheme for the third generation communication systems, research in this field will grow rapidly. Although CDMA possesses good features, there is still a lot of work to be done before the full benefits of this innovative technology can be realized.

7. REFERENCES

[1] Simon Haykin, "*Digital Communications*" , Wiley, 1988.

[2] R. Kohno, R. Meidan & L.B. Milstein, "*Spread Spectrum Access Methods for Wireless Communications*" , IEEE Communications Magazine, pp. 58-67, January 1995.

[3] Theodore S. Rappaport, "*Wireless Communications, Principles & Practice*" , Prentise-Hall, 1995.

[4] R. Kohno, R Meidan & L.B. Milstein, "*Spread Spectrum Access Methods for Wireless Communications*" , IEEE Communications, Vol. 33, No. 1, January 1995.

[5] R. Steele. J. Whitehead & W.C. Wong, "*System Aspects of Cellular Radio*" , IEEE Communications, Vol. 33, No. 1, January 1995.

[6] Jerry D. Gibson, "*The Mobile Communications Handbook*" , IEEE Press, 1996.

[7] Kamilo Feher, "*Wireless Digital Communications: Modulation and Spread Spectrum Applications*" , Prentice Hall, 1995.

[8] Ramjee Prasad, "*CDMA for Wireless Personal Communications*" ,Artech House Publications, 1996.

[9] Andrew J. Viterbi, "*CDMA, Principles of Spread Spectrum Communication*" , Addison-Wesley Publishing Company, 1996.

[10] Saleh Faruque, "*Cellular Mobile Systems Engineering*" , Artech House Publications, 1996.

[11] F. Simpson & J.M. Holtzman, "*Direct Sequence CDMA Power Control, Interleaving and Coding*" , IEEE Journal on selected areas in Communications, Vol. 11, No. 7, September 1993.

[12] L.B. Milstein, Theodore S. Rappaport & Rashad Barghouti, "*Performance Evaluation for Cellular CDMA*" , IEEE Journal on selected areas in Communications, Vol. 10, No. 4, May 1992.

[13] Andrew J. Viterbi, "*Other-Cell Interference in Cellular Power-Controlled CDMA*" , IEEE Transactions on Communications, Vol. 42, No. 2/3/4, February/March/April 1994.

[14] Toufic Chebaro & Philippe Godlewski, *"Average External Interference in Cellular Radio CDMA Systems*" , IEEE Transactions on Communications, Vol. 44, No. 1, January 1996.

[15] Dara Parsavand & Mahesh K. Varansi, "*RMS Bandwidth Constrained Signature Waveform that Maximize the Total Capacity of PAM-Synchronous CDMA Channels*" , IEEE Transactions on Communications, Vol. 44, No. 1, January 1996.

[16] Todd K. Moon, Craig K. Rusgforth & Robert T. Short, "*Parameter Estimation in a Multi-User Communication System*" , IEEE Transactions on Communications, Vol. 42, No. 8, August 1994.

[17] Yukitoshi Sanada & Qiang Wang, "*A Co-Channel Interference Cancellation Technique Using Orthogonal Convolutional Codes*" , IEEE Transactions on Communications, Vol. 44, No. 5, May 1996.

[18] Zoran Zvonar & David Brady, "*Linear Multipath-Decorrelating Receivers for CDMA Frequency-Selective Fading Channels*" , IEEE Transactions on Communications, Vol. 44, No. 6, June 1996.

[19] Audrey M. Viterbi & Andrew J. Viterbi, *"Erlang Capacity of a Power Contolled CDMA System*" , IEEE Journal on selected areas in Communications, Vol. 11, No. 6, August 1992.

[20] Behnaam Aazhang & Vincent Poor, "*Performance of DS/SSMA Communications in Impulsive Channels - Part 2: Hard-Limiting Correlation Receivers*" , , IEEE Transactions on Communications, Vol. 16, No. 1, January 1988.

[21] Mahesh K. Varansi & Behnaam Aazhang, "*Multistage Detection in Asynchronous Code-Division Multiple Access Communications*" , , IEEE Transactions on Communications, Vol. 38, No. 4, April 1990.

[22] Evaggelos Geraniotis & Behzad Ghaffari, "*Performance of Binary and Quaternary Direct-Sequence Spread-Spectrum Multiple-Access Systems with Random Signature Sequences*" , , IEEE Transactions on Communications, Vol. 39, No. 5, May 1991.

[23] Alex W. Lam & Faith M. Ozluturk, "*Performance Bounds for DS/SSMA Communications with Complex Signature Sequences*" , , IEEE Transactions on Communications, Vol. 40, No. 10, October 1992.

[24] Marcelo S. Alencar & Ian F. Blake, "*The Capacity for a Discrete-State Code Division Multiple Access Channel*" , IEEE Journal on Selected Areas in Communications, Vol. 12, No. 5, June 1994.

[25] W.C.Y. Lee, "*Overview of Cellular CDMA*" , IEEE Transactions on Vehicular Technology, Vol. 40, No. 2, May 1991.

[26] Victor M. DaSilva & Elvino S. Sousa, "*Multicarrier Orthogonal CDMA Signals for Quasi-Synchronous Communications Systems*" , IEEE Journal on Selected Areas in Communications, Vol. 12, No. 5, June 1994.

[27] Louay M.A Jalloul & Jack M. Holtzman, "*Performance Analysis of DS/CDMA with Noncoherent M-ary Orthogonal Modulation in Multipath Fading Channels*" , IEEE Journal on Selected Areas in Communications, Vol. 12, No. 5, June 1994.

[28] R.K. Morrow & J.S. Lehnert, "*Bit-to-bit error dependence in slotted DS/SSMA packet systems with random signature sequences*" , IEEE Trans. Commun., Vol. COM-37, Oct 1989.

[29] J.M. Holtzman, "*On using pertubation analysis to do sensitive analysis: Derivatives vs differences*" , IEEE Trans. Automat. Contr., Vol. 37, Feb. 1992.

[30] George L. Turin, "*The effects of multipath and fading on the performance of direct-sequence CDMA systems*" , IEEE Journal on Selected Areas in Communications, Vol. 2, No. 4, July 1984.

[31] Elvino S. Sousa, "*Throughput of spread-spectrum systems with a large number of users*" , Proc. Inst. Elec. Eng., Vol. 136, No. 3, June 1989.

[32] D. Bertsekas & R. Gallager, "*Data Networks*" , Englewood Cliffs, NJ: Prentice-Hall, 1987.

[33] K.S. Gilhousen, I.M.. Jacobs, R. Padovani, A.J. Viterbi, L.A. Weaver & C.E. Wheatley, "*On the capacity of a cellular CDMA system*" , IEEE Trans. Veh. Technol., Vol. 40, May 1991.

[34] Per-Goran Andermo & Lars-Magnus Ewerbring, "*A CDMA-Based Radio Access Design for UMTS*" , IEEE Personal Communications, Vol. 2, No. 1, February 1995.

[35] Alexandra Duel-Hallen, Jack Holtzman & Zoran Zvonar, "*Multiuser Detection for CDMA systems*" , , IEEE Personal Communications, Vol. 2, No. 2, April 1995.

[36] Internet site, "*Radio Transmission Technology (RTT) Proposals*" , http://www.itu.int/imt/2-radio-dev/proposals/index.html.