Use of RNS Based Pseudo Noise Sequence in DS-CDMA and 3G WCDMA

A Thesis submitted in partial fulfillment
of the Requirements for the degree of

MASTER OF TECHNOLOGY
in
ELECTRONICS AND COMMUNICATION ENGINEERING
Specialization: Communication and Signal Processing

by

Chithra R
Roll no: 210EC4002

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA
ROURKELA, ODISHA, 769 008, INDIA
JUNE 2012

Use of RNS Based Pseudo Noise
Sequence in DS-CDMA and 3G WCDMA

A Thesis submitted in partial fulfillment
of the Requirements for the degree of

Master of Technology

in

Electronics and Communication Engineering
Specialization: Communication and Signal Processing

by

Chithra R
Roll no: 210EC4002

Under the guidance of

Prof. SARAT KUMAR PATRA

Department of Electronics and Communication Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, 769 008, India

June 2012

Dedicated to My Loving Parents...

Dept of Electronics and Communication Engineering
National Institute of Technology Rourkela
Rourkela-769 008, Odisha, India.

Certificate

This is to certify that the work in the thesis entitled **Use of RNS based Pseudo Noise Sequence in DS-CDMA and 3G WCDMA** by **Chithra R** is a record of an original research work carried out by her during 2011 - 2012 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in Electronics and Communication Engineering (**Communication and Signal Processing**), National Institute of Technology, Rourkela. Neither this thesis nor any part of it has been submitted for any degree or diploma elsewhere.

Place: NIT Rourkela
Date: 04 June 2012

Dr. Sarat Kumar Patra
Professor

Acknowledgments

With deep regards and profound respect, I avail this opportunity to express my deep sense of gratitude and indebtedness to Prof. Sarat Kumar Patra, Department of Electronics and Communication Engineering, NIT Rourkela for his valuable guidance and support. I am deeply indebted for the valuable discussions at each phase of the project. I consider it my good fortune to have got an opportunity to work with such a wonderful person.

Sincere thanks to Prof. K. K. Mahapatra, Prof. S. Meher, Prof. S. K. Behera, Prof. S. K. Das, Prof. Samit Ari, Prof. A. K. Sahoo and Prof.Poonam Singh for teaching me and for their constant feedbacks and encouragements. I would like to thank all faculty members and staff of the Department of Electronics and Communication Engineering, NIT Rourkela for their generous help.

I take immense please to thank our senior namely Pallab Maji for his endless support and help throughout this project work. I would like to mention the names of Shaibu V B, Anil Chacko and Neethu Krishna and all other friends who made my two year stay in Rourkela an unforgettable and rewarding experience and for their support to polish up my project work. Last but not least I also convey my deepest gratitude to my parents and family for whose faith, patience and teaching had always inspired me to walk upright in my life.

Finally, I humbly bow my head with utmost gratitude before the God Almighty who always showed me a path to go and without whom I could not have done any of these.

CHITHRA R
chithrar14@gmai.com

Abstract

Code Division Multiple Access (CDMA) based on Spread Signal (SS) has emerged as one of the most important multiple access technologies for Second Generation (2G) and Third Generation (3G) wireless communication systems by its wide applications in many important mobile cellular standards. CDMA technique relies on spreading codes to separate different users or channels and its properties will govern the performance of the system. So many of the problems of communication systems based on CDMA technology stem from the spreading codes/sequences, which includes two sub-categories, one being the orthogonal codes, such as Walsh Hadamard (WH) codes and Orthogonal Variable Spreading Factor (OVSF) codes, and the other being pseudo-noise or Pseudo Random (PN) sequences, such as Gold sequences, Kasami sequences, m-sequences, etc.

In this thesis a PN sequence generation based on Residue Arithmetic is investigated with an effort to improve the performance of existing interference-limited CDMA technology for mobile cellular systems. This interference-limited performance is due to the fact that all the existing CDMA codes used in mobile cellular standards does not consider external interferences, multipath propagation, Doppler effect etc. So the non-ideal correlation properties of the pseudo-random CDMA codes results in MAI when used in a multi-user system. The PN codes appear random yet they are completely deterministic in nature with a small set of initial conditions. Consequently this work focuses on CDMA code design approach based on Residue Number System (RNS) which should take into account as many real operational conditions as possible and to maintain a sufficiently large code set size.

First, the thesis reviews RNS, DS-CDMA and CDMA codes that are already implemented in various mobile cellular standards. Then the new PN Sequence

generator design based on RNS is discussed. Comparison of the generated PN sequence with respect to other standard sequence is done in terms of number of codes and correlation properties. Monte-Carlo simulations with the generated sequence are carried out for performance analysis under multi-path environment. The system has been evaluated in AWGN, Rayleigh Fading channel and different Stationary Multipath Channels for different cross-correlation threshold.

It is known that orthogonal Codes are used to multiplex more than one signal for downlink transmission over cellular networks. This downlink transmission is prone to self interference caused by the loss of orthogonality between spreading codes due to multipath propagation. This issue is investigated in detail with respect to WCDMA standards, which is very good representative for CDMA based 3G mobile cellular systems where the channelization code is OVSF code. The code assignment blocking (CAB) (If a particular code in the tree is used in a cell, then all its parent codes and child codes should not be used in the same cell to maintain orthogonality among the users) problem of OVSF codes restricts the number of available codes for a given cell. Since the 3^{rd} generation WCDMA mobile communication systems apply the same multiple access technique, the generated sequence can also be the channelization code for downlink WCDMA system to mitigate the the same. The performance of the system is compared with Walsh Hadamard code over multipath AWGN and different Fading channels. This thesis work shows that RNS based PN sequence has enhanced performance to that of other CDMA codes by comparing the bit error probability in multi-user and multipath environment thus contributing a little towards the evolution of next generation CDMA technology.

Contents

Acknowledgement **iv**

Abstract **v**

Contents **vii**

Nomenclature **ix**

Abbreviations **xii**

List of Figures **xv**

List of Tables **xviii**

1 Introduction **1**

1.1 Background 1

1.2 Literature Survey 3

1.3 Objective of the work 5

1.4 Motivation 5

1.5 Thesis Organization 6

2 Residue Number System **8**

2.1 Basics of RNS 8

2.2 Advantages 9

2.3 Chinese Remainder Theorem 10

2.4 Moduli Selection and Mapping 11

2.4.1 Consecutive Moduli Selection 12

2.4.2 Exponential Moduli Selection 13

2.5 Overview of RNS Applications 13

3 RNS Based PN Sequence for Multiuser DS-CDMA **15**
3.1 Spread Spectrum Communication 16
3.2 Spreading Codes in CDMA 17
3.2.1 Maximal Length Sequence 18
3.2.2 Gold Sequence 18
3.2.3 Kasami Sequence 19
3.2.4 Walsh-Hadamard Sequences 19
3.2.5 Orthogonal Variable Spreading Factor Codes 20
3.3 RNS Based PN Sequence Generator 21
3.4 DS-CDMA System Model 23
3.5 Comparison of RNS based PN sequence with other CDMA codes . 25
3.5.1 Number of Sequences 26
3.5.2 Correlation Properties 26
3.6 Simulation Results and Discussion 27
3.6.1 AWGN Channel 28
3.6.2 Rayleigh Fading Channel 31
3.6.3 Stationary Multipath Channel 33

4 3G WCDMA with RNS Based PN Sequence **36**
4.1 WCDMA - Review 36
4.1.1 Physical Channel Structure 37
4.1.2 Spreading and Modulation 38
4.2 System Model Description 41
4.3 Results and Discussion 42
4.3.1 AWGN Multipath Channel 43
4.3.2 Ricean Fading Multipath Channel 45
4.3.3 Rayleigh Fading Multipath Channel 45

5 Conclusion **48**
5.1 Conclusion 48
5.2 Limitations of the work 49
5.3 Scope of Future work 49

Appendix A
CAB of OVSF Code **50**

Appendix B
Simulation Parameters **52**

Publication **54**

Bibliography **55**

Nomenclature

β	Spreading Factor
$\bigotimes$	Convolution Operator
$\eta(t)$	White Gaussian Noise
ω_c	Carrier Frequency
ϕ_u	Carrier Phase Shift of u^{th} User
$\psi(t)$	Chip Waveform
τ_u	Delay of u^{th} User
B	Unspread Signal Bandwidth
b	Number of bits in the binary representation of a number
C	Channel Capacity
c_{scr}	Scrambling Code
$c_{u,n}$	n^{th} chip of u^{th} user's spreading code
c_u	u^{th} user's spreading code
$d(k)$	k^{th} data bit
$d_u(k)$	k^{th} data bit of user u
$H(z)$	Channel Impulse Response

J	Primal Pool
J_i	i^{th} Primal of Primal Pool
k	Number of elements in the binary representation of each Moduli
L	Spreading Sequence Length
L_p	Number of Paths in a Multipath Environment
M	Moduli Set/Divisor set
m_i	moduli/divisor
n	Number of co-prime numbers in the moduli set
N_0	Thermal Noise Density
N_J	Jamming Power
N_p	Number of Transmitted Symbols in one Slot
P	Signal Power
P_u	u^{th} user's Signal Power
R	Range/Product of Moduli
$R_s(J_i)$	Residue Set of i^{th} Primal
$s_u(t)$	Spreading Waveform of User u
t	time
T_b	Bit interval
T_c	Chip duration
T_{slot}	Duration of one Slot in WCDMA frame structure
U	Number of Users active in the System
W	Spread Signal Bandwidth

$x(t)$ Received Noise free signal

$x_u(t)$ Received Signal of u^{th} user

$y(kL+n)$ n^{th} Chip of the k^{th} symbol with spreading length L

$y(t)$ Received Noise Corrupted Signal

Abbreviations

2G	Second Generation.
3G	Third Generation.
3GPP	Third Generation Partnership Project.
AMPS	Advanced Mobile Phone System.
AWGN	Additive White Gaussian Noise.
BPSK	Binary Phase Shift Keying.
CCPCH	Common Control Physical Channel.
CDMA	Code Division Multiple Access.
CF	Cross Correlation Threshold.
CRT	Chinese Remainder Theorem.
DPCCH	Dedicated Physical Control Channel.
DPDCH	Dedicated Physical Data Channel.
DS	Direct Sequence.
DSP	Digital Signal Processing.
ETSI	European Telecommunications Standards Institute.
FBI	Feedback Information.
FDD	Frequency Division Duplex.
FH	Frequency Hopping.
GSM	Global System for Mobile.
ISI	Inter-Symbol Interference.
LCM	Least Common Multiple.
LUT	Look Up Table.
MAI	Multiple-Access Interference.
MI	Multipath Interference.

MS	Mobile Station.
OVSF	Orthogonal Variable Spreading Factor.
PG	Processing Gain.
PN	Pseudo Random.
PRACH	Physical Random Access Channel.
QPSK	Quaternary Phase Shift Keying.
RNS	Residue Number System.
SCH	Synchronization Channel.
SF	Spreading Factor.
SNR	Signal to Noise Ratio.
SRG	Shift Register Generator.
SS	Spread Signal.
TDD	Time Division Duplex.
TDMA	Time Division Multiple Access.
TFCI	Transport Format Combination Indicator.
TH	Time Hopping.
TPC	Transmit Power Control.
UMTS	Universal Mobile Telecommunication System.
VLSI	Very Large Scale Integrated Circuit.
WCDMA	Wideband Code Division Multiple Access.
WH	Walsh Hadamard.

List of Figures

1.1 Multiple Access Frequency Division Multiple Access Technique . . 2
1.2 Multiple Access Time Division Multiple Access Technique 2
1.3 Multiple Access Code Division Multiple Access Technique 3

2.1 Bit Distribution of Modulis in Consecutive Moduli Selection . . . 12
2.2 Bit Distribution of Modulis in Exponential Moduli Selection . . . 13

3.1 Spreading of data using DS-SS technique 17
3.2 Linear Feed Back Shift Register(LFSR) for m-sequence generation 18
3.3 Generation of Gold Sequence from m-sequences 19
3.4 Code Tree for Generation of OVSF Codes 20
3.5 Offline process for RNS Based PN Sequence Generation 21
3.6 RNS Based PN Sequence Generation - On-line Process 24
3.7 Block Diagram of DS-CDMA System 25
3.8 BER performance versus the Number of Active Users with spreading factor, $\beta = 8$ for Maximal Length Sequence, Gold Sequence and RNS based PN Sequence 29
3.9 Performance Comparison of DS-CDMA system with cross correlation threshold, CF, 0.20 and 0.10 for different loading scenarios, $\beta = 128$ 29
3.10 BER plot of DS-CDMA system using RNS based PN sequence with $\beta = 64$ for different loading scenarios 30
3.11 BER plot of DS-CDMA system using RNS based PN sequence with $\beta = 128$ for different loading scenarios 30

3.12 BER performance versus the number of active users for E_b/N_o of 5 dB and 20 dB with $\beta = 64$ and $\beta = 128$ 31
3.13 Comparison of RNS based PN sequence with Gold codes, Kasami codes and Maximal Length sequence based on BER Plot for 5 Users DS-CDMA System, $\beta = 64$ 32
3.14 BER Performance of DS-CDMA system using RNS based PN sequence with $\beta = 128$ for different loading scenarios. The channel considered is Rayleigh Fading Channel with cross-correlation threshold, CF, 0.20 and 0.10 32
3.15 BER plot of DS-CDMA system in Minimum Phase Channel, $1 + 0.5z^{-1} + 0.2z^{-2}$ with $\beta = 128$ for different loading scenarios . . . 33
3.16 BER plot of DS-CDMA system in Maximum Phase Channel, $0.5 + z^{-1}$ with $\beta = 128$ for different loading scenarios 34
3.17 BER plot of DS-CDMA system in Mixed Phase Channel, $0.3482 + 0.8704z^{-1} + 0.3482z^{-2}$ with $\beta = 128$ for different loading scenarios 34

4.1 Frame Structure for Uplink DPDCH/DPCCH 38
4.2 Frame Structure for Downlink DPCH 39
4.3 Transmitter - WCDMA Uplink 39
4.4 Transmitter - WCDMA Downlink 40
4.5 Spreading and Modulation of Downlink WCDMA 41
4.6 Comparison of RNS based PN sequence with Gold codes, Maximal Length sequence and orthogonal Walsh Hadamard code based on BER Plot for 8 Users downlink WCDMA System, $\beta = 128$ 43
4.7 BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in an AWGN Multipath Channel for different loading scenarios. 44
4.8 BER Performance of downlink WCDMA system using Walsh Hadamard Code with $\beta = 128$ in an AWGN Multipath Channel for different loading scenarios. 44
4.9 BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in a Ricean Multipath Channel for different loading scenarios. 45

4.10 BER Performance of downlink WCDMA system using Walsh Code with $\beta = 128$ in a Ricean Multipath Channel for different loading scenarios. 46
4.11 BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in a Rayleigh Multipath Channel. . . . 46
4.12 BER Performance of downlink WCDMA system using Walsh Code with $\beta = 128$ in a Rayleigh Multipath Channel. 47

List of Tables

2.1 Residues for prime and non-prime Modulis 10

3.1 Generated Moduli Set and Dynamic Range for different Spreading Factors 22
3.2 RNS Based PN Sequence Generation 23
3.3 Correlation Matrix of the Generated Sequence 23
3.4 Length of the code set for different CDMA Codes 26
3.5 Correlation Matrix for RNS based PN Sequence, $\beta = 8$ 27
3.6 Correlation Matrix for Gold Sequence, $\beta = 8$ 27
3.7 Correlation Matrix for Maximal Length Sequence, $\beta = 8$ 28

1 Introduction

1.1 Background

The worlds first cellular network i.e., Advanced Mobile Phone System (AMPS) - based on analog radio transmission technologies was put into service in the early 1980s [1]. It uses separate frequencies, or ”sub-channels” of the common channel for each user, see Figure 1.1. Within few years of launching, the network began to hit a capacity ceiling as millions of new subscribers signed up for mobile voice services. To accommodate more users within a limited amount of spectrum, a new set of wireless technology called Time Division Multiple Access (TDMA) has been developed. Figure 1.2 shows how a TDMA system works. Several users share a common channel but they are separated by time. DAMPS (Digital AMPS) and Global System for Mobile (GSM) then came onto the stage [3]. An even better solution was CDMA technology and the working of which is shown in Figure 1.3. In this technology usually, within a network there are two channels, one for the uplink (mobile to base station) and one for the downlink (base station to mobile). All user share both channels at the same time.

The most important milestone in the application of CDMA technologies is the time when IS-95 - the first CDMA-based civilian mobile cellular communi-

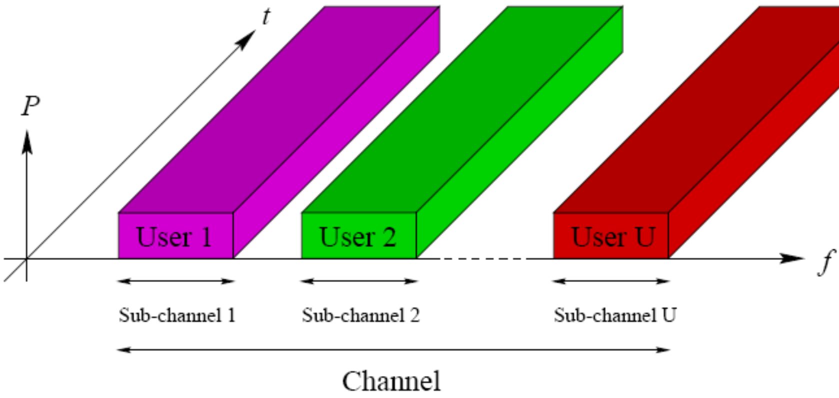


Figure 1.1: Multiple Access Frequency Division Multiple Access Technique [2]

cation standard was successfully developed by Qualcomm in the 1990s. Since then, CDMA-based mobile cellular has become the fastest growing of all wireless technologies. Since then, it has been successfully demonstrated that a CDMA system based on the direct sequence (DS) spreading technique can in fact offer a higher bandwidth efficiency than its predecessors, with additional advantages such as low probability of interception, privacy, good protection against multi-path interference, attractive overlay operation with existing radio systems, etc. Today, DS-based CDMA technology has become one of the prime multiple access radio technologies for many wireless networks and mobile cellular standards, such as cdma2000, WCDMA and TD-SCDMA [4].

In contrast to the fact that mobile cellular has advanced beyond 3G, it is very sad to see that CDMA technology itself has stayed virtually at the same

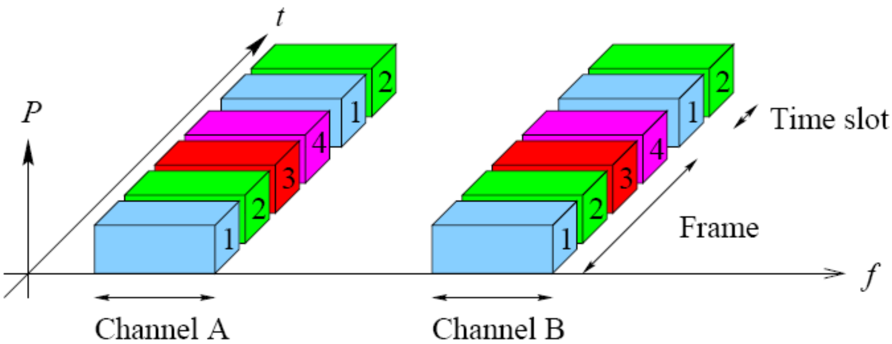


Figure 1.2: Multiple Access Time Division Multiple Access Technique [2]

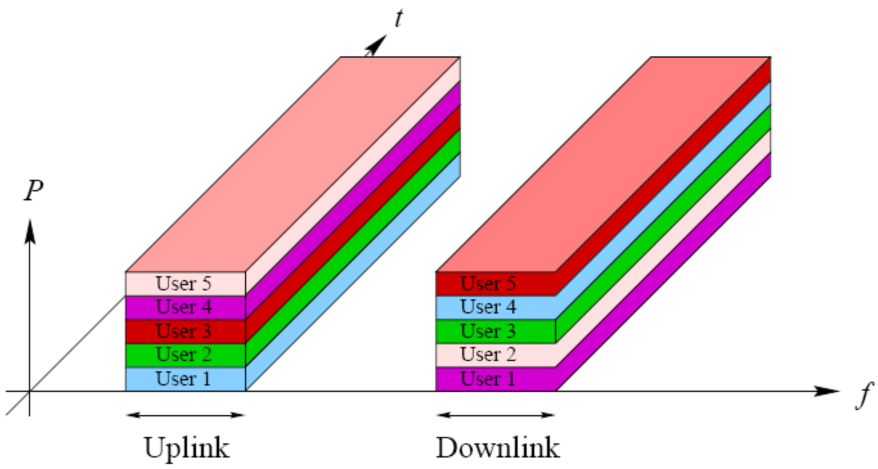


Figure 1.3: Multiple Access Code Division Multiple Access Technique [2]

place with a strictly interference-limited performance. CDMA is still a viable and strong candidate for wide application in wireless systems. To develop next generation CDMA technologies, much innovation is required in spreading code design and approaches. Since RNS has received wide attention due to its robust signal processing properties, a spreading code design based on residue arithmetic is discussed in this thesis.

1.2 Literature Survey

RNS were introduced in field of DS-CDMA by many researchers as early as late 90s by Lie Liang Yang and Lajos Hanzo [5], [6], [7]. In conventional systems, due to the carry forward required by the weighted number system, a bit error may affect all the bits of the result. In [5], [6], [7] they proposed a parallel communication scheme based on RNS, which is a non-weighted carry-free number system. The symbol to be transmitted is transformed to RNS representation, mapped into a set of orthogonal sequences and are transmitted in parallel. Error control was also incorporated in this paper using redundant RNS (RRNS) code. Performance of the same system over bursty communication channels is done by Madhukumar and Chin [8]. They have also proposed a modulation technique by combining RNS representation, PSK/QAM modulation and orthogonal modulation for bandwidth efficiency in [9]. The error control properties of RRNS were exploited in [10] to be used as channel codes for protecting the speech bits. In [11] residue arithmetic is used for representing the symbol to be transmitted. Redundant residue arithmetic system based multi-carrier DS-CDMA (MC/DS - CDMA) dynamic multiple access scheme has been proposed in [12] for dynamically accessing the frequency spectrum available for Cognitive Radio communication. All references basically points to a parallel communication scheme where the symbol to be transmitted by each user is represented in residue arithmetic and an inverse RNS transform block is used at the receiver to get back the symbol. But generation of PN sequences by exploiting the properties of RNS and use of these to spread message signals for multiple user transmission has never been investigated.

Wideband Code Division Multiple Access (WCDMA), the air interface technology for third generation (3G) systems specified by 3^{rd} Generation Partenership Project (3GPP) applies DS-CDMA technique with Orthogonal Variable Spreading (OVSF) Code as Channelization code for multiplexing different users [13]. The WCDMA downlink transmission is prone to self interference caused by the loss of orthogonality between spreading codes due to multipath propagation [14, 15, 16, 17] There are several techniques for interference cancellation and multiuser detection that improves the performance and capacity of the downlink WCDMA system [19, 20, 21, 22]. Most of these techniques are designed at the expense of higher receiver complexity and with OVSF codes derived from Walsh-Hadamard code. Construction methods of OVSF-ZCZ sequences have been proposed in [23] to mitigate interference due to multipath propagation. Since the number of OVSF-ZCZ sequences is limited, various assignment algorithms are required to meet the demand of large number of users. The use of Orthogonal Variable Spreading Code (OVSF) code requires that a dedicated rate matching algorithm to be used in the transceivers [1]. This algorithm consumes a great amount of hardware and software resources and increases computation load and processing latency. In the OVSF code generation tree structure, the codes in the upper layer with lower spreading factor blocks the codes in the lower layer with higher spreading factor. ie, fewer users can be accommodated in a cell. These issues indeed demand for the existing existing code replacement. In this context this theses presents a Channelization code based on Residue Arithmetic which counter the said limitations. RNS is already used in the design of decimation filters for WCDMA receivers [24, 25].

1.3 Objective of the work

The main objective of this work is to present a PN Sequence based on RNS to counter the limitations of existing CDMA technology. Various analysis and investigations are needed in support of the above statement which includes:

- Generation of spreading sequences based on RNS with different spreading factors and with different cross-correlation threshold.
- Analysis of the generated sequence in a general DS-CDMA system in comparison with other existing codes and under different channel environment and for different loading scenarios.
- This work can be extended by implementing the generated sequence as the channelization code in WCDMA system which is the basic system in 3G mobile networks. The analysis should be done under different multipath environment and for different loading scenarios in comparison with already existing orthogonal WH codes

1.4 Motivation

The current CDMA system is considered as an interference-limited system mainly due to the existence of Multiple-Access Interference (MAI) and Multipath Interference (MI). Many problems of a communication system based on CDMA technology stem from the spreading codes/sequences, which includes two subcategories, one being the orthogonal codes and the other being pseudo-random or pseudo-noise (PN) sequences.

The CDMA codes were proposed a long time ago by researches working in information theory who might not have had sufficient knowledge on wireless channels, in which many impairing factors exist, such as external interferences, multipath propagation, Doppler effect, etc. The most serious problem arises in a multi-user system because of the non-ideal correlation properties of spreading sequences which result in MAI. PN sequences appear random yet they are completely deterministic in nature with a small set of initial conditions. The security of the concerned system is hence undesirably compromised at times. The orthogonality of all those codes is bad in general, and some of them are not orthogonal at all when they are used in multipath transmission channels. This is due to high cross-correlation between the spreading sequences with arbitrary time shifts. This is the main source of interference in a CDMA system where Orthogonal codes are employed (for example, WCDMA - the main air interface technology for 3G, employing orthogonal WH as spreading codes).

These issues indeed demand for the generation of innovative spreading sequences. RNS provides a huge dynamic range and unique representation of numbers in that range (based on Chinese Remainder Theorem (CRT) which is discussed in Chapter 2). This property of RNS can be exploited for generating spreading sequences. Because of the huge dynamic range, this sequence offers provision to vary correlation threshold based on the channel properties and error tolerance unlike any existing techniques.

1.5 Thesis Organization

This thesis is organized into five chapters. The current chapter begins with the background details of cellular networks. The objective for this thesis work is framed after literature review and this chapter ends with the outline of the thesis.

Chapter-2 Residue Number System

This chapter discusses in more detail about Residue Number System. The basics of RNS and its advantages are discussed in the initial sections. A thorough analysis of the famous CRT which forms the basis for this project work is also done. The two techniques for the generation of co-prime moduli (divisor) selection for the conversion of decimal number to residue number are limned. This is followed by an overview of RNS applications.

Chapter-3 RNS Based PN Sequence for Multi-user CDMA

This chapter deals with CDMA system based on Direct Sequence (DS) spreading technique and the spreading codes for spreading the data. Only those codes that are the basis for the construction of the codes used in the existing standards are covered in this chapter. A new design for PN Sequence generator based on Residue Arithmetic is then discussed to get through the limitations of already existing CDMA codes. The performance analysis of the generated sequence in DS-CDMA system is done in comparison with existing spreading codes for different loading scenarios and under various channel environment.

Chapter-4 3G WCDMA with RNS Based PN Sequence

The purpose of this Chapter is to present the principles of the Wideband Code Division Multiple Access (WCDMA) - Universal Mobile Telecommunication System (UMTS) system model as specified in the Third Generation Partnership Project (3GPP) standards. WCDMA downlink system with the generated PN Sequence as the channelization code is modelled to overcome multipath propagation impairments. The performance of the designed system in comparison with already existing orthogonal code based system is done for various multipath channels.

Chapter-5 Conclusion and Scope of Future work

The last chapter is a summary and discussion on the work presented in this thesis where also further work is outlined

2

Residue Number System

This chapter discusses in more detail about Residue Number System. The basics of RNS and its advantages are discussed in the initial sections. A thorough analysis of the famous CRT which forms the basis for this project work is also done. The two techniques for the generation of co-prime moduli (divisor) selection for the conversion of decimal number to residue number are limned. This is followed by an overview of RNS applications.

2.1 Basics of RNS

Residue number systems are based on the congruence relation as : two integers, a and b are said to be congruent modulo m if m divides exactly the difference of a and b; it is common, especially in mathematics tests, to write $a \equiv b(mod\ m)$ to denote this. Thus, for example, $10 \equiv 7(mod\ 3)$, $10 \equiv 4(mod\ 3)$, $10 \equiv 1(mod\ 3)$ and $10 \equiv -2(mod\ 3)$. The number m is a modulus or base, and its values exclude unity produces only trivial congruences [26, 27].

If q and r are the quotient and remainder, respectively, of the integer division of a by m, that is, $a = q * m + r$ then, by definition, $a \equiv r(mod\ m)$. The number r is said to be the residue of a with respect to m, and is denoted by $r = |a|_m$.

The set of m smallest values, $\{0, 1, 2, 3...(m-1)\}$ that the residue may assume is called the set of least positive residues modulo m. Consider a set $\{m_1, m_2...m_n\}$, of n positive and pairwise relatively prime moduli [1]. Let R be the product of the moduli. Then every number $X < R$ has a unique representation in the residue number system [26, 27]. A partial proof of this is as follows.

Suppose X_1 and X_2 are two different numbers with the same residue set,then

$$|X_1|_{m_i} = |X_2|_{m_i} \Longrightarrow |X_1 - X_2|_{m_i} = 0 \tag{2.1}$$

Therefore X_1 and X_2 are the Least Common Multiple (LCM) of m_i. But if the m_i are relatively prime, then their LCM is R, and it must be that X_1 and X_2 is a multiple of R. So it cannot be that $X_1 < R$ and $X_2 < R$. Therefore, the set $\{|X|_{m_i} : 1 \leq i \leq n\}$ is unique and may be taken as the representation of X and such a representation can be written in the form $\langle x_1, x_2...x_n\rangle$, where $x_i = |X|_{m_i}$, and relationship between X and its residues can be indicated by writing $X \cong \langle x_1, x_2...x_n\rangle$. The number R is called the dynamic range of the RNS, because the number of numbers that can be represented is R.

As an example, the residues of the integers zero through fifteen relative to the moduli two, three, and five (which are pairwise relatively prime) are given in the left half of Table 2.1. And the residues of the same numbers relative to the moduli two, three and four (which are not pairwise relatively prime) are given in the right half of the same table. Observe that no sequence of residues is repeated in the first half, whereas there are repetitions in the second.

2.2 Advantages

Most important advantage of residue arithmetic over conventional arithmetic is the absence of carry propagation, in the two main operations of addition and multiplication, and the relatively low precisions required ranging to individual prime or co-prime number of the moduli set, which enables Look Up Table (LUT) implementations in various operations. In practice, these may make residue arithmetic worthwhile, even though in terms of practical applications such arithmetic has

[1] for every j and k, if $j \neq k$, then m_j and m_k have no common divisor larger than unity.

Table 2.1: Residues for prime and non-prime Modulis

X	Relatively prime moduli			Relatively non-prime moduli		
	$m_1 = 2$	$m_2 = 3$	$m_3 = 5$	$m_1 = 2$	$m_2 = 3$	$m_3 = 4$
0	0	0	0	0	0	0
1	1	1	1	1	1	1
2	0	2	2	0	2	2
3	1	0	3	1	0	3
4	0	1	4	0	1	0
5	1	2	0	1	2	1
6	0	0	1	0	0	2
7	1	1	2	1	1	3
8	0	2	3	0	2	0
9	1	0	4	1	0	1
10	0	1	0	0	1	2
11	1	2	1	1	2	3
12	0	0	2	0	0	0
13	1	1	3	1	1	1
14	0	2	4	0	2	2
15	1	0	0	1	0	3

little fields over conventional arithmetic to cover. However the concept of break and process can be very useful in places where integer arithmetic is predominant. Because of the robust signal processing properties of RNS, it also find application in the field of Communication. Basic advantages of residue arithmetic are:

- High Speed
- Low Power
- Superior Fault Tolerance
- Reduction of Computational Load

2.3 Chinese Remainder Theorem

According to the CRT, if the set of divisors is all co-primes to each other, then the residue representation of any number is unique provided the number is within the range R, where R is product of all the numbers in the set of divisors [27, 28]. Since the divisor set is not limited, hereby as we extend the set of divisor, the bit representation of the number in RNS will be incremented by the number bits of the divisor added to the set of divisors.

Let m_1 and m_2 be positive integers which are relatively prime. Let n_1 and n_2 be any two integers. Then there is an integer N such that

$$N \equiv n_1(mod\ m_1) and N \equiv n_2(mod\ m_2) \tag{2.2}$$

Moreover, N is uniquely determined modulo $(m_1\ .\ m_2)$. An equivalent statement is that if gcd(m_1, m_2) = 1 then every pair of residue classes modulo m_1 and m_2 corresponds to a simple residue class modulo $(m_1\ .\ m_2)$. Given a set of simultaneous congruences $n \equiv n_i(mod\ m_i)$, for $i = 1, 2....n$ and for which m_i are relatively prime. Then the solution to the set of congruences is

$$x = [a_1 * b_1 \frac{M}{m_1},\ a_2 * b_2 \frac{M}{m_2}\ ...\ a_p * b_n \frac{M}{m_n}] \tag{2.3}$$

where $M = \{m_1, m_2\ ...\ m_n\}$, and the b_i are determined from:

$$b_1 \frac{M}{m_1} = 1(mod\ m_1) \tag{2.4}$$

2.4 Moduli Selection and Mapping

If we consider any prime number, then there exists at least one primitive root $r \leq n - 1$, such that the set $\{|r_i|_n : i = 0, 1, 2....n - 2\}$ is set of all possible non-zero residues with respect to n. 5 and 7 are examples of primitive root. For any digital application moduli set should be chosen such that representation is efficient, unique and the difference between the moduli be as small as possible to increase the dynamic range. The moduli set selection is done either by Consecutive Moduli Selection method or by Exponential Moduli Selection method [28].

2.4.1 Consecutive Moduli Selection

Theorem: Let $N_1, N_2......N_n$ be a set of n consecutive co-prime numbers. Let these numbers be expressed as

$$N_i = N_1 - m_{i-1} \tag{2.5}$$

for $i = 1, 2, 3...n$, where $m_{i-1} > m_{i-2} > m_{i-3} > ... > 0$. Let N_{n+1} be another number that can be added to the set of co-prime numbers, i.e. $N_{n+1} = N_1 - m_n$ then N_{n+1} will be co-prime if $gcd(N_1, m_n - m_{i-1}) = 0$, for $i = 1, 2, 3...n$. Fig 2.1 shows the bit distribution in consecutive moduli system for $b = 32$ bits system. Here the number of co-primes, $n = 4$ of $k = 8$ bits each is shown.

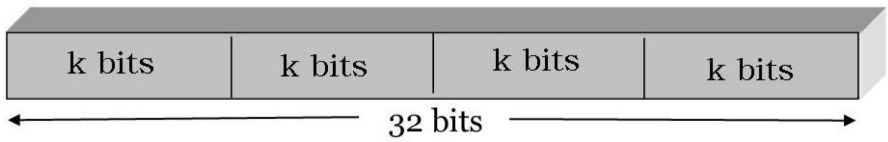


Figure 2.1: Bit Distribution of Modulis in Consecutive Moduli Selection

Proof

For N_{k+1} to be co-prime to every other numbers in the set $N_1, N_2......N_k$,

$$gcd(N_i, N_{K+1}) = 1 \tag{2.6}$$

$$\Rightarrow gcd(N_{K+1}, N_i - N_{K+1}) = 1 \tag{2.7}$$

$$\Rightarrow gcd(N_{K+1}, m_i - m_{i-1}) = 1 \tag{2.8}$$

In order to improve dynamic range of RNS with high bit efficiency, N_1 must be selected as $2^m - 1$ which will be a m bit number. Then by the above method one can generate the set of co-prime numbers and use them as moduli set for RNS.

2.4.2 Exponential Moduli Selection

Fig 2.2 shows the bit distribution in exponential moduli system for the same 32 bit system. Here the number of co-primes, $n = 4$ of t,s,r and q bits respectively. In the figure, $t = 32 - (s + r + q)$. Consider a set of number M such that

$$M_i = 2^{n-k} - 1 \tag{2.9}$$

where $k = k \varepsilon N : \forall k, gcd(2^{n-k}, P) is 1$

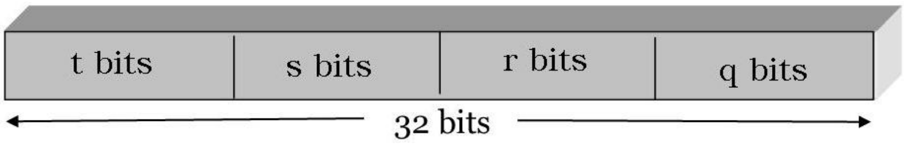


Figure 2.2: Bit Distribution of Modulis in Exponential Moduli Selection

Example

Choose co-prime numbers with $b = 32$ and $n = 4$, i.e., close to $2^8 (= 256)$, gives us P_{con} = [255 254 253 251] and P_{exp} = [31 127 511 2047] when consecutive moduli selection and exponential moduli selection is used respectively. Since there cannot be any other combination of co-prime numbers close to 2^8, hence this is the most bit efficient moduli set with widest dynamic range possible in range of 8 bit numbers. The dynamic range R is hence:

$$R = \prod_{i=1}^{n} p_i \tag{2.10}$$

Now calculating R as in eq 2.10, $R_{con} = 4113089310$ and $R_{exp} = 4118168929$.

2.5 Overview of RNS Applications

RNS is mostly used in Very Large Scale Integrated Circuit (VLSI) implementation of Digital Signal Processing (DSP) architecture for achieving low power and high speed [29, 30, 31, 32]. Among the application of RNS, implementation of FIR filters, IIR filters, adaptive filters, digital frequency synthesis, two dimensional filters, image encryption and coding are most significant.

Most significant research work in the field of RNS was done in forward and reverse conversion. Recent research on reverse converters [33, 34] uses New Chinese Remainder Theorem proposed by Y. Wang [35]. RNS had been effectively used in FIR filter design [36, 37]. One dimensional and two dimensional Discrete Wavelet Transform architecture based on residue arithmetic made a crucial impact [38, 39].

RNS had been effectively used in encryption and coding [40, 41]. In field of communication, RNS were introduced. Frequency hopping techniques [42], DS-CDMA [5, 6, 7, 8, 9, 10, 11] and MC-CDMA [12, 43] based on RNS were proposed and designed. Yet another application of RNS in PN sequence generation for CDMA system is discussed in this theses.

Summary

The main aim of this chapter has been to introduce the essential aspects of residue number system. Digital communication applications demand the generation of PN sequence such that the transmitted data appear random to the channel but be predictable to the users. This can be achieved by exploiting the concept of CRT and the details of which is discussed in Page 21.

3

RNS Based PN Sequence for Multiuser DS-CDMA

This chapter begins with spread spectrum transmission schemes which spreads the data to increase the channel bandwidth much greater than is required by the Nyquist Sampling theorem. The spreading codes for data spreading have to be carefully chosen for efficient communication systems. The technique for generating code sequences should be aimed at a large family of sequences in order to accommodate a large number of users with an impulsive-type autocorrelation which enhances system synchronization and possibly with low cross-correlation functions, to reduce multiple access interference. Since the existing CDMA codes fail to satisfy all these properties, a new PN sequence Generated based on RNS is proposed.

Correlation properties of the generated code is compared with other standard PN sequences since it defines the amount of interference generated from multiple users. Finally, multiple access properties of the spread spectrum is analysed and an analytical model for evaluating the system performance is made.

3.1 Spread Spectrum Communication

Shannon [44] stated that the stationary Gaussian noise process which maximizes capacity is the one that spreads its available power uniformly across the given bandwidth. Thus the capacity C for a given bandwidth B of a jamming channel is derived from the well known equation $C = BXlog_2(1 + SNR)$ where Signal to Noise Ratio (SNR) is defined as

$$SNR = \frac{P}{BN_0 + N_J} \tag{3.1}$$

where P is the signal power, N_0 the thermal noise density and N_J the jamming power. The motivation is then to expand(spread) B in jamming situations until the total received noise power BN_0 dominates N_J [45]. The spreading leads to a reduction in required SNR which is very advantageous for communications and can be represented as a Processing Gain (PG):

$$PG = \frac{W}{B} \tag{3.2}$$

where W denotes the SS bandwidth and B the unspread signal bandwidth. In many practical applications, the ratio between the chip rate and original data information rate can also be used as the PG [46]. SS systems can be categorised by the techniques used to spread and despread the transmitted signal. There are three main techniques :

- Direct Sequence(DS)
- Frequency Hopping (FH)
- Time Hopping (TH)

It is stressed that this project work is concerned only with DS-based CDMA systems. DS SS averages the interference over a large period of time, whereas the other techniques combat interference by separating the desired signal in frequency or time (on average) from the majority of the interference. The spreading in DS SS is done by multiplying the users bit with a signature sequence of bits (code), where these bits are called chips, which are generated by a pseudo-noise (PN)

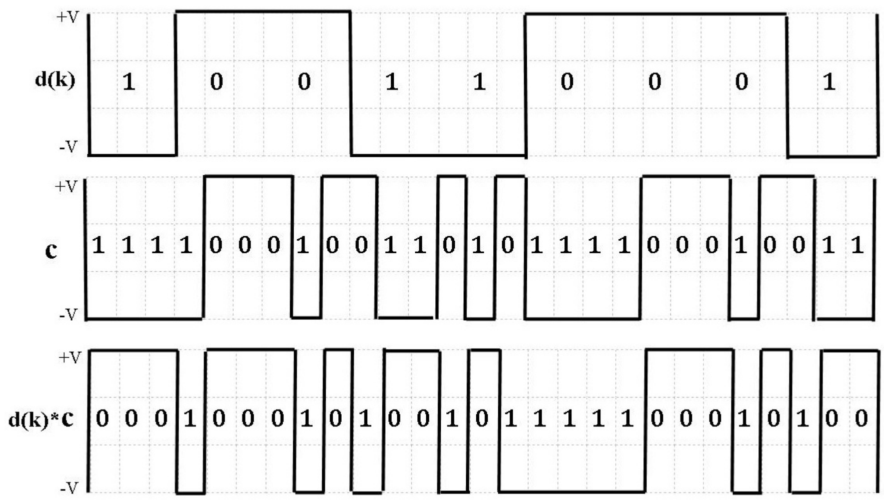


Figure 3.1: Spreading of data using DS-SS technique

or random generator [47]. The spreading sequences used for the system under consideration are generated based on residue arithmetic. Such a transmitted sequence, which contains the information of the user bit is also referred to as a symbol. Consider T_b as the bit duration of k^{th} bit of the data sequence, d and that of the PN sequence, c is T_c which is called as chip period. Now when the bit is multiplied to the PN sequence, the output also has a bit duration of T_c shown in Figure 3.1. Since $T_b >> T_c$, the frequency of the transmitted bit becomes very large compared to the signal.

3.2 Spreading Codes in CDMA

Many problems of a communication system based on CDMA technology stem from the unitary spreading codes/sequences, which includes two sub-categories, one being the orthogonal codes, such as Walsh-Hadamard codes and OVSF codes, and the other being pseudo-random or PN sequences, such as Gold sequences, Kasami sequences, m-sequences, etc.

Long codes in IS-95 is an m-sequence generated by a polynomial of degree n=42. Channelization codes on the downlink are Walsh codes. In UMTS, Gold codes are used for scrambling. Different channels of the same user on the uplink are separated by using OVSF codes. A large set of Kasami codes is used in the

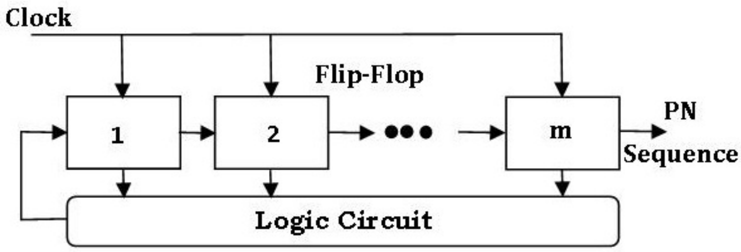


Figure 3.2: Linear Feed Back Shift Register(LFSR) for m-sequence generation

primary and secondary synchro channel [48, 49].

Pseudo-Random CDMA codes have been found to be more suitable for their use in many wireless applications since orthogonal CDMA codes usually perform extremely bad if they are used for asynchronous channel transmissions where as other category of CDMA codes offer relatively uniform performance for their operation in both synchronous and asynchronous channels.

3.2.1 Maximal Length Sequence

Pseudo Random Binary Sequences (PRBSs), also known as pseudo noise, Linear Feedback Shift Register (LFSR) (Figure 3.2) sequences or maximal length binary sequences (msequences), are widely used in digital communications. This sequence is generated using a shift register and modulo-2 adders. Certain outputs of the shift register are modulo-2 added and the adder output is fed back to the register. An m-stage shift register can generate a maximal length sequence of 2^m-1 bits. Only certain outputs, or taps, can generate a maximal length sequence[50].

3.2.2 Gold Sequence

Gold Sequence was proposed by Robert Gold [51]. These are constructed by modulo-2 addition of two m-sequences of the same length generated from Shift Register Generator (SRG) with each other. These code sequences are added chip by chip through synchronous clocking as shown in Figure 3.3. Thus, for a Gold sequence of length $m = 2^l - 1$, one uses two linear feedback shift register (LFSR), each of length $m = 2^l - 1$. Choosing LFSRs appropriately, Gold sequences give better cross-correlation properties than maximum length LSFR sequences.

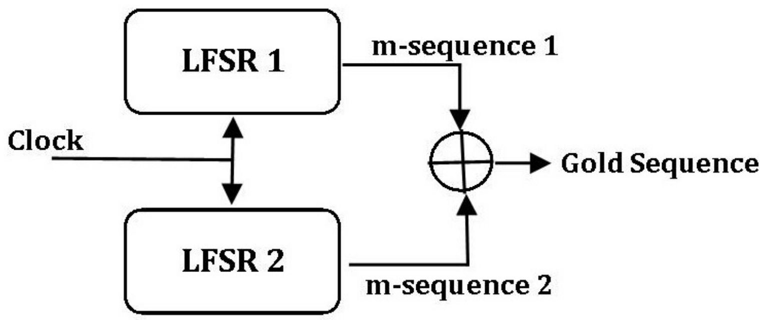


Figure 3.3: Generation of Gold Sequence from m-sequences

3.2.3 Kasami Sequence

Kasami sequence sets are one of the important types of binary sequence sets because of their very low cross-correlation. For sequence generation, a sequence A' is formed from an m-sequence A by decimating A by $2^{n/2} + 1$. It can be verified that the resulting A' is an m-sequence with period $2^{n/2} - 1$. Now, by taking $N = 2^n - 1$ bits of sequences A and A', a new set of sequences is formed by adding, modulo-2, the bits from A and the bits from A' and all $2^{n/2} - 2$ cyclic shifts of the bits from A'. By including A in the set, a set of $2^{n/2}$ binary sequences of length $N = 2^n - 1$ is obtained [52].

3.2.4 Walsh-Hadamard Sequences

The WH sequence is often used to improve the bandwidth efficiency of a DSSS system. One way to generate the WH sequence with block length $N = 2^n$, where n is a positive integer, is to use a Hadamard matrix with recursive procedures [52], which is given by

$$H_1 = [0]$$

$$H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & \bar{H}_1 \end{bmatrix}$$

$$H_{2N} = \begin{bmatrix} H_N & H_N \\ H_N & \bar{H}_N \end{bmatrix} \tag{3.3}$$

where N is the power of two and $\bar{H}_N$ is the binary complement of the elements in H_N. Since the auto-correlation values of the WH sequences are generally worse than the cross-correlation values, it may not be appropriate to use the WH sequence for the DS-SS system for a channel with Inter-Symbol Interference (ISI).

3.2.5 Orthogonal Variable Spreading Factor Codes

OVSF Codes are generated by using tree structure as shown in Figure 3.4 [53].Starting from $C_1 = 1$, a set of 2^K spreading codes can be generated at the k^{th} layer $\{k = 1, 2, ...K\}$ from the root of the tree. Let C_k^b be an OVSF code on k^{th} layer with b^{th} branch where $k = 0, 12, ...$ and $b = 0, 1, 2....2^k - 1$. The code length of the k^{th} layer is 2^K chips. The generated codes of the same layer form a set of WH codes and they are orthogonal.

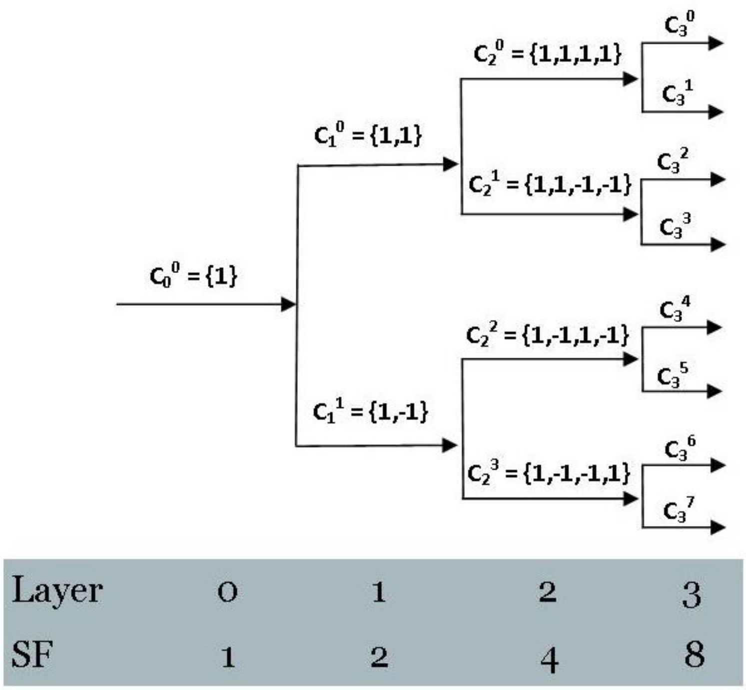


Figure 3.4: Code Tree for Generation of OVSF Codes

Any two codes of different layers shown in Figure 3.4 are orthogonal except except for the case that one of the two codes is a mother of the other. Furthermore, if a code of any layer is assigned to a user, all the codes generated from this code cannot be assigned to other users of the same bandwidth requesting lower rates. This restriction is to maintain orthogonality.

3.3 RNS Based PN Sequence Generator

In most communication systems, spreading codes or sequences can be generated in an off-line way and is saved in a look-up table, which can be called whenever needed. Similarly RNS based PN sequence generation [27] also consists of an off-line process for the generation of Initial Primal Vector and finally the generation of the required PN sequence from the stored primal vectors which is done on-line. The off-line process is summarized in Fig 3.5. The external inputs to these blocks include spreading factor, β and the Cross Correlation Threshold (CF). Moduli set, M, for a given β are selected either by consecutive method or exponential method which is already explained in Chapter 1. Consecutive method of moduli selection is used here. Table 3.1 shows the generated moduli set and dynamic range, R for various spreading factors using Consecutive moduli selection method. For a given spread factor, the number of users that can be accommodated is huge in comparison to other spreading codes.

A primal, J_1 is randomly selected from the range, R in eq. 2.10. The corresponding residue set, $R_s(J_1)$

$$R_s(J_1) = \{|J_1|_{p_1}, |J_1|_{p_2}, ...|J_1|_{p_m}\} \tag{3.4}$$

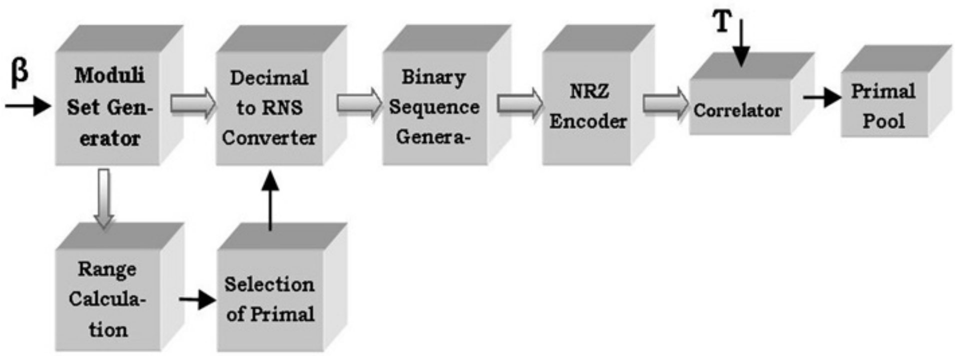


Figure 3.5: Offline process for RNS Based PN Sequence Generation

Table 3.1: Generated Moduli Set and Dynamic Range for different Spreading Factors

β	**MODULI SET** $P = \{p_1, p_2, p_3, ...p_m\}$	**RANGE, R**
8	[255]	255
16	[255 254]	64770
32	[255 254 253 251]	4113089310
64	[255 254 253 251 247 241 239 233]	$\cong 10^{19}$
128	[255 254 253 251 247 241 239 233 229 227 223 217 211 199 197 193]	$\cong 10^{40}$

is the output of Decimal to Residue Arithmetic Converter. The generated residue numbers are concatenated and converted into 8 bit (since k = 8) binary sequence of 1 and 0. This sequence is passed through the NRZ encoder to get the sequence c_1 corresponding to primal J_1. This procedure is repeated for every primals in range, R. The generated sequences are tested for correlation amongst themselves such that

- correlation between c_i and c_j, $i = j$ has to be unity.
- correlation between c_i and c_j, $i \neq j$ has to be preferably less than a threshold T. This threshold can vary for different applications based on the channel properties and error tolerance.

The primals which satisfies this criteria forms the Primal Pool, J. Consider an example for the proposed PN Sequence Generation for $\beta = 16$, M =[255 254] and CF = 0.25. Table 3.2 shows the generated the PN Sequence for the randomly selected primals. These sequences are then tested for correlation among themselves which is listed in Table 3.3. Since the defined system requires a threshold of 0.25, discard J_5 and add J_1, J_2, J_3, J_4 to the final primal pool, J.

The next phase, shown in Figure 3.6, starts when the system under consideration demands for signature waveforms. Depending upon the application and number of users active in the system, the Primal Vector, J

$$J = [J_1, J_2, J_3, ...J_U]^T \tag{3.5}$$

Table 3.2: RNS Based PN Sequence Generation

Primal, J [1]	**PN Sequence Based on RNS, c**
1	-1 -1 -1 -1 -1 -1 -1 1 -1 -1 -1 -1 -1 -1 -1 1
321	-1 1 -1 -1 -1 -1 1 -1 -1 1 -1 -1 -1 -1 1 1
550	-1 -1 1 -1 1 -1 -1 -1 -1 -1 1 -1 1 -1 1 -1
2356	-1 -1 1 1 1 1 -1 1 -1 1 -1 -1 -1 1 1 -1
64000	1 1 1 1 1 -1 1 -1 1 1 1 1 -1 1 1 -1

[1] Primals are selected within the Range, R

$$R = 255X254 = 64770$$

is selected from the Primal Pool with spread factor, β along with number of active users, U as input. The residue matrix $R_s = |J|_M$ is created in RNS converter block such that $R_s = [R_s(J_1),\ R_s(J_2),\ R_s(J_3), ...\ R_s(J_U)]$. Finally the required RNS based PN code matrix, c = $[c_1\ c_2 ...\ c_U]$ of size U X β is formed after binary conversion and encoding. The maximum size of the proposed code set is very large with respect to other PN sequences. This offers the provision to vary correlation threshold based on the channel properties and error threshold of the system under consideration.

3.4 DS-CDMA System Model

Consider a mobile receiver for CDMA with U simultaneous transmissions plus Additive White Gaussian Noise (AWGN) as shown in Figure 3.7. The transmitted

Table 3.3: Correlation Matrix of the Generated Sequence

	C_1	C_2	C_3	C_4	C_5
C_1	1	0.15	-0.25	0	-0.65
C_2	0.15	1	-0.16	-0.13	0.07
C_3	-0.25	-0.16	1	0.13	0.07
C_4	0	-0.13	0.13	1	0
C_5	-0.65	0.07	0.07	0	1

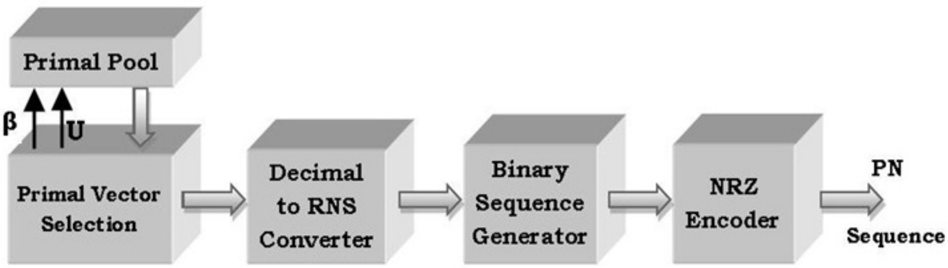


Figure 3.6: RNS Based PN Sequence Generation - On-line Process

signal at time t is constructed by summing the spread sequence of each user. The noise corrupted received signal y(t) is defined as

$$y(t) = x(t) + \eta(t) \tag{3.6}$$

where $\eta(t)$ denotes the white Gaussian noise. The u^{th} users transmitted data bit for bit k is denoted as $d_u(k)$ and is either +1 or -1 with equal probability and all users are transmitting with equal power, normalised to one. Then, the received signal x(t) due to the u^{th} user is given by:

$$x_u(t) = \sum_{u=1}^{U} \sqrt{2P_u} \sum_{k=-\infty}^{\infty} d_u(k) s_u(t - kT_b - \tau_u) cos(\omega_c t + \phi_u) \tag{3.7}$$

where P_u, τ_u and ϕ_u are the power, delay and carrier phase shift of the u^{th} user, and ω_c is the carrier frequency; $s_u(t)$ is the u^{th} spreading sequence (signature) waveform given by

$$s_u(t) = \sum_{n=0}^{L-1} c_{u,n} \psi(t - nT_c) \tag{3.8}$$

where $c_{u,n} \in \{1, -1\}$ is the n^{th} element of the spreading sequence for user u, $\psi(t)$ is the chip waveform and L the spreading sequence length. In order to simplify the notation, it is assumed that all carrier phases are equal to zero and baseband notation can be used [47]. Since the signal processing task is done on sampled signals, it is more convenient to make use of vector and matrix notation. Therefore Equation 3.6 can be rewritten for a fully synchronised downlink antipodal $\{+1, -1\}$ DS-CDMA system with U independent users and a non-dispersive

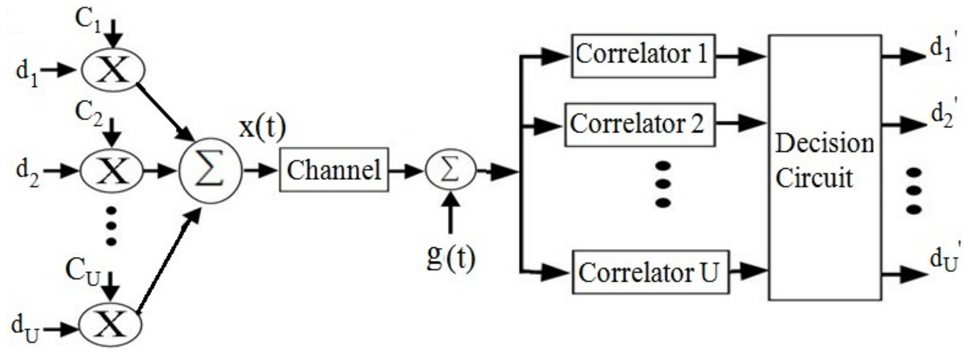


Figure 3.7: Block Diagram of DS-CDMA System

AWGN channel.

$$y(kL+n) = \sum_{u=1}^{U} d_u(k)c_{u,n} + \eta(kL+n) \tag{3.9}$$

The received signal becomes y(k) in vector notation, where k denotes the k^{th} user bit. If the signal is transmitted through a channel with ISI, then equation 3.6 becomes

$$y(kL+n) = H(z) \bigotimes x(kL+n) + \eta(kL+n) \tag{3.10}$$

where $\bigotimes$ represents convolution operation and $H(z)$ is the channel impulse response [54]. A CDMA receiver processes the received signal with either a bank of matched filters (MFs) or RAKEs. To recover the data, the received signal is multiplied by the required sequence, which is generated locally by the receiver. For a multipath scenario, the spreading codes c_i where i=1 to U is replaced by the convolution between $C_i \bigotimes H_{ch}$. RNS based PN Sequences are used as spreading sequence for the system under consideration.

3.5 Comparison of RNS based PN sequence with other CDMA codes

A comparison in terms of number of codes in the code set and correlation properties is made for the proposed sequence with respect to other CDMA codes that are used in various mobile cellular standards.

3.5.1 Number of Sequences

Table 3.4 shows the comparison of number of available codes for a cell for the proposed sequence with other CDMA codes for a given spreading factor. N length Walsh - Hadamard (WH) sequences are derived from Walsh - Hadamard matrix of size $N \times N$ to support N different users [52]. For a particular sequence length, the OVSF codes are basically the same as WH sequences. The only difference between the two is that the latter allow combinational use of WH sequences with different lengths [53]. This creates Code Assigment Blocking problem thus limiting the number of users close to one fifth of the maximal spreading factor [1]. An n-stage shift register can generate a maximal length sequence of 2^n-1 bits [52]. Shifted combinations of this sequence gives $N = 2^n$-1 number of sequences. Gold Sequence are constructed by modulo-2 addition of two m-sequences of the same length with each other [51]. Including the two m-sequences used for addition a total of N+1 sequences are formed.

The data in Table 3.4 shows that the number of sequences from the proposed PN Sequence Generator with the moduli set in Table 3.1 is very huge. This range can also be altered by changing the moduli set.

3.5.2 Correlation Properties

For comparing cross-correlation properties with other standard PN sequence, the proposed PN sequences are generated for $\beta = 8$ and moduli set P = [255]. The

Table 3.4: Length of the code set for different CDMA Codes

β	**Orthogonal Code**		**Pseudo Random Sequence**		
	WH code	**OVSF code**	**m - sequence**	**Gold sequence**	**RNS based sequence**
8	8	8	7	9	255
16	16	16	15	17	64770
32	32	32	31	33	4113089310
64	64	64	63	65	$\cong 10^{19}$
128	128	128	127	129	$\cong 10^{40}$

Table 3.5: Correlation Matrix for RNS based PN Sequence, $\beta = 8$

	PN_1	PN_2	PN_3	PN_4	PN_5	PN_6	PN_7
PN_1	1	0	0	0	0	0.14	0.14
PN_2	0	1	0	0	0	-0.25	-0.25
PN_3	0	0	1	0	0	0.25	0.25
PN_4	0	0	0	1	0	0.25	0.25
PN_5	0	0	0	0	1	-0.25	-0.25
PN_6	0.14	-0.25	0.25	0.25	-0.25	1	-0.06
PN_7	0.14	-0.25	0.25	0.25	-0.25	-0.06	1

primal vector, $J = [10\ 39\ 60\ 77\ 86\ 25\ 140]$, is generated by varying the threshold value from 0 to 0.25. The correlation matrix of RNS based PN sequence, Gold sequence and Maximal Length sequence are tabulated in Table 3.5, Table 3.6 and Table 3.7 respectively. The data shows that the maximum cross correlation between any two sequences is limited to 0.25 for RNS based PN sequence whereas it come up to 0.41 and 0.73 for gold sequences and maximal length sequences, while the auto correlation reaches to 1.

Table 3.6: Correlation Matrix for Gold Sequence, $\beta = 8$

	PN_1	PN_2	PN_3	PN_4	PN_5	PN_6	PN_7
PN_1	1	0.41	-0.09	-0.16	-0.09	-0.09	-0.35
PN_2	0.41	1	-0.09	0.41	-0.09	-0.09	-0.35
PN_3	-0.09	-0.09	1	-0.09	-0.40	-0.40	0.25
PN_4	-0.16	0.41	-0.09	1	-0.09	-0.09	-0.35
PN_5	-0.09	-0.09	-0.40	-0.09	1	-0.40	0.25
PN_6	-0.09	-0.09	-0.40	-0.09	-0.40	1	0.25
PN_7	-0.35	-0.35	0.25	-0.35	0.25	0.25	1

3.6 Simulation Results and Discussion

The behaviour of RNS based PN sequence in a DS-CDMA system is estimated using Monte Carlo simulations. BER is considered as the performance index

Table 3.7: Correlation Matrix for Maximal Length Sequence, $\beta = 8$

	PN_1	PN_2	PN_3	PN_4	PN_5	PN_6	PN_7
PN_1	1	0.54	-0.30	0.54	0.09	-0.30	0.40
PN_2	0.54	1	0.09	0.41	-0.41	0.09	-0.54
PN_3	-0.30	0.09	1	0.09	-0.09	0.30	-0.40
PN_4	0.54	0.41	0.09	1	0.16	-0.54	0.09
PN_5	0.09	-0.41	-0.09	0.16	1	-0.73	0.54
PN_6	-0.30	0.09	0.30	-0.54	-0.73	1	-0.40
PN_7	0.40	-0.54	-0.40	0.09	0.54	-0.40	1

through out. Extensive simulations were carried out by varying Cross Correlation Factor, CF and Spreading Factor, β under different channel environment and with different loading scenarios. The moduli set for generation of PN sequence with $\beta = 8$, $\beta = 64$ and $\beta = 128$ are chosen from Table 3.1.

3.6.1 AWGN Channel

The variation in DS - CDMA system performance with respect to cross-correlation factor is shown in Fig 3.8 and Fig 3.9. Fig 3.8 compares the system performance for different PN codes whose cross correlation factors are listed in Table 3.5, Table 3.6 and Table 3.7 with $\beta = 8$. The difference in the cross correlation factor is directly reflected in the system performance. The superior performance of residue arithmetic code shows that it has better resilience to inter-user interference than other standard PN sequences. Fig 3.9 demonstrates the variation in system performance with RNS based PN sequence for cross-correlation threshold of 0.10 and 0.20 and $\beta = 128$. Result shows that for 12.5 percent loading of a system with spread factor, $\beta = 128$ and 12 users being active in the system, the bit error rate went down to 10^{-5} for cross-correlation threshold of 0.10 whereas it is only $4 * 10^{-3}$ for 0.20.

The performance of DS-CDMA system using RNS based PN sequence over an AWGN channel for $\beta = 64$ in Fig 3.10 and $\beta = 128$ in Fig 3.11 is shown. The E_b/N_o characteristics were varied from 1 to 20 dB for different loading scenarios. Here the cross correlation threshold value is chosen to be 0.20. Additional tests

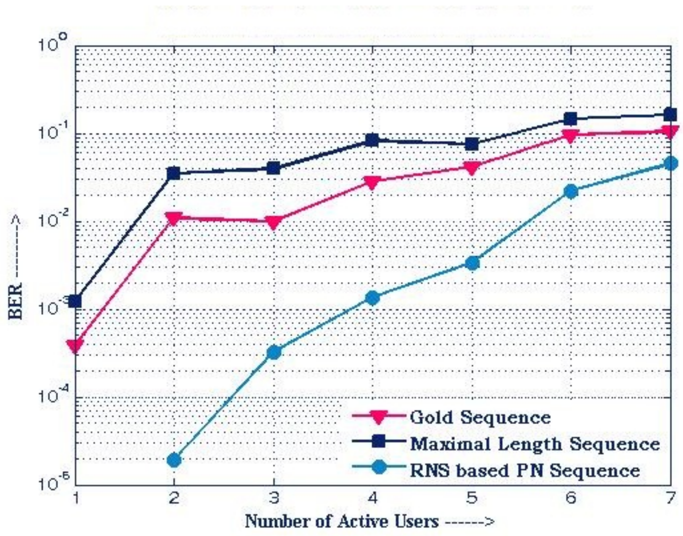


Figure 3.8: BER performance versus the Number of Active Users with spreading factor, $\beta = 8$ for Maximal Length Sequence, Gold Sequence and RNS based PN Sequence

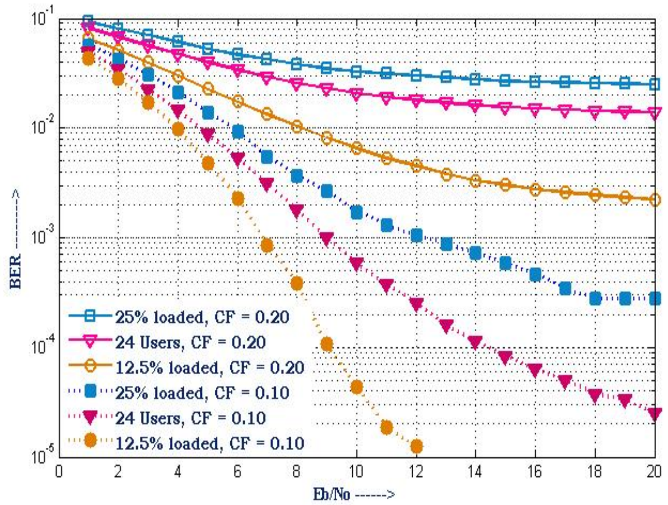


Figure 3.9: Performance Comparison of DS-CDMA system with cross correlation threshold, CF, 0.20 and 0.10 for different loading scenarios, $\beta = 128$

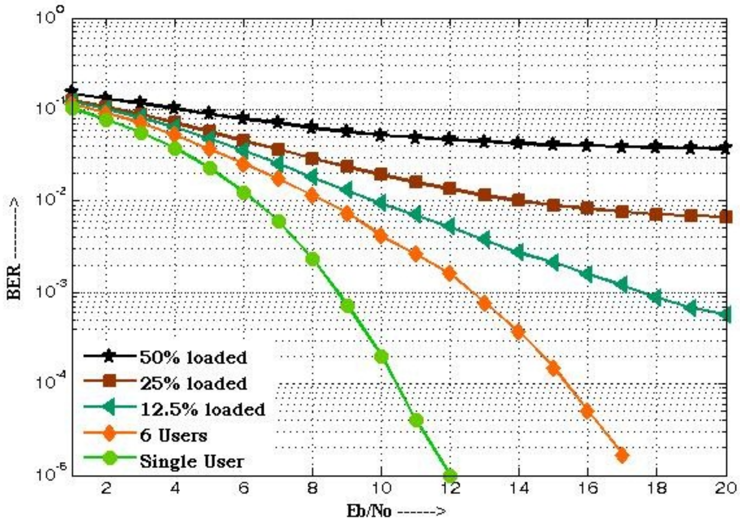


Figure 3.10: BER plot of DS-CDMA system using RNS based PN sequence with $\beta = 64$ for different loading scenarios

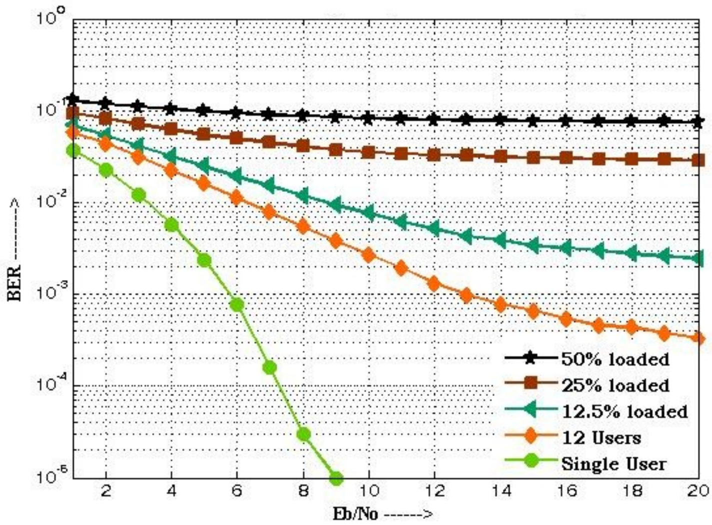


Figure 3.11: BER plot of DS-CDMA system using RNS based PN sequence with $\beta = 128$ for different loading scenarios

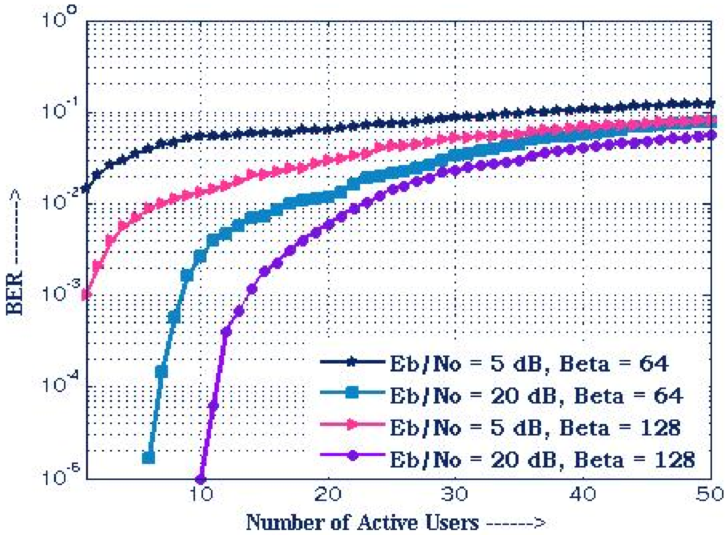


Figure 3.12: BER performance versus the number of active users for E_b/N_o of 5 dB and 20 dB with $\beta = 64$ and $\beta = 128$

were also conducted by varying number of active users in the system for E_b/N_o of 5 dB and 20 dB shown in Fig 3.12. From the results, for a given target BER, for example, 10^{-3} and for a given E_b/N_o of 12 dB, 6 users can be accommodated with $\beta = 64$ while it is doubled for $\beta = 128$.

Comparison of RNS based PN sequence with the most widely used quasi-orthogonal CDMA codes, which includes Gold codes, Kasami codes and Maximal Length sequence is shown in Fig 3.13. The superior performance of residue arithmetic code even for a cross correlation threshold of 0.20 shows that it has better resilience to inter-user interference than other standard PN sequences. Simulations are done for $\beta = 64$ and 5 users are active in the DS-CDMA system.

3.6.2 Rayleigh Fading Channel

BER versus signal-to-noise ratio for a DS-CDMA system in Rayleigh Fading channel, $\beta = 128$ is shown in Figure 3.14. The analysis has been carried out under flat Rayleigh fading channels and multiple-access interference. Since the spread spectrum processing gain makes uncorrelated noise negligible after despreading, equalization is not considered. So for the required number of users in the system,

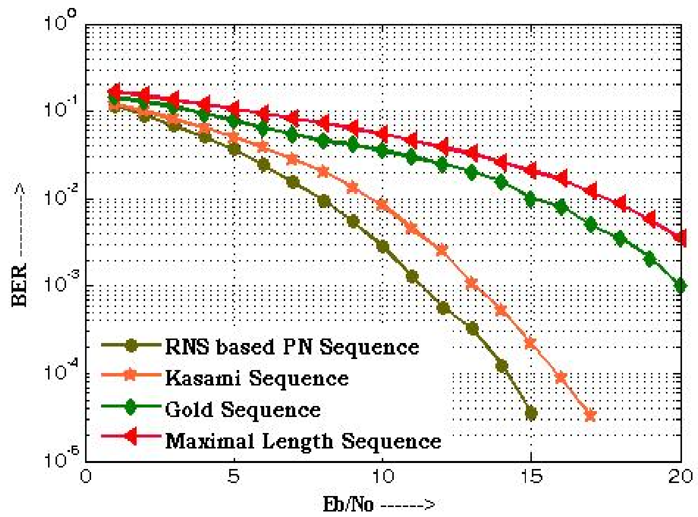


Figure 3.13: Comparison of RNS based PN sequence with Gold codes, Kasami codes and Maximal Length sequence based on BER Plot for 5 Users DS-CDMA System, $\beta = 64$

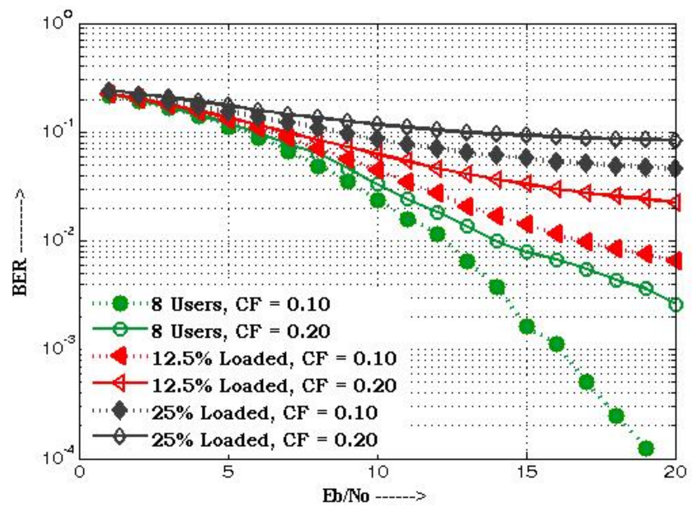


Figure 3.14: BER Performance of DS-CDMA system using RNS based PN sequence with $\beta = 128$ for different loading scenarios. The channel considered is Rayleigh Fading Channel with cross-correlation threshold, CF, 0.20 and 0.10

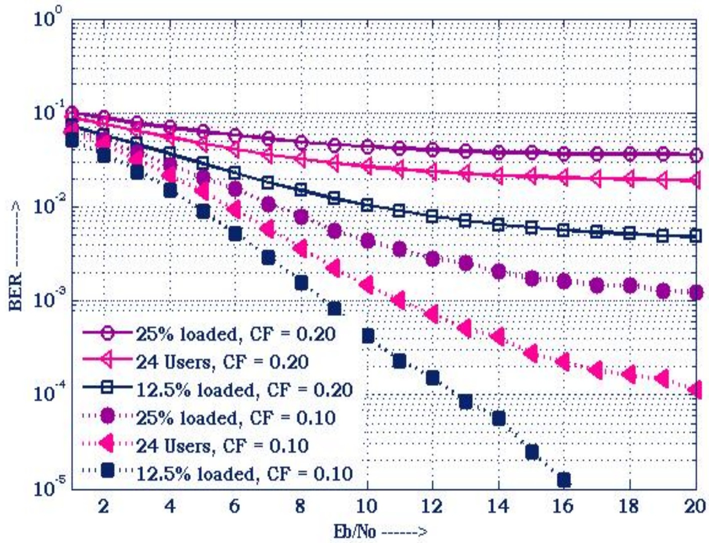


Figure 3.15: BER plot of DS-CDMA system in Minimum Phase Channel, $1 + 0.5z^{-1} + 0.2z^{-2}$ with $\beta = 128$ for different loading scenarios

the performance degradation due to fading is compensated by reducing cross correlation threshold, CF, from 0.20 to 0.10.

3.6.3 Stationary Multipath Channel

For the next phase, the channel which corrupts the transmitted signal with both MAI and MI was taken into account. Here, the consideration was for different types of AWGN multipath channels with following transfer functions:

- $1 + 0.5z^{-1} + 0.2z^{-2}$, Minimum Phase Channel - with zeros located inside the unit circle.
- $0.5 + z^{-1}$, Maximum Phase Channel - with a zero located outside the unit circle.
- $0.3482 + 0.8704z^{-1} + 0.3482z^{-2}$, Mixed/Non-minimum Phase Channel - with some of its zeros inside the unit circle and the remaining zeros outside the unit circle.

The simulations were conducted for different levels of E_b/N_o and varying number of users active in the cell. A minimum phase system in Figure 3.15 is affected

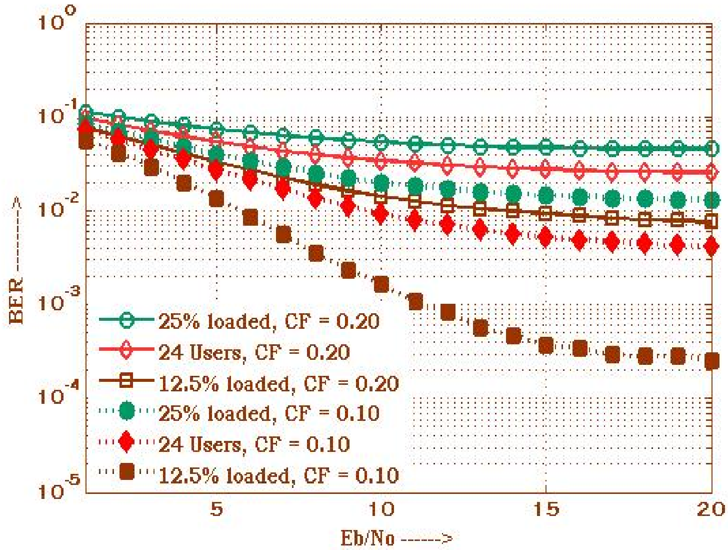


Figure 3.16: BER plot of DS-CDMA system in Maximum Phase Channel, $0.5 + z^{-1}$ with $\beta = 128$ for different loading scenarios

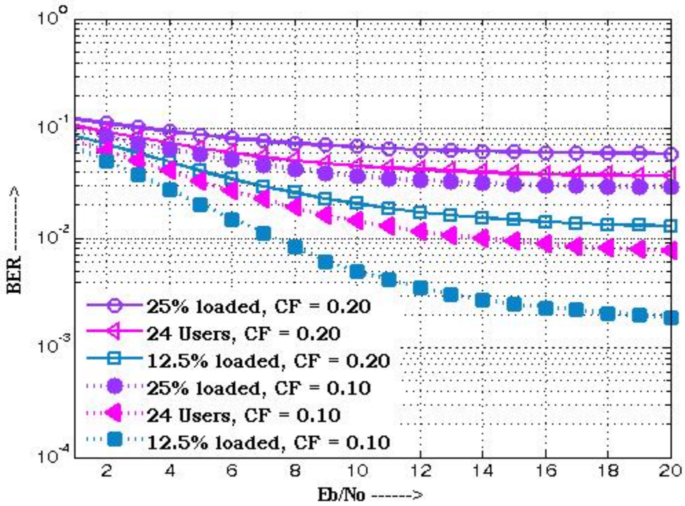


Figure 3.17: BER plot of DS-CDMA system in Mixed Phase Channel, $0.3482 + 0.8704z^{-1} + 0.3482z^{-2}$ with $\beta = 128$ for different loading scenarios

only with MI. On the other hand, maximum and mixed phase channel undergoes a net phase change [55] along with MI. As a result of this, the performance of Figure 3.16 and Figure 3.17 degrades further. From the results, it is clear that sequences having cross-correlation threshold above 0.20 does not have any significance. Here the cross correlation threshold has to be 0.10 and below.

Summary

The performance variations in different channels and the error floor reduction with increase in spreading factor shows that the proposed sequence behaves like PN sequences. In addition, the above results illustrate that it also incorporate real operational conditions with a provision to vary the correlation properties as per the system requirements. For applications which require better performance, the cross-correlation threshold should be reduced further so as to mitigate the multiple access interference.

4
3G WCDMA with RNS Based PN Sequence

From the previous chapter it is clear that the CDMA system architecture has a lot to do with the spreading code design approach, and they come together in many cases. This statement is also true for various CDMA based mobile cellular standards. The purpose of this Chapter is to present the main CDMA based 3G air interface technology - WCDMA as specified in the 3GPP standards. The details of WCDMA model are investigated in terms of operation modes, physical channel frame structure, spreading and modulation etc. Simulation results of WCDMA downlink system with the generated sequence in Chapter 3 and with the existing orthogonal code under the influence of both MAI and MI is also analysed.

4.1 WCDMA - Review

One of the most promising approaches to 3G is to combine a WCDMA air interface with the fixed network of GSM without ignoring the numerous advantages of the already existing GSM networks. The standard that has emerged is based on

European Telecommunications Standards Institute (ETSI) - UMTS and is commonly known as UTRA [56, 57, 58, 59]. This air interface technology specified by 3^{rd} Generation Partenership Project (3GPP) applies DS-CDMA technique for multiplexing different users [13, 60, 61, 62, 63]. The information is spread over a band of approximately 5 MHz. This wide bandwidth has given rise to the name Wideband CDMA or WCDMA. There are two different modes namely :

- Frequency Division Duplex (FDD) : The uplink and downlink transmissions employ two separated frequency bands for this duplex method. A pair of frequency bands with specified separation is assigned for a connection. All the system description provided in this chapter holds for the FDD mode only.
- Time Division Duplex (TDD) : In this duplex method, uplink and downlink transmissions are carried over the same frequency band by using synchronized time intervals Thus time slots in a physical channel are divided into transmission and reception part.

4.1.1 Physical Channel Structure

WCDMA defines two dedicated physical channels in both links: Dedicated Physical Data Channel (DPDCH) and Dedicated Physical Control Channel (DPCCH). Each connection is allocated one DPCCH and zero, one or several DPDCHs. In addition, there are common physical channels defined as Primary and secondary Common Control Physical Channel (CCPCH), Synchronization Channel (SCH) and Physical Random Access Channel (PRACH) [61, 64, 65].

Frame Structure

Figure 4.1 shows the principal frame structure of the uplink dedicated physical channels [61, 64, 65]. Each frame of 10 ms is split into 15 slots. Each slot is of length $T_{slot} = 0.666ms$ with 2560 chips, corresponding to one power control period. The super frame length is 720 ms; i.e. a super frame corresponds to 72 frames. Pilot bits assist coherent demodulation and channel estimation. Transport Format Combination Indicator (TFCI) is used to indicate and identify several simultaneous services. Feedback Information (FBI) bits are to be

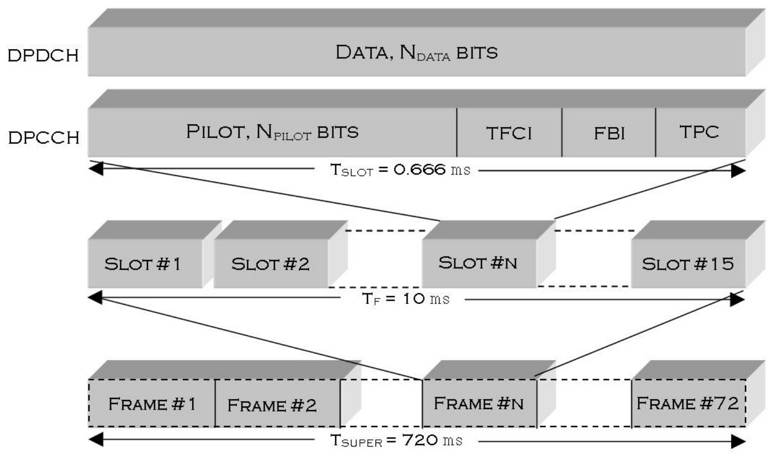


Figure 4.1: Frame Structure for Uplink DPDCH/DPCCH

used to support techniques requiring feedback. Transmit Power Control (TPC) which stands for transmit power control is used for power control purposes. The Spreading Factor (SF) may range from 256 down to 4. The spreading factor is selected according to the data rate.

Figure 4.2 shows the principal frame structure of the downlink dedicated physical channels [61, 64, 65]. As in the uplink, each frame of 10 ms is split into 15 slots with a length of 2560 chips and 0.666ms duration. A super frame corresponds to 720ms, i.e. the super frame length corresponds to 72 frames. The spreading factor thus has a range of 4 to 512. The different control bits have similar meaning to those in the uplink.

4.1.2 Spreading and Modulation

The basic modulation chip rate is 3.84 Mcps and can be extended to $2 \times 3.84Mcps$ and $4 \times 3.84Mcps$. The block diagram of uplink spreading and modulation is shown in Figure 4.3 [13, 64, 65]. In the uplink the data modulation of both the DPDCH and the DPCCH is Binary Phase Shift Keying (BPSK). The modulated DPCCH is mapped to the Q-channel, while the first DPDCH is mapped to the I-channel. Subsequently added DPDCHs are mapped alternatively to the I or the Q-channel. Quaternary Phase Shift Keying (QPSK) is applied for data modulation in the downlink. Each pair of two bits are serial-to-parallel converted and mapped to the I and Q branches respectively. The data in the I and Q branches

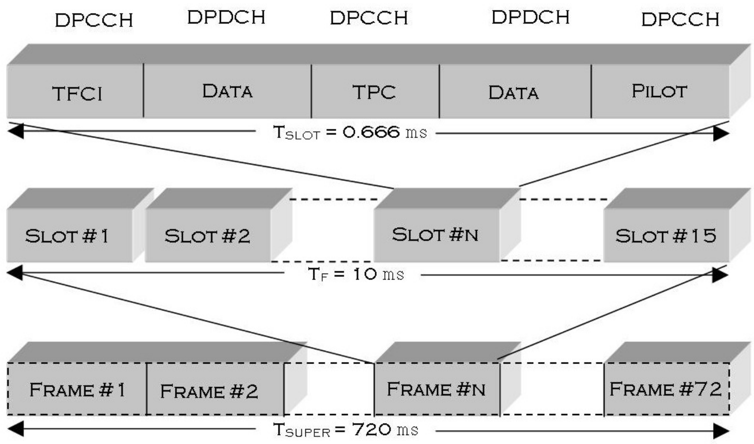


Figure 4.2: Frame Structure for Downlink DPCH

are spread to the chip rate by the same channelization code. This spread signal is then scrambled by a cell specific scrambling code. Figure 4.4 shows the spreading and modulation for a downlink user [13, 64, 65]. Spreading modulation consists of two different operations [13, 64, 65]. The first one is spreading where each data symbol is spread to the chip rate by the channelization code. This increases the bandwidth of the signal. The second operation is scrambling where a complex valued scrambling code is applied to spread signal.

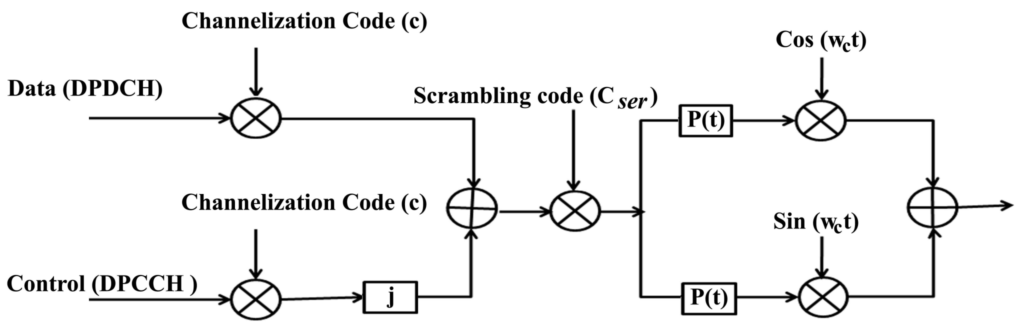


Figure 4.3: Transmitter - WCDMA Uplink

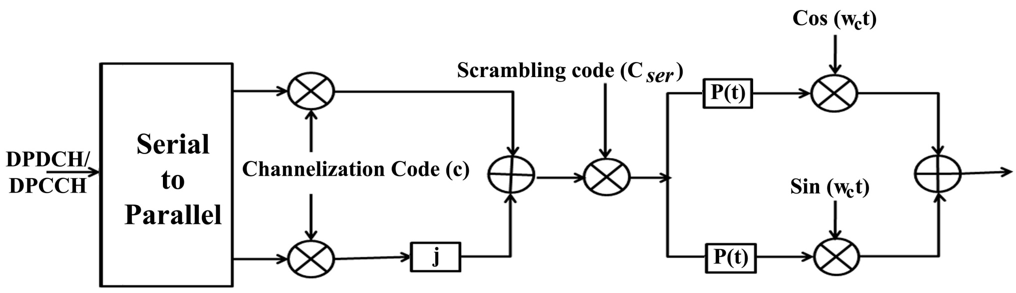


Figure 4.4: Transmitter - WCDMA Downlink

Channelization Code

OVSF codes are used for channelization [13, 64, 65]. All the codes within the code tree can not be used simultaneously by a mobile station. A code can be used by an MS if and only if no other code on the path from the specific code to the root of the tree or in the sub-tree below the specific code is used by the same MS. Uplink channelization code may be allocated if more than one uplink DPDCH is required whereas different physical channels use different channelization code in downlink.

Scrambling Code

The scrambling codes are designed so that they have very low cross-correlation among them. This ensures good Multiple Access Interference (MAI) rejection capability. Either short or long scrambling codes can be used in the uplink. Short scrambling codes are recommended for base stations equipped with advanced receivers employing multiuser detection or interference cancellation. Long scrambling codes are used since a simple rake receiver is employed in the simulator design. These are Gold codes generated from the position wise modulo 2 sum of two binary m-sequences [13, 64, 65]. The generator polynomials for uplink are

$$\begin{aligned} P_1(X) &= X^{25} + X^3 + 1 \\ P_2(X) &= X^{25} + X^3 + X^2 + X + 1 \end{aligned} \tag{4.1}$$

The downlink scrambling codes are generated in the same way as the uplink scrambling codes. However the generator polynomials are different. The primitive polynomial for downlink are

$$\begin{aligned} P_1(X) &= 1 + X^7 + X^{18} \\ P_2(X) &= 1 + X^5 + X^7 + X^{10} + X^{18} \end{aligned} \quad (4.2)$$

The scrambling code is cell specific in the downlink, whereas it is mobile station specific in the uplink.

4.2 System Model Description

In downlink WCDMA system, dedicated physical channel and control channel are time multiplexed. So each slot of 10ms frame consists of data bits and pilot bits. 15 such slots each with 2560 chips form one frame. The direct-sequence code division multiple access scheme is applied here to support multiple simultaneous users. The spreading of data consists of two operations such as Channelisation and Scrambling. The data symbols are spread to the chip rate by channelization code, C_U and further chip by chip multiplication by scrambling code, C_{scr}. Users within the same cell share the same scrambling code while using different channelization codes. Channelization codes are short spreading codes with a chip length between 4 and 512 whereas Gold codes of length $2^{18} - 1$ chips truncated to 2560 chips form the code for scrambling[64, 65]. In this paper, OVSF code, the downlink channelization code is replaced with RNS based PN Sequence to reduce multipath interference.

Fig 4.5 shows the downlink scenario where the mobile unit receives signal from the base station. The received signal within one slot can be represented by

$$y(t) = \sum_{n=1}^{N_s} \sum_{u=1}^{U} \sum_{l=0}^{L_p-1} d_u(n) h_l(t) c_{scr}(t - \tau_l) s_u(t - nT_b - \tau_l) + \eta(t) \quad (4.3)$$

where c_{scr} is the scrambling code. At the receiver it is assumed that there is a total of U active users in an L_p multipath environment and N_s transmitted symbols in one slot. The received signal stream in equation 4.3 at chip rate can be represented as

$$y(kN_s + n) = H(z) \otimes (c_{scr}(kN_s + n) x(kN_s + n)) + \eta(kN_s + n) \quad (4.4)$$

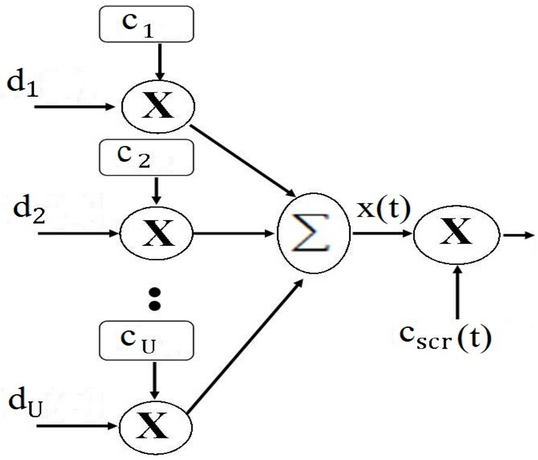


Figure 4.5: Spreading and Modulation of Downlink WCDMA

The channel, H(z) corrupts the signal with inter symbol interference and effects of fading. So RAKE receivers are employed to recover the transmitted data. Descrambling is performed by multiplying the resampled signal by the the desired Mobile Station (MS) specific scrambling code. This is followed by despreading operation and then hard decision is made on the bit.

4.3 Results and Discussion

The BER performance of the 3G WCDMA system is evaluated for downlink multipath channel using extensive computer simulations. The parameters which are representative of a WCDMA downlink is provided for simulations.

- The system with a chip rate of 3.84 Mcps as in standard WCDMA communication system is considered.
- The data bits are grouped into frames. Each 10ms frame is subdivided into 15 slots with 2560 chips [65].
- Channelization code : The generated RNS based PN Sequence is used with a spreading factor, $\beta = 128$ and $CF = 0.10$ is used.
- Each slot have 20 bits (18 data bits and 2 pilot bits). The simulation is

carried out for 100 such slots. BPSK modulation technique is used for simplicity [22].

- Scrambling code : A Gold code of length $2^{18}-1$ chips truncated to 2560 chips is used [22]. The scrambling code remains the same for all users since single cell scenario is considered here. The scrambling code is generated by modulo 2 sum of two pseudo-noise sequences generated by the primitive polynomials as in

$$\begin{aligned} P_1(X) &= 1+X^7+X^{18} \\ P_2(X) &= 1+X^5+X^7+X^{10}+X^{18} \end{aligned} \tag{4.5}$$

- Channel : Multipath propagation channel which consists of 3 paths, one at zero propagation delay and the others with one chip and two chip delays respectively is considered. The system is evaluated in both AWGN and fading multipath channels.

4.3.1 AWGN Multipath Channel

Figure 4.6 shows the comparison of orthogonal code with PN Sequences in a multipath channel. A fixed 3-ray AWGN multipath channel with 1, 0.5 and 0.2 being the respective channel gains is considered for simulation. The result shows that the orthogonality of the users is lost in multipath channels causing multiple access interference with orthogonal codes. This is due to the high cross correlation between the spreading sequences with arbitrary time shifts which results in MAI and interpath interference. Figure 4.7 and Figure 4.8 compares the performance of WCDMA system with RNS based PN sequence and existing Walsh Hadamard code under different loading scenarios. In all the cases the generated sequence outperforms all the other sequences in due to its less cross correlation factor.

4.3.2 Ricean Fading Multipath Channel

In this section fading effects along with external interferences and multipath propagation is also considered for simulations. For Figure 4.9 and Figure 4.10, the

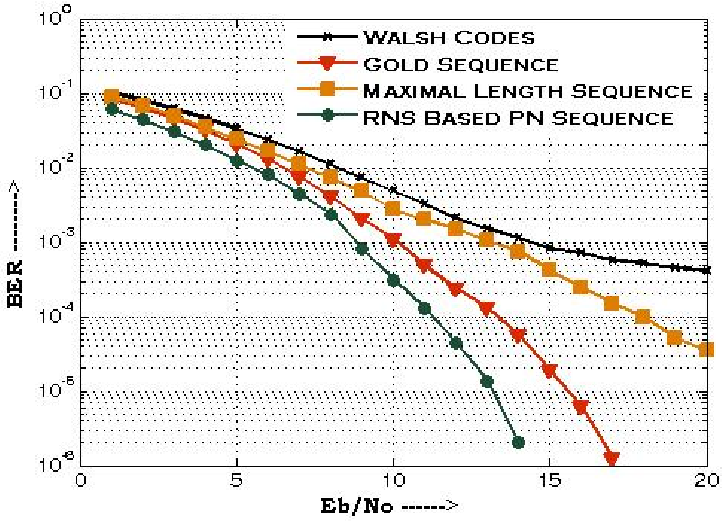


Figure 4.6: Comparison of RNS based PN sequence with Gold codes, Maximal Length sequence and orthogonal Walsh Hadamard code based on BER Plot for 8 Users downlink WCDMA System, $\beta = 128$

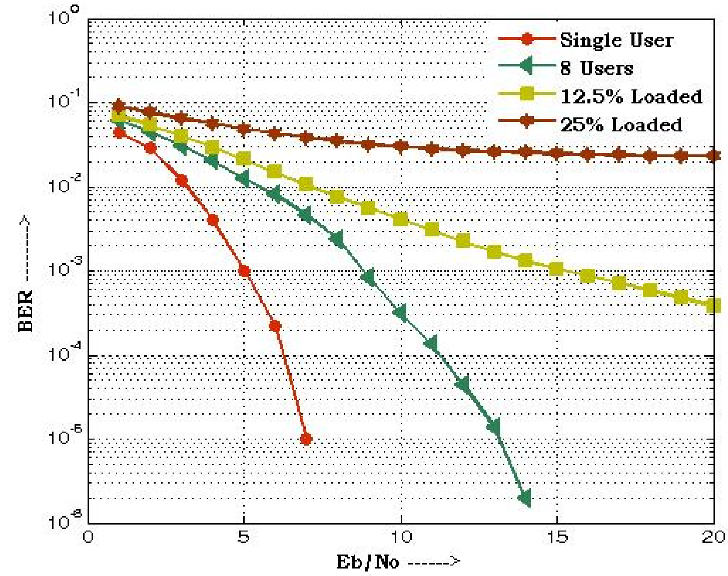


Figure 4.7: BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in an AWGN Multipath Channel for different loading scenarios.

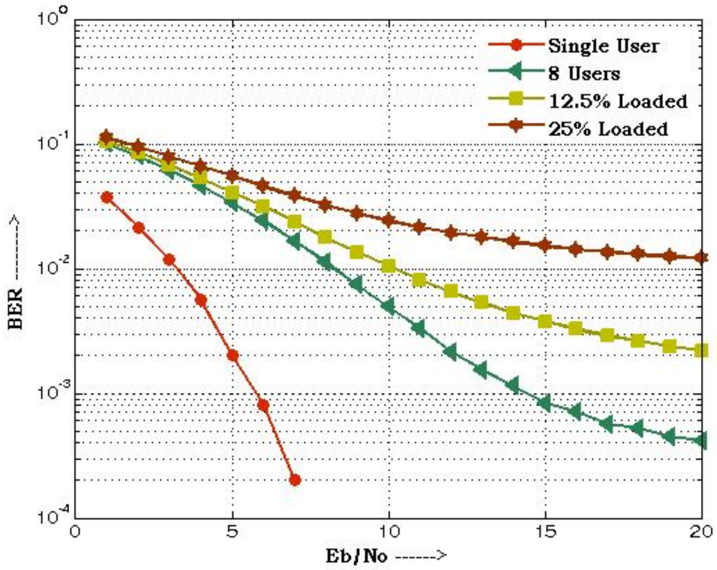


Figure 4.8: BER Performance of downlink WCDMA system using Walsh Hadamard Code with $\beta = 128$ in an AWGN Multipath Channel for different loading scenarios.

channel is a three path Ricean fading channel having 1, 0.5 and 0.2 as the respective channel gains. Ricean fading channel results by adding a line of sight path to rayleigh fading components [70].

4.3.3 Rayleigh Fading Multipath Channel

Figure 4.11 and Figure 4.12 compares the performance of WCDMA system with RNS based PN sequence and existing Walsh Hadamard code under different loading scenarios. A three path rayleigh fading channel with the same gain as before is considered for simulation. In fading channel also the the generated sequence has superior performance.

Summary

Computer simulation results of WCDMA downlink system with the generated sequence and with the existing orthogonal code under the influence of both MAI and MI shows that proposed sequence have better resilience to inter user inter-

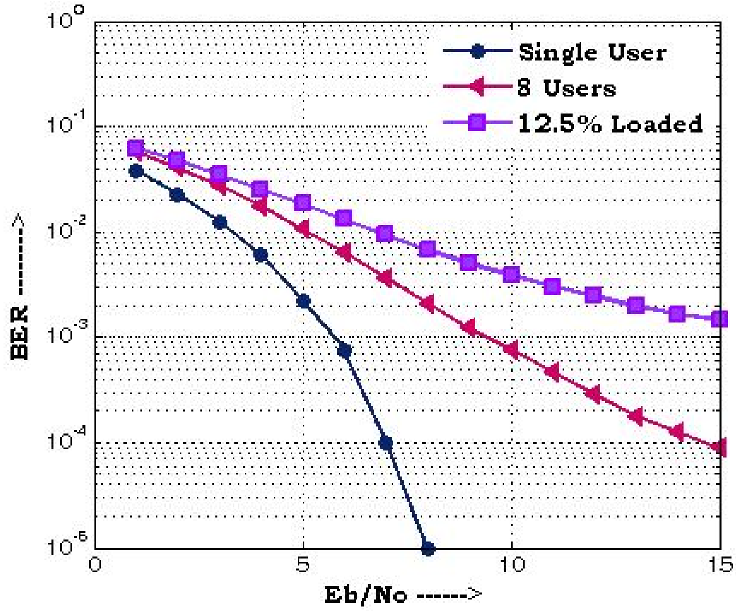


Figure 4.9: BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in a Ricean Multipath Channel for different loading scenarios.

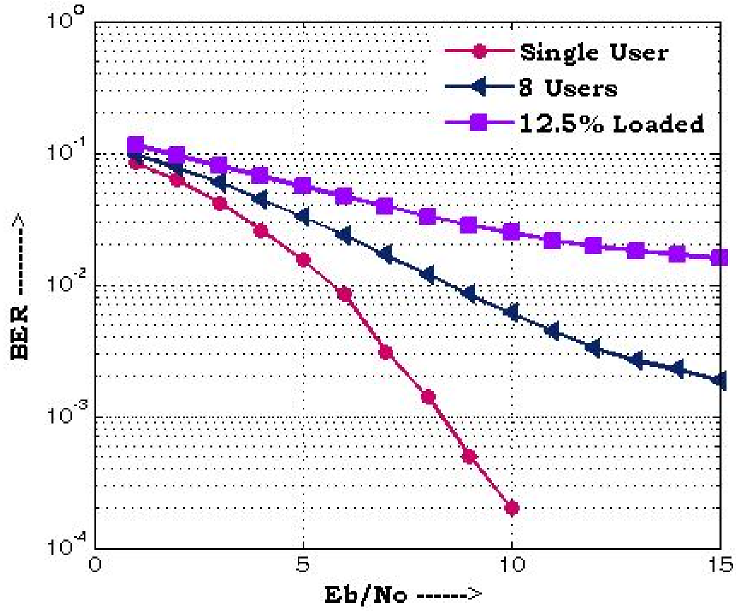


Figure 4.10: BER Performance of downlink WCDMA system using Walsh Code with $\beta = 128$ in a Ricean Multipath Channel for different loading scenarios.

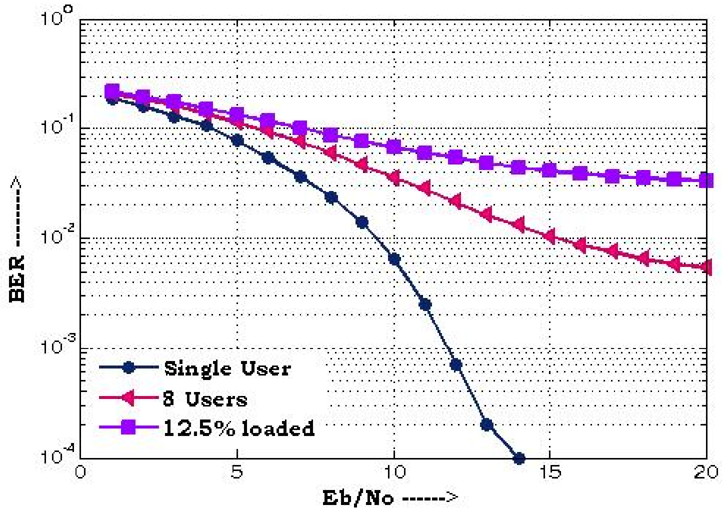


Figure 4.11: BER Performance of downlink WCDMA system using RNS based PN sequence with $\beta = 128$ in a Rayleigh Multipath Channel.

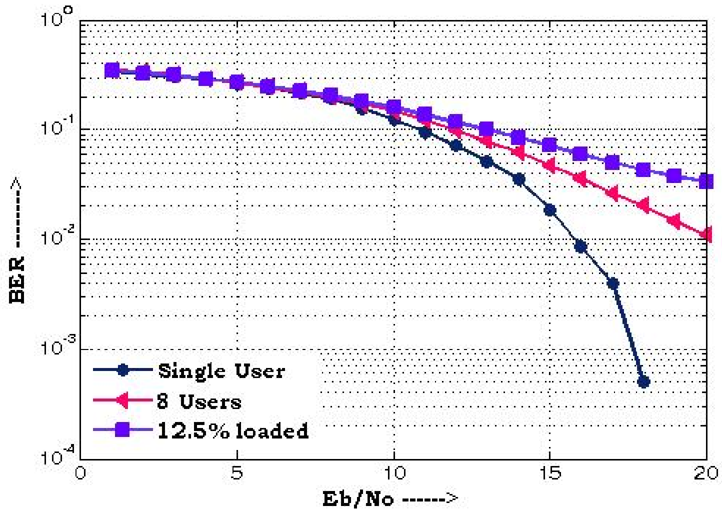


Figure 4.12: BER Performance of downlink WCDMA system using Walsh Code with $\beta = 128$ in a Rayleigh Multipath Channel.

ference. The generated sequence based on Residue Arithmetic offers an efficient way to reduce the impairment factor due to multipath propagation. So PN Sequence possesses several advantages compared with conventional CDMA systems currently available in 3G standards using a relatively cost-effective way.

5
Conclusion

5.1 Conclusion

The core of the next generation CDMA technology lies in CDMA code design approach which should take into account as many real operational conditions as possible and to maintain a sufficiently large code set size. In this context, this thesis work contributed a little towards the evolution of next generation CDMA technology because the generated PN sequence based on Residue arithmetic:

- Offers provision to vary correlation threshold based on the channel properties and error tolerance thus providing real operational conditions for spreading code design unlike any existing techniques.
- Inherits high dynamic key range to maintain large code sets such that large number of users can be accommodated.
- Offers MAI-resistant operation for DS-CDMA systems in both synchronous and asynchronous MAI - AWGN channels, reducing co-channel interference and increasing capacity in a mobile cellular system. The joint effect of ideal auto-correlation function and good cross correlation function makes RNS

based PN sequence superior to all other standard PN sequences like Gold codes, Kasami codes and Maximal Length sequence.

- In multipath AWGN, Ricean Fading and Rayleigh Fading environments, the generated PN sequence outperforms the existing Walsh Hadamard code as channelization code for downlink WCDMA system. Thus the obtained spreading sequences can inherently address MAI in a multi-user system and MI in a multipath environment without using other external auxiliary subsystems to overcome those impairments.

5.2 Limitations of the work

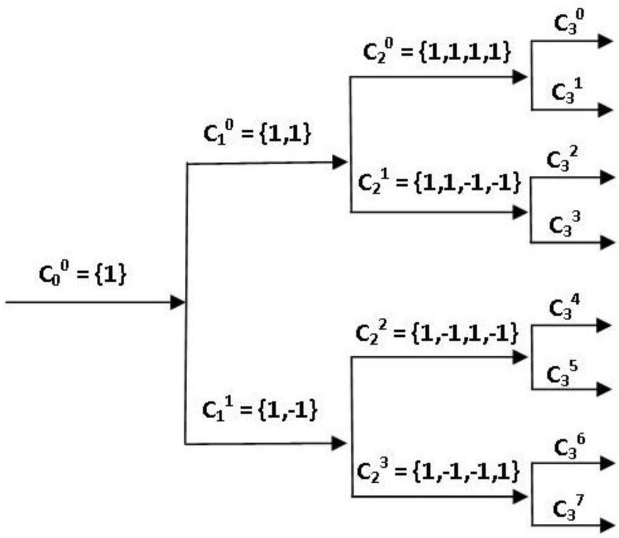
- Implementation of user-unlimited system by exploiting the properties of RNS was not done because further investigations are are required for the interference limited performance.
- Standardized Channel models were not used for simulation.
- Only downlink transmission channel is considered for simulations with the expectation of getting similar results in uplink channel also.

5.3 Scope of Future work

- VLSI implementation of the RNS based PN Sequence generator
- Design of interference cancellation technique for RNS based PN sequence can be done to handle overloading scenarios.
- Incorporating RNS based spreading sequence in RNS based CDMA System.
- The work can be extended to a mobile wireless communication systems

Appendix A

CAB of OVSF Code



Layer	0	1	2	3
SF	1	2	4	8

Figure A.1: Generation tree structure for OVSF codes, where SF denotes spreading factor or processing gain of a CDMA system using the OVSF codes

OVSF codes are generated using a tree structure as shown in Figure A.1. It is noted that if [C] is a code length 2^r at depth r in the tree structure, where the root has depth 0, the two branches leading out of C are labeled by the sequences [C C] and [C C], which have length 2^{r+1}. The codes at depth r in the tree are the rows of the matrix C_N, where $N = 2r$. Note that two OVSF codes are orthogonal if and only if neither code lies on the path from the other code to the root. Since codes assigned to different users in the same cell must be orthogonal, this restricts the number of available codes for a given cell. For example, if the code C_2^0 in the tree is assigned to a user, the codes C_0^0, C_1^0, C_3^0, C_3^1 and so on, cannot be assigned to any other user in the same cell. In general, if a code is used in a cell, all its parent codes and all its child codes should not be used in the same cell to maintain orthogonality among the users. This restriction of the OVSF codes is called as the code assignment blocking (CAB) problem.

Appendix B

Simulation Parameters

This appendix lists the parameters used in the simulation results presented in all chapters.

Spreading Sequences

The spreading sequences or the polynomials used to generate the spreading sequence for a particular value of β is listed below :

Spreading Factor, $\beta = 8$

m-sequences

$$
\begin{aligned}
c_1 &= [-1\ -1\ \ 1\ -1\ -1\ -1\ \ 1] \\
c_2 &= [-1\ \ 1\ \ 1\ -1\ -1\ \ 1\ \ 1] \\
c_3 &= [-1\ \ 1\ \ 1\ \ 1\ \ 1\ \ 1\ -1] \\
c_4 &= [-1\ -1\ \ 1\ \ 1\ -1\ \ 1\ \ 1] \\
c_5 &= [-1\ -1\ -1\ \ 1\ \ 1\ -1\ \ 1] \\
c_6 &= [\ 1\ \ 1\ \ 1\ -1\ \ 1\ \ 1\ -1] \\
c_7 &= [\ 1\ -1\ \ 1\ \ 1\ \ 1\ -1\ \ 1]
\end{aligned}
$$

Gold Sequences

$c_1 =$ [-1 1 1 -1 -1 -1 1]
$c_2 =$ [-1 1 1 -1 1 -1 -1]
$c_3 =$ [1 1 1 1 -1 1 -1]
$c_4 =$ [-1 1 -1 -1 1 1 -1]
$c_5 =$ [-1 -1 1 1 1 1 1]
$c_6 =$ [1 1 -1 1 1 -1 1]
$c_7 =$ [-1 -1 -1 1 -1 -1 -1]

Spreading Factor, $\beta = 64$
m-sequences : $z^6 + z^5 + z^4 + 1$
Gold Sequences : $z^6 + z^5 + z^4 + 1$ and $z^6 + z^5 + z^2 + 1$
Kasami Sequences : $z^6 + z^5 + z^2 + 1$

Spreading Factor, $\beta = 128$
m-sequences : $z^7 + z^5 + 1$
Gold Sequences : $z^7 + z^5 + 1$ and $z^7 + z^2 + 1$

Stationary Multipath Channel Impulse Response

H_{ch}	**Channel Type**
$1 + 0.5z^{-1} + 0.2z^{-2}$	$\Rightarrow$ Minimum Phase Channel
$0.5 + z^{-1}$	$\Rightarrow$ Maximum Phase Channel
$0.3482 + 0.8704z^{-1} + 0.3482z^{-2}$	$\Rightarrow$ Mixed/Non-minimum Phase Channel

During the simulation, the H_{ch} was normalised to unity ie, $h_1^2 + h_2^2 + h_3^2 + = 1$

Publication

- Chithra R, Pallab Maji, Sarat Kumar Patra and Girija Sankar Rath, "**A PN Sequence Generator based on Residue Arithmetic for Multi-User DS-CDMA Applications**," *International Conference on Computer, Communication and Information Sciences, and Engineering*, Copenhagen, Denmark, June 11-12, 2012 (Accepted).

Bibliography

[1] H. H. Chen, *The Next Generation CDMA Technologies*, 1st ed. John Wiley and Sons, 2007.

[2] R. Tanner, “Nonlinear receivers for ds-cdma,” Ph.D. dissertation, The University of Edinburgh., September 1998.

[3] K. Raith and J. Uddenfeldt, “Capacity of digital cellular tdma systems,” *IEEE Transactions on Vehicular Technology*, vol. 40, pp. 323 – 332, 1991.

[4] J. Korhonen, *Introduction to 3G Mobile Communications*, 2nd ed. Artech House Mobile Communications Series, 2003.

[5] L.-L. Yang and L. Hanzo, “Performance of residue number system based ds-cdma over multipath fading channels using orthogonal sequences,” *European Transactions on Telecommunications*, vol. 9, no. 6, pp. 525 – 535, 1998.

[6] L.-L. Yang and Hanzo, “Residue number system based multiple code ds-cdma systems,” in *IEEE 49th Vehicular Technology Conference*, vol. 2, jul 1999, pp. 1450 –1454.

[7] Yang and L. Hanzo, “A residue number system based parallel communication scheme using orthogonal signaling .i. system outline,” *IEEE Transactions on Vehicular Technology*, vol. 51, no. 6, pp. 1534 – 1546, nov 2002.

[8] Madhukumar and F. Chin, "Performance studies of a reside number system based cdma system over bursty communication channels," *Wireless Personal Communications*, vol. 22, no. 1, pp. 89–102, 2002, cited By (since 1996) 0.

[9] A. Madhukumar and F. Chin, "Enhanced architecture for residue number system-based cdma for high-rate data transmission," *IEEE Transactions on Wireless Communications*, vol. 3, no. 5, pp. 1363 – 1368, sept. 2004.

[10] H. How, T. Liew, E.-L. Kuan, L.-L. Yang, and L. Hanzo, "A redundant residue number system coded burst-by-burst adaptive joint-detection based cdma speech transceiver," *IEEE Transactions on Vehicular Technology*, vol. 55, no. 1, pp. 387 – 396, jan. 2006.

[11] M. I. Youssef, A. E. Emam, and M. A. Elghany, "Direct sequence spread spectrum technique with residue number system," *International Journal of Electrical and Electronics*, vol. 3:4, pp. 223 – 229, 2009.

[12] S. Zhang, Y. Zhang, and L.-L. Yang, "Redundant residue number system based multicarrier ds-cdma for dynamic multiple-access in cognitive radios," in *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, may 2011, pp. 1 –5.

[13] "Technical specification of universal mobile telecommunications system (umts) ; spreading and modulation (fdd)," 3GPP TS 25.213, Tech. Rep. Version 10.0.0, Release 10 2011-05. [Online]. Available: www.3gpp.org

[14] K. Shanmugan, "Loss of orthogonolity in wcdma downlinks," in *International Conference on Communications and Signal Processing (ICCSP)*, feb. 2011, pp. 19 –22.

[15] K. A. Hamdi, "Theoretical analysis of the orthogonality factor in wcdma downlinks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 11, pp. 5394–5399, 2009, cited By (since 1996) 2.

[16] Y. Li and S. Kishore, "Average orthogonality factor in wcdma downlinks for independent rayleigh fading multipath channels," *Wireless Communications, IEEE Transactions on*, vol. 6, no. 4, pp. 1213 –1217, april 2007.

[17] D. Liu and H. Zare, “A multipath interference cancellation technique for wcdma downlink receivers,” *International Journal of Communication Systems*, vol. 20, pp. 661 – 668, 2006.

[18] N. Mehta, A. Molisch, and L. Greenstein, “Orthogonality factor in wcdma downlinks in urban macrocellular environments,” in *IEEE GLOBECOM ’05 Global Telecommunications Conference,*, vol. 6, dec. 2005, pp. 5 pp. –3382.

[19] M. Sangeetha and V. Bhaskar, “Downlink blind channel estimation for w-cdma systems and performance analysis under various fading channel conditions,” in *International Conference onCommunications and Signal Processing (ICCSP)*, feb. 2011, pp. 470 –474.

[20] K. Waheed and F. M. Salem, “Blind information-theoretic multiuser detection algorithms for ds-cdma and wcdma downlink systems,” *IEEE Transactions on Neural Networks*, vol. 16, no. 4, pp. 937–948, 2005, cited By (since 1996) 26.

[21] H. Yu, H. Cho, C. Kang, and D. Hong, “A new multipath interference mitigation technique for high-speed packet transmission in wcdma downlink,” *IEEE Signal Processing Letters*, vol. 12, no. 9, pp. 601–604, 2005, cited By (since 1996) 3.

[22] M. Guenach and L. Vandendorpe, “Downlink performance analysis of a bpsk-based wcdma using conventional rake receivers with channel estimation,” *Selected Areas in Communications, IEEE Journal on*, vol. 19, no. 11, pp. 2165 –2176, nov 2001.

[23] X. T. Chao Zhang and J. Lu, “Construction and application of ovsf-zcz originated from ls and go sequences,” in *3rd International Workshop on Signal Design and Its Applications in Communications, IWSDA*, 2007, pp. 34–38.

[24] T. K. Shahana, B. R. Jose, R. K. James, K. P. Jacob, and S. Sasi, “Rns based programmable multi-mode decimation filter for wcdma and wimax,” in *Proc. IEEE Vehicular Technology Conf. VTC Spring*, 2008, pp. 1831–1835.

[25] T. K. Shahana, Jose, R. K. James, K. P. Jacob, and S. Sasi, "Dual-mode rns based programmable decimation filter for wcdma and wlan," in *Proc. IEEE Int. Symp. Circuits and Systems ISCAS*, 2008, pp. 952–955.

[26] A. Omundi and B. Premkumar, *Residue Number System: Theory and Implementation.* Imperial College Press, 2007, vol. 2.

[27] P. Maji, "Application of residue arithmetic in communication and signal processing," Master's thesis, National Institute of Technology, Rourkela, 2011.

[28] P. V. A. Mohan, *Residue Number Systems: Algorithms and Architectures.* Kluwer Academic Publisher, 2002.

[29] C. Huang, D. Peterson, H. Rauch, J. Teague, and D. Fraser, "Implementation of a fast digital processor using the residue number system," *IEEE transactions on circuits and systems*, vol. CAS-28, no. 1, pp. 32 – 38, 1981.

[30] A. Skavantzos, "Efficient residue to weighted converter for a new residue number system," *Proceedings of the IEEE Great Lakes Symposium on VLSI*, pp. 185 – 191, 1998.

[31] H.T.Vergos, "A 200-mhz rns core," *European Conference on Circuit Theory and Design*, pp. II/249 – 252, 2001.

[32] J. Ramrez, A. Garca, and A. Lpez-Buedo, S. andLloris, "Rns-enabled digital signal processor design," *Electronics Letters*, vol. 38, no. 6, pp. 266 – 268, 2002.

[33] C.-L. Wang, "New bit-serial vlsi implementation of rns fir digital filters," *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing.*

[34] A. Skavantzos and Y. Wang, "The applications of the new chinese remainder theorems for three moduli sets," *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing*, 1999.

[35] Y. Wang, "New chinese remainder theorems," *Conference Record of the Thirty - Second Asilomar Conference on Signals, Systems and Computers*, 1998.

[36] T. K. Shahana, R. K. James, B. R. Jose, K. P. Jacob, and S. Sasi, "Performance analysis of fir digital filter design: Rns versus traditional," *Proceedings - International Symposium on Communications and Information Technologies*, pp. 1–5, 2007.

[37] W. K. Jenkins and B. J. Leon, "Use of residue number systems in the design of finite impulse response digital filters." *IEEE Trans Circuits Syst*, vol. CAS-24, no. 4, pp. 191–201, 1977, cited By (since 1996) 41.

[38] J. Ramirez, P. Fernandez, U. Meyer-Base, F. Taylor, A. Garcia, and A. Lloris, "Index-based rns dwt architectures for custom ic designs," *IEEE Workshop on Signal Processing Systems*, 2001.

[39] Y. Liu and E. M.-K. Lai, "Design and implementation of an rns-based 2-d dwt processor," *IEEE Transactions on Consumer Electronics*, vol. 50, no. 1, pp. 376 – 385, 2004.

[40] J. Bajard and L. Imbert, "A full rns implementation of rsa," *Transactions on Computers*, vol. 53, no. 6, pp. 769 – 774, 2004.

[41] D. M. Schinianakis, A. P. Kakarountas, and T. Stouraitis, "A new approach to elliptic curve cryptography: An rns architecture," *Proceedings of the Mediterranean Electro-technical Conference - MELECON*, pp. 1241 – 1245, 2006.

[42] D. Zhu and B. Natarajan, "Residue number system arithmetic inspired hopping pilot pattern design for cellular downlink ofdma," *Wireless Telecommunications Symposium*, 2010.

[43] A. Madhukumar and F. Chin, "Residue number system-based multicarrier cdma system for high-speed broadband wireless access," *IEEE Transactions on Broadcasting*, vol. 48, no. 1, pp. 46–52, 2002, cited By (since 1996) 5.

[44] C. E. Shannon, "Communications in the presence of noise," *Proceedings of the IRE*, vol. 37, pp. 10–21, 1949.

[45] R. Scholtz, "The evolution of spread-spectrum multiple-access communications," in *IEEE Third International Symposium on Spread Spectrum Techniques and Applications*, jul 1994, pp. 4 –13 vol.1.

[46] R. C. Dixon, *Spread Spectrum System with Commercial Application*, 3rd ed. Wiley-Interscience, 1994.

[47] S. Moshavi, "Multi-user detection for ds-cdma communications," *IEEE Communications Magazine*, vol. 34, no. 10, pp. 124 –136, oct 1996.

[48] T. A. Dowing and R. J. McEliece, "Cross-correlation of reverse maximal-length shift register sequences," *Technical Report, JPL Space Programs Summary*, vol. 3, pp. 192–193, 1968.

[49] D. Sarwate and M. Pursley, "Crosscorrelation properties of pseudorandom and related sequences," *Proceedings of the IEEE*, vol. 68, no. 5, pp. 593 – 619, may 1980.

[50] R. N. Mutagi, "Pseudo noise sequences for engineers," *Electronics and Communication Engineering Journal*, vol. 8, no. 2, pp. 79–87, 1996.

[51] R. Gold, "Optimal binary sequences for spread spectrum multiplexing," *IEEE Transactions on Information Theory*, vol. 13, pp. 619–621, 1967.

[52] B. Dinan, Esmael H.and Jabbari, "Spreading codes for ds-cdma and wide-band cellular networks," *IEEE Communications Magazine*, September 1998.

[53] F. Adachi, M. Sawahashi, and K. Okawa, "Tree-structured generation of orthogonal spreading codes with different lengths for forward link of ds-cdma mobile radio," *Electronics Letters*, vol. 33, no. 1, pp. 27 –28, jan 1997.

[54] S. Panda, "Non-linear fuzzy receivers for ds-cdma communication system," Master's thesis, National Institute of Technology, Rourkela, 2004.

[55] J. G. Proakis, *Digital Signal Processing - Principles, Algorithms and Applications*, 4th ed. Pearson Education Inc., 2007.

[56] Y. Sung, Y. Lim, L. Tong, and A. J. van der Veen, "Signal processing advances for 3g wcdma: From rake receivers to blind techniques," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 48 –54, january 2009.

[57] M. Oliphant, "The mobile phone meets the internet," *IEEE Spectrum,*, vol. 36, no. 8, pp. 20 –28, aug 1999.

[58] E. Dahlman, B. Gudmundson, M. Nilsson, and A. Skold, "Umts/imt-2000 based on wideband cdma," *IEEE Communications Magazine,*, vol. 36, no. 9, pp. 70 –80, sep 1998.

[59] E. Dahlman, P. Beming, J. Knutsson, F. Ovesjo, M. Persson, and C. Roobol, "Wcdma-the radio interface for future mobile multimedia communications," *IEEE Transactions on Vehicular Technology,*, vol. 47, no. 4, pp. 1105 –1118, nov 1998.

[60] "Technical specification of universal mobile telecommunications system (umts) ; user equipment (ue) radio transmission and reception (fdd)," 3GPP TS 25.101, Tech. Rep. Version 10.5.0, Release 10 2012-03. [Online]. Available: www.3gpp.org

[61] "Technical specification of universal mobile telecommunications system (umts); physical channels and mapping of transport channels onto physical channels (fdd)," 3GPP TS 25.211, Tech. Rep. version 10.0.0, Release 10 2011-05. [Online]. Available: www.3gpp.org

[62] "Technical specification of universal mobile telecommunications system (umts); multiplexing and channel coding (fdd)," 3GPP TS 25.212, Tech. Rep. version 10.2.0, Release 10 2012-03. [Online]. Available: www.3gpp.org

[63] "Technical specification of universal mobile telecommunications system (umts); physical layer procedures (fdd)," 3GPP TS 25.214, Tech. Rep. version 10.6.0, Release 10 2012-03. [Online]. Available: www.3gpp.org

[64] S. G. Glisic, *Adaptive WCDMA: Theory and Practice*, 1st ed. John Wiley & Sons, 2003.

[65] K. Tachikawa, Ed., *W-CDMA Mobile Communication Systems*, 1st ed. John Wiley & Sons, Ltd, 2002.

[66] P. Haghighat and A. Ghrayeb, "A hybrid serial-parallel interference cancellation scheme for wcdma systems," in *Electrical and Computer Engineering, 2007. CCECE 2007. Canadian Conference on*, april 2007, pp. 621 –624.

[67] T. Nihtila, J. Kurjenniemi, M. Lampinen, and T. Ristaniemi, "Performance of receive diversity and lmmse chip equalization in wcdma hsdpa network," *Wirel. Pers. Commun.*, vol. 43, no. 2, pp. 261–280, 2007.

[68] V. Kumar, "Downlink performance of a finite word length implemented rake receiver for 3g wcdma," in *IEEE TENCON*, nov. 2005, pp. 1 –5.

[69] M. Heikkila, "A novel blind adaptive algorithm for channel equalization in wcdma downlink," in *Personal, Indoor and Mobile Radio Communications, 2001 12th IEEE International Symposium on*, vol. 1, sep 2001, pp. A–41 – A–45.

[70] W. H. Tranter, K. S. Shanmugan, T. S. Rappaport, and K. L. Kosbar, *Principles of Communication Systems Simulation with Wireless Applications*, 1st ed. Prentice Hall, 2004.