Simulation of a Wideband CDMA system

by

Hemlata Ahir

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Electrical Engineering

Major Professor: Julie A. Dickerson

Iowa State University

Ames, Iowa

2000

Copyright © Hemlata Ahir, 2000. All rights reserved.
Graduate College
Iowa State University

This is to certify that the Master’s thesis of

Hemlata Ahir

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
# TABLE OF CONTENTS

## ACKNOWLEDGEMENTS  

## ABSTRACT

## CHAPTER 1 INTRODUCTION

1.1 Problem statement

1.2 Motivation

1.3 Thesis organization

## CHAPTER 2 BACKGROUND

2.1 Multiple Access techniques

2.2 Spread Spectrum techniques

2.3 Capacity comparison of CDMA, FDMA and TDMA systems

2.4 General architecture of the cellular network

2.4.1 Mobile Station (MS)

2.4.2 Base Station Subsystem (BSS)

2.4.3 Network and Switching Subsystem (NSS)

2.5 Second generation mobile systems and the IS-95 standard

2.5.1 Role of PN sequences in IS-95 system

2.5.2 Features of the IS-95 standard

2.6 Third generation mobile systems

2.6.1 System Requirements of the 3G systems

2.6.2 Characteristics of the UMTS/IMT-2000 radio access:

2.6.3 W-CDMA and cdma2000

2.6.4 3G PCS system in United States based upon WCDMA technology

## CHAPTER 3 REVERSE AND FORWARD LINKS OF WCDMA SYSTEM

3.1 WCDMA system overview

---

**xii**  

**xiii**  

**1**  

**5**  

**15**  

**19**
3.2 Forward link
   3.2.1 Pilot channel
   3.2.2 Sync Channel
   3.2.3 Paging Channel
   3.2.4 Forward Traffic Channel

3.3 Reverse link
   3.3.1 Access Channel
   3.3.2 Reverse Traffic Channel

CHAPTER 4 SIMULATION OF THE FORWARD TRAFFIC CHANNEL
4.1 Development Environment:
4.2 FTC transmitter structure
4.3 Convolutional Encoder
4.4 Interleaver
4.5 Symbol repetition
4.6 Power Control Subchannel
4.7 Signaling Subchannel
4.8 Multiplexer
4.9 Scrambler
4.10 Orthogonal Spreading with Walsh codes
4.11 Spreading with the long code
4.12 Baseband Filtering
4.13 Quadrature Phase Shift Keying
4.14 FTC receiver structure
4.15 Coherent detection
4.16 Low pass filtering
4.17 Sampling the filtered output
4.18 Decorrelation with the pilot PN sequence
4.19 Demodulation using Walsh sequence
4.20 Descrambling and Demultiplexing
4.21 Deinterleaver
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.22</td>
<td>Viterbi decoding</td>
<td>63</td>
</tr>
<tr>
<td>5.1</td>
<td>Summary of parameters set for the simulations</td>
<td>64</td>
</tr>
<tr>
<td>5.2</td>
<td>Overall operation of the simulator in the absence of noise</td>
<td>65</td>
</tr>
<tr>
<td>5.3</td>
<td>PN sequence synchronization issues</td>
<td>65</td>
</tr>
<tr>
<td>5.4</td>
<td>Performance in AWGN channel</td>
<td>67</td>
</tr>
<tr>
<td>5.5</td>
<td>Performance in the presence of multiple users</td>
<td>69</td>
</tr>
<tr>
<td>5.6</td>
<td>Performance in the presence of interfering signal from another BS</td>
<td>70</td>
</tr>
<tr>
<td>5.7</td>
<td>Performance in Rayleigh fading channel</td>
<td>72</td>
</tr>
<tr>
<td>6.1</td>
<td>Summary</td>
<td>77</td>
</tr>
<tr>
<td>6.2</td>
<td>Applications of the simulator</td>
<td>77</td>
</tr>
<tr>
<td>6.3</td>
<td>Recommendations for future work</td>
<td>78</td>
</tr>
</tbody>
</table>

**BIBLIOGRAPHY**
**LIST OF FIGURES**

<p>| Figure 2.1 | General cellular network architecture | 8 |
| Figure 2.2 | Forward and Reverse links of IS-95 | 10 |
| Figure 2.3 | The proposed spectrum allocation in UTRA | 16 |
| Figure 2.4 | The proposed spectrum allocation in IMT-2000 | 16 |
| Figure 3.1 | Forward link of WCDMA system | 21 |
| Figure 3.2 | Pilot channel structure of WCDMA system | 22 |
| Figure 3.3 | Sync channel structure of WCDMA system | 23 |
| Figure 3.4 | Paging channel structure of WCDMA system | 24 |
| Figure 3.5 | Forward traffic channel structure of WCDMA system | 25 |
| Figure 3.6 | Reverse link of WCDMA system | 26 |
| Figure 3.7 | Access channel structure of WCDMA system | 27 |
| Figure 3.8 | Reverse traffic channel structure of WCDMA system | 28 |
| Figure 4.1 | Flowchart for the FTC transmitter | 31 |
| Figure 4.2 | Convolutional Encoder | 33 |
| Figure 4.3 | Flowchart for the Convolutional Encoder | 34 |
| Figure 4.4 | Flowchart for the Interleaver | 38 |
| Figure 4.5 | Flowchart for the Repeater | 40 |
| Figure 4.6 | Flowchart for the Multiplexer | 42 |
| Figure 4.7 | PN code generator for the long code | 44 |
| Figure 4.8 | Flowchart for the PN long code generator | 45 |
| Figure 4.9 | Flowchart for the Walsh sequence generator | 48 |
| Figure 4.10 | Flowchart for the Walsh Modulator | 49 |
| Figure 4.11 | Raised cosine filter response for different values of rolloff factor | 50 |
| Figure 4.12 | Baseband filters frequency response limits specified in [1] | 52 |</p>
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.13</td>
<td>Normalized FIR filter response for the square root RC filter with $\alpha = 0.22$</td>
<td>53</td>
</tr>
<tr>
<td>4.14</td>
<td>Normalized FIR filter response of the cascade of the transmitter and the receiver filters with $\alpha = 0.22$</td>
<td>54</td>
</tr>
<tr>
<td>4.15</td>
<td>Forward traffic channel receiver structure</td>
<td>56</td>
</tr>
<tr>
<td>4.16</td>
<td>Flowchart for the FTC receiver</td>
<td>57</td>
</tr>
<tr>
<td>4.17</td>
<td>Frequency and phase response of the FIR square root RC filter</td>
<td>60</td>
</tr>
<tr>
<td>5.1</td>
<td>Auto correlation function for the PN sequence used in the WCDMA system</td>
<td>66</td>
</tr>
<tr>
<td>5.2</td>
<td>Autocorrelation value of the PN sequence for zero phase shift</td>
<td>66</td>
</tr>
<tr>
<td>5.3</td>
<td>Performance of the receiver when its PN sequence is unsynchronized with the base station’s PN sequence in the absence of noise</td>
<td>67</td>
</tr>
<tr>
<td>5.4</td>
<td>Performance of the receiver when its PN sequence is unsynchronized with the base station’s PN sequence in the presence of AWGN</td>
<td>68</td>
</tr>
<tr>
<td>5.5</td>
<td>Performance comparisons in AWGN channel</td>
<td>69</td>
</tr>
<tr>
<td>5.6</td>
<td>Performance of the receiver in the presence of an interfering signal from another BS in the absence of noise</td>
<td>71</td>
</tr>
<tr>
<td>5.7</td>
<td>Performance of the receiver in AWGN channel in the presence of an interfering signal from another BS</td>
<td>72</td>
</tr>
<tr>
<td>5.8</td>
<td>Performance of the receiver in Rayleigh fading channel with $E{R^2} = 1$ in the presence of AWGN</td>
<td>74</td>
</tr>
<tr>
<td>5.9</td>
<td>Performance of the receiver in Rayleigh fading channel with $E{R^2} = 0.8$ in the presence of AWGN</td>
<td>74</td>
</tr>
<tr>
<td>5.10</td>
<td>Performance of the receiver in Rayleigh fading channel with $E{R^2} = 0.6$ in the presence of AWGN</td>
<td>75</td>
</tr>
<tr>
<td>5.11</td>
<td>Performance of the receiver in Rayleigh fading channel with $E{R^2} = 0.4$ in the presence of AWGN</td>
<td>75</td>
</tr>
<tr>
<td>5.12</td>
<td>Performance of the receiver in Rayleigh fading channel with $E{R^2} = 0.2$ in the presence of AWGN</td>
<td>76</td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Capacity comparison of CDMA, FDMA and TDMA systems</td>
<td>7</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Comparison between cdma2000 and W-CDMA</td>
<td>17</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Block Designators and WCDMA system frequency correspondence</td>
<td>20</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>I channel interleaver array for 5 ms span length and 64 kbps data rate</td>
<td>36</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Q channel interleaver array for 5 ms span length and 64 kbps data rate</td>
<td>37</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>Multiplexer table for data at 64 kbps, power bits at 2 kbps and signaling bits at 4 kbps</td>
<td>41</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>3G PP</td>
<td>3G Partnership Project</td>
<td></td>
</tr>
<tr>
<td>cdmaOne</td>
<td>End-to-end CDMA wireless system of 2G</td>
<td></td>
</tr>
<tr>
<td>cdma2000</td>
<td>Wideband CDMA system of 3G based upon cdmaOne</td>
<td></td>
</tr>
<tr>
<td>AuC</td>
<td>Authentication Center</td>
<td></td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced mobile phone system</td>
<td></td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
<td></td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
<td></td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
<td></td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
<td></td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
<td></td>
</tr>
<tr>
<td>BSC</td>
<td>Base Station Controller</td>
<td></td>
</tr>
<tr>
<td>BTS</td>
<td>Base Transceiver Station</td>
<td></td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>Direct Sequence</td>
<td></td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
<td></td>
</tr>
<tr>
<td>EIA</td>
<td>Electronic Industries Alliance</td>
<td></td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplexing</td>
<td></td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
<td></td>
</tr>
<tr>
<td>FEC</td>
<td>Forward Error Correction</td>
<td></td>
</tr>
<tr>
<td>FH</td>
<td>Frequency Hopping</td>
<td></td>
</tr>
<tr>
<td>FTC</td>
<td>Forward Traffic Channel</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>Global Systems for Mobile communications</td>
<td></td>
</tr>
<tr>
<td>GSM MAP</td>
<td>GSM Mobile Application Part</td>
<td></td>
</tr>
<tr>
<td>Acronym</td>
<td>Meaning</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>HLR</td>
<td>Home Location Register</td>
<td></td>
</tr>
<tr>
<td>IMT-2000</td>
<td>International Mobile Telecommunications-2000</td>
<td></td>
</tr>
<tr>
<td>IS-54</td>
<td>Interim Standard – 54</td>
<td></td>
</tr>
<tr>
<td>IS-95</td>
<td>Interim Standard – 95</td>
<td></td>
</tr>
<tr>
<td>ISDN</td>
<td>Integrated Services Digital Network</td>
<td></td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
<td></td>
</tr>
<tr>
<td>JR</td>
<td>Jam Resistance</td>
<td></td>
</tr>
<tr>
<td>LFSR</td>
<td>Linear Feedback Shift Register</td>
<td></td>
</tr>
<tr>
<td>LPI</td>
<td>Low Probability of Intercept</td>
<td></td>
</tr>
<tr>
<td>MS</td>
<td>Mobile Station</td>
<td></td>
</tr>
<tr>
<td>MSC</td>
<td>Mobile service Switching Center</td>
<td></td>
</tr>
<tr>
<td>NAMTS</td>
<td>Nippon Advanced Mobile Telephone System</td>
<td></td>
</tr>
<tr>
<td>OMC</td>
<td>Operation and Maintenance Controller</td>
<td></td>
</tr>
<tr>
<td>OQPSK</td>
<td>Offset Quaternary Phase Shift Keying</td>
<td></td>
</tr>
<tr>
<td>PCS</td>
<td>Personal Communications Systems</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo Noise</td>
<td></td>
</tr>
<tr>
<td>PSTN</td>
<td>Public Switched Telephone Network</td>
<td></td>
</tr>
<tr>
<td>QPSK</td>
<td>Quaternary Phase Shift Keying</td>
<td></td>
</tr>
<tr>
<td>R-CDMA</td>
<td>Random Code Division Multiple Access</td>
<td></td>
</tr>
<tr>
<td>RC</td>
<td>Raised Cosine</td>
<td></td>
</tr>
<tr>
<td>RTT</td>
<td>Radio Transmission Technology</td>
<td></td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
<td></td>
</tr>
<tr>
<td>TACS</td>
<td>Total Access Communication Systems</td>
<td></td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplexing</td>
<td></td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
<td></td>
</tr>
<tr>
<td>TIA</td>
<td>Telecommunication Industries Alliance</td>
<td></td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telephone Systems</td>
<td></td>
</tr>
<tr>
<td>UTRA</td>
<td>UMTS Terrestrial Radio Access</td>
<td></td>
</tr>
<tr>
<td>VLR</td>
<td>Visitor Location Register</td>
<td></td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access technology</td>
<td></td>
</tr>
</tbody>
</table>
W-CDMA

Wideband CDMA system of 3G based upon UMTS proposals
ACKNOWLEDGMENTS

I would like to thank Dr. Julie Dickerson, my major professor, for her guidance, patience and advice during this research. I would like to extend special thanks to Dr. Richard Barton and Dr. Les Miller for serving as members of my graduation committee. I would also like to express my gratitude to Dr. Richard Barton and Dr. Rajarathnam Chandramouli for their invaluable suggestions and insights.

I would like to take this opportunity to show my appreciation to all my friends with whom I shared rational discussions on topics that assisted me during the design. I thank my fiancé, Amit, for his patience and encouragement throughout my studies and for the immense joy and love he has brought to my life. Last but not the least, I am most grateful to my wonderful parents and my brother for their unconditional love and the confidence that they have shown in me in all my endeavors.
ABSTRACT

Third generation (3G) mobile communication systems promise to provide a gamut of services from simple voice telephony to high speed, high quality multimedia data services. A key part of the air access technology for these systems is the Wideband Code Division Multiple Access (WCDMA) technique. WCDMA features a wider bandwidth in addition to the advantages of a CDMA system such as higher capacity, low spectral density, and enhanced security. In this thesis, we investigate the Wideband CDMA system based on the J-STD-015 draft standard specifications for Personal Communication Services (PCS) system in the United States. A simulator based upon the physical layer specifications is implemented for the forward traffic channel of the system. The transmitter is designed for a data rate of 64 kbps with a span length of 5ms. The processing of the data is done on a span by span basis. The receiver employs a simple matched filter structure at its front end. Different receiver structures and channel models can be inserted into the simulator. Scenarios typical of the downlink of any mobile environment are investigated. The inherent robustness of the system employing error correction coding and interleaving, to combat interference and fading, is verified in the presence of AWGN and for Rayleigh fading channel conditions. The simulator is written in MATLAB and C. It provides a simple, flexible and efficient tool to test the performance of the system under different channel conditions.
CHAPTER 1  INTRODUCTION

1.1 Problem statement

Wideband code division multiple access (WCDMA) technology is attracting a lot of attention as a potential air access scheme for the cellular and personal communications systems (PCS) of the third generation (3G) mobile communication systems. It is based upon the direct sequence code division multiple access (DS/CDMA) technique, one of the prominent air interface schemes of the second generation (2G) systems, and features a wider bandwidth. The study and testing of the air interface (between the base station and the mobile station of the mobile communication system) aspects requires a simulator model for its transmitter and receiver sections. This thesis creates such a simulator based upon the draft specifications for the air interface of the 3G system in the United States [1].

The first generation of mobile communication systems was the era of the analog systems. The introduction of spread spectrum digital radio systems in the past decade marked the beginning of the second generation. The two major 2G mobile systems are the Global Systems for Mobile communications (GSM) [2], [3], [4] in Europe and the cdmaOne [5] in the United States. GSM employs a combination of Time Division Multiple Access and Frequency Division Multiple Access (TDMA/FDMA) techniques for the air interface whereas cdmaOne employs the DS/CDMA technique. GSM is based upon the GSM Mobile Application Part (GSM MAP) core network architecture and cdmaOne has the American National Standards Institute/Electronic Industries Alliance/ Telecommunication Industries Alliance – 41 (ANSI/EIA/TIA-41) as its core network architecture. These two 2G technologies with differences in their implementation, have debated over establishment as a better technology.
The 3G systems basically provide an opportunity to update the existing 2G systems. The decision to adopt WCDMA technique as its air access scheme has been promoted by both GSM and cdmaOne systems. However, different versions of the WCDMA technique for the 3G systems are being proposed by each of these two systems such that their present system can evolve to achieve it. The debate hence continues on which version should be used to provide all different services to the users on the same system. International Mobile Telecommunications-2000 (IMT-2000) [6] standard defined by the International Telecommunications Union (ITU), and its European counterpart, Universal Mobile Telephone Systems (UMTS) [7] are making attempts to standardize the air access techniques. The third generation partnership project (3GPP) [8], encompassing different standards committees supporting UMTS Terrestrial Radio Access (UTRA) technology like frequency division duplexing (FDD) and time division duplexing (TDD), has cooperatively produced technical specifications for the 3G system, referred to as W-CDMA\(^1\) based on the GSM core network architecture. The third generation partnership project 2 (3GPP2) [9] spearheaded by the ANSI board of directors, on the other hand, has proposed cdma2000, the 3G system based on the ANSI/TIA/EIA-41 network architecture and related radio transmission technologies (RTTs).

W-CDMA and cdma2000 thus remain the main contenders for the 3G systems. The final decision should see a coexistence of the two versions if their convergence is not possible.

The WCDMA technique will play a salient role as the air interface of 3G mobile systems. Models of the transmitter and receiver sections of the interface can serve as stand-alone units for investigating the performance of the mobile system. The flexibility of replacing the front-end block of the receiver section by another receiver design suited for a different air channel\(^2\) model without changing the rest of the blocks in the receiver section will aid testing of the

\(^1\) Wideband CDMA refers to the technique but is also used as a registered name for some 3G systems. In this thesis to avoid confusion, WCDMA will be used to refer to the technique and W-CDMA for the systems unless otherwise mentioned.

\(^2\) The term ‘channel’ commonly used in communication systems to denote the air interface between the transmitter and the receiver antennas is referred to as ‘air channel’ here to avoid confusion with the term ‘channel’ used in mobile systems.
system performance under different scenarios. To build such independent sections that can be used for further research and testing is the main objective of this thesis.

1.2 Motivation

As the technology for the 3G systems is still burgeoning, there is a lot of scope to research the various aspects of the air interface of the system. Delving deeper into its intrinsic mechanisms can put some light on the functioning of the system under different air channel conditions. Such modeling of noise in the air channel and testing a receiver designed for it, calls for the modeling of the signals itself that are transmitted by them. Typically, the signals in any multiple access systems are theoretically represented neglecting most of the practical aspects of the system such as scrambling, encoding and other intermediate processing. These assumptions result in a rather poor representation of the on-the-site situation and consequently a compromise on the model of the system. This necessitates the availability of models of the transmitter and receiver sections of the air interface of the system that can be used per se for the signals representation.

3G systems are still in an embryonic stage and are planned to be commercially available in a year or two. Some of the presently available 2G simulators that can be adapted to simulate the 3G systems do not have a simple design. In an attempt to make them as general purpose as possible the design is made so complex that performing even simple tasks requires setting a number of parameters for the system to work. Another hassle is the use of proprietary language by such simulators, which makes addition of a new functionality a formidable task. Moreover, interfacing such a tool with easily available powerful engineering tools like MATLAB is not always possible. On the other hand, MATLAB routines though very efficient for matrix computations are inefficient when repeated processing on data is required. The need for a simple, flexible and yet time efficient simulator has been the predominant motivation for this research. Combining the advantages of flexible programming language like C with that of MATLAB, we have endeavored to model the forward traffic channel of the 3G system employing WCDMA for PCS applications in the United States. The air interface between the base station and the mobile station basically consists of two main links, viz., the forward link and the reverse link. Each of these is further
constituted by different channels. The basic building blocks for the different channels are common for the most part. The transmitter and the receiver sections of the traffic channel of forward traffic channel of the forward link will be analyzed and implemented here. In general the blocks of the traffic channel can be used to implement other channels too. The implementation has been mainly done using MATLAB's application interface with C [11].

1.3 Thesis organization

Chapter 2 sets the stage by introducing the preliminary concepts that will be dealt with in detail in the chapters to follow. A brief overview of the multiple access concepts is outlined in the first section. The next section provides a deeper analysis of the CDMA technique followed by a brief discussion of the 3G technologies and an overview of the WCDMA technique. Chapter 3 provides a general description of the forward and the reverse links of the WCDMA system. Chapter 4 provides a detailed infrastructural description of the forward traffic channel with a demonstration of its implementation. The algorithm and other implementation details are also included for each block. Chapter 5 summarizes the complete system with basic simulation results. Chapter 6 concludes the thesis with a few suggestions for future work.
CHAPTER 2  BACKGROUND

2.1 Multiple Access techniques

The users in a wireless communication system share a common frequency spectrum. This resource must be used efficiently. The methods of allocating spectrum to the different users defines three multiple access techniques:

- Frequency Division Multiple Access (FDMA) - Different users of the system are assigned narrow slices of the frequency spectrum. The total number of users $N$, equals the total number of frequency bands. The first generation analog system AMPS (Advanced Mobile Phone System) employs the FDMA technique.

- Time Division Multiple Access (TDMA) - Different users operate in $M$ different time slices on $N$ frequency bands and hence the total number of users in such a system equals $M \times N$. This technique is more spectrally efficient than FDMA [12]. The second generation interim standard (IS-54) for the air access technique exceeds the AMPS capacity by a factor of three ($M$) and employs the TDMA technique [12].

- Code Division Multiple Access (CDMA) – Each user is assigned a unique orthogonal code that separates the different users. The users of this system simultaneously use the same frequency band, which leads to high spectral efficiency. The standard IS-95, initially proposed by Qualcomm Inc. and later adopted as the digital cellular standard for the cdmaOne second generation system, employs CDMA.

2.2 Spread Spectrum techniques

Spread spectrum modulation refers to any modulation scheme that produces a spectrum for the modulated signal much wider than the bandwidth of the information signal. The advantages of such a system are characteristics like jam resistance (JR), low probability of
intercept (LPI) and multipath interference resistance [13]. Two of the most popular spread spectrum techniques are frequency hopping (FH) and direct sequence (DS). The frequency hopped spread spectrum technique involves shifting of the data modulated carrier frequency pseudo-randomly according to a pseudo noise (PN) sequence. It gets its name from the fact that the transmitted signal appears as a data-modulated carrier hopping from one frequency to the next. Direct sequence spread-spectrum systems (DSSS) directly modulate the data sequence by a wide-band spreading signal called the PN sequence or the PN code. The DSSS CDMA signal possesses low spectral density providing it an edge over the other techniques in terms of the interference and average transmitted power [13], [14]. Thus inherently, it is interference resistant and difficult to detect by any receiver but its own [13]. The second generation system in the US, cdmaOne, employs DS spread-spectrum technique.

2.3 Capacity comparison of CDMA, FDMA and TDMA systems

Here a simplified discussion on the capacity comparisons of the CDMA, FDMA and TDMA systems is presented. The detailed analysis can be obtained from chapters three and ten of [12]. General information about frequency reuse in the systems is given in [15], [16].

The capacity of any communication system is defined in terms of traffic load measured in units of Erlangs. The traffic load is proportional to the number of channels available for assignment to the mobile calls in the system. The number of channels available, in turn, is limited by the blocking probability, which is defined as the probability that a call is rejected by the system. This value needs to be kept low for any system for efficient communications and is usually 1% to 2% [12].

The Erlang capacities of the three systems can be found for the value of the blocking probability to be maintained for that particular system. The results are tabulated in Table 2.1 and as seen, in terms of the Erlang capacities for each of the systems, the CDMA IS-95 system has advantage over the AMPS and the IS-54 systems computed as [12]:

Table 2.1: Capacity comparison of CDMA, FDMA and TDMA systems

<table>
<thead>
<tr>
<th>System Type</th>
<th>Number of channels available per sector</th>
<th>Erlang Capacity&lt;sup&gt;A&lt;/sup&gt; (in Erlangs)</th>
<th>Capacity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMA (IS-95)</td>
<td>$30^B \times 9^C = 270$</td>
<td>248</td>
<td>20.2</td>
</tr>
<tr>
<td>FDMA (AMPS)</td>
<td>$19^D$</td>
<td>12.3</td>
<td>1</td>
</tr>
<tr>
<td>TDMA (IS-54)</td>
<td>$57^E$</td>
<td>46.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

<sup>A</sup> Erlang Capacity is calculated for a blocking factor of 1% for the IS-95 and IS-54 systems and 2% for the AMPS system using Table 3.2 of [12].

<sup>B</sup> The calculation is considering one frequency allocation of the IS-95 system, based upon first order and second order frequency reuse factors of 0.55 and 0.086 respectively and $E_b/N_0 = 7$ dB [12].

<sup>C</sup> The IS-95 system can use up to 9 frequency allocations.

<sup>D</sup> The AMPS system is based upon $K=7$ frequency reuse subset for a three sector system, based upon requirement of $\text{Carrier/Interference} \geq 18$ dB. Refer Table 3.8 of [12].

<sup>E</sup> The IS-54 system supports $19 \times 3 = 57$ channels.

\[
\text{IS-95 capacity advantage over AMPS} = \frac{248}{12.3} = 20.2
\]

\[
\text{IS-95 capacity advantage over IS-54} = \frac{248}{46.8} = 5.3
\]

2.4 General architecture of the cellular network

Figure 2.1 shows the layout of a generic wireless cellular network [3], [18]. The network can be broadly classified into three main parts: The mobile station, the base station subsystem, and the network and switching subsystem. Each of these is dealt in detail in the following sections.

2.4.1 Mobile Station (MS)

The mobile station consists of the mobile device that is the subscriber’s interface with the cellular network. It handles the digitization of speech and other preprocessing for transmission over the digital network. It interfaces with the base station (BS) over the radio links. The radio transmission link from the base station to the mobile station is referred to as the ‘forward link/channel’ or the ‘downlink’ whereas that from the mobile station to the base station is called the ‘reverse link/channel’ or the ‘uplink’.
Figure 2.1: General cellular network architecture.

MS - Mobile station
BSS - Base Station Subsystem
BTS - Base Transceiver Station
BSC - Base Station Controller
NSS - Network and Switching Subsystem
MSC - Mobile Services Switching Center
AuC - Authentication Center
HLR - Home Location Register
VLR - Visitor Location Register
OMC - Operations and Maintenance Control
PSTN - Public Switched Telephone System
ISDN - Integrated Services Digital Network
2.4.2 Base Station Subsystem (BSS)

The base station communicates with the mobile station over the air interface. The BS is divided into two sub-modules: the base transceiver station (BTS) and the base station controller (BSC).

The BTS houses the radio circuitry for transmission and reception and handles the radio protocols with the mobile station. The BSC manages the radio resources of one or more base stations. It forms the link between the BTS and the mobile services switching center (MSC) and passes control messages to the MSC. It can either be located in a base station or at a remote site.

2.4.3 Network and Switching Subsystem (NSS)

The NSS is the interconnection of the cellular network to the fixed networks and the other networks. It provides the intelligence for switching calls, storage and authentication functions for the subscriber information and routes the calls. The MSC is the brain of the network subsystem which provides all functionality needed to handle a mobile subscriber like call routing, registration, authentication, location updating and handoffs. It also acts as a gateway for communicating with the fixed networks like Public Switched Telephone Network (PSTN) and the Integrated Services Digital Network (ISDN).

The home location register (HLR) and the visitor location register (VLR) serve as databases for the administrative information of the subscribers. Together with the MSC they provide the call routing for the mobile subscriber. The HLR contains the profile of each of the subscribers. In addition, it also maintains the information of its subscribers who might be accessing a different service area. One or more MSCs can share a HLR. The VLR contains information of a subset of the subscribers who are active and operating under that particular MSC. The authentication center (AuC) contains secure information about each subscriber and validates the identity of the user accessing the system.

This thesis focuses mainly on the air interface between the mobile station and the base station.
2.5 Second generation mobile systems and the IS-95 standard

The analog systems for wireless cellular communications used FDMA for transmission. These were referred to as the first generation systems and were mainly for speech transmission. Examples of the first generation cellular systems include the AMPS in the United States, the Total Access Communication Systems (TACS) in United Kingdom, and the Japanese Nippon Advanced Mobile Telephone System (NAMTS) [18], [16].

The cellular systems based on TDMA and CDMA are referred to as the second generation systems. Examples of the second generation systems include GSM, IS-54, and IS-95 systems.

The motivation for describing certain details of the IS-95 in the following sections comes from the fact that the WCDMA system, which is the focus of this thesis, is similar to IS-95 systems in many respects.

IS-95 specifications [19] define the standards for air interface between the base station and the mobile station for the second generation mobile systems based on the CDMA technique and was introduced by Qualcomm Inc. of USA. This standard is titled ‘Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System’. The dual-mode keyword stresses the fact that the IS-95 system can operate in both analog and digital mode. The forward and the reverse links in the IS-95 system are divided as shown in Figure 2.2 [12], [19], [20].

![Figure 2.2: Forward and Reverse links of IS-95](image)

The forward link channel structure consists of transmission of up to 64 simultaneous, distinct channels with varying functions that are orthogonally multiplexed onto the same RF carrier. The channels can be any of the four types: pilot, synchronization, paging and forward traffic. The pilot channel is a high power signal that is transmitted continuously as a coherent phase reference. The synchronization channel or the ‘sync channel’ is used to transmit
system information to all users in a cell and provide the initial frame synchronization. One to seven paging channels can be used to convey channel assignments and pages to individual mobile stations. The rest of the channels are used to transmit data and voice traffic to the users.

The reverse link channels are the access and traffic channels. The mobile station uses the access channel to initiate communication with the base station and also to respond to pages sent by the base station. The reverse traffic channel transmits data or voice traffic to the base station.

### 2.5.1 Role of PN sequences in IS-95 system

The spreading of the information-carrying signal in the transmitter of the CDMA systems is carried out using PN sequences. The receiver needs to know and be synchronized to the PN sequence so that the modulated signal can be despread to obtain the information signal. This requires that the PN sequences have certain properties so that they can be determined only by the intended receivers and appear random to the others. In general, the properties that make their role crucial in the functioning of the CDMA system are discussed below [12], [21]:

**Balance property** – The difference in the number of ones and number of zeros is at the most one in a full period of the PN sequence.

**Autocorrelation property** - The correlation of the sequence with itself (autocorrelation) should give a peak and with any shifted version (cross-correlation) should give a near zero value. In the digital domain, this translates to the number of agreements minus the number of disagreements in the bit-by-bit position of the two sequences. Hence the autocorrelation of the two digital sequences should give the maximum value, which is ‘n’ for an n-length shift register, and the cross correlation should give the minimum value, which is −1.

Consider an example of the sequence of length seven as shown below

\[ P = (1,1,1,0,1,0,0) \]

P has 4 logical zeros and 3 logical ones in it. Hence it satisfies the balance property of PN sequences.
The modulo-2 addition operation (denoted by $\oplus$) of two binary sequences gives the number of agreements in the bit-by-bit position of the two sequences by the number of logical zeros in it, and the number of disagreements by the number of logical ones in it.

\[
\text{Autocorrelation} = \text{Number of zeros in } P \oplus P - \text{Number of ones in } P \oplus P
\]
\[
= \text{Number of zeros in } (0,0,0,0,0,0,0) - \text{Number of ones in } (0,0,0,0,0,0,0)
\]
\[
= 7 - 0 = 7 = \text{Length of } P.
\]

$P_1 = P$ shifted by 1 bit = (0,1,1,1,0,1,0)

Cross-correlation of $P$ with $P_1$
\[
= \text{Number of zeros in } P \oplus P_1 - \text{Number of ones in } P \oplus P_1
\]
\[
= \text{Number of zeros in } (1,0,0,1,1,1,0) - \text{Number of ones in } (1,0,0,1,1,1,0)
\]
\[
= 3 - 4 = -1.
\]

Similarly, the cross-correlation of $P$ with its other shifted versions also gives -1. Hence it satisfies the correlation property of PN sequences.

Hence $P$ is a PN sequence.

PN sequences are generated using linear feedback shift register (LFSR). For an ‘n’ length shift register, the output is periodic with a period of $2^n$ which is also the total number of distinct sequences possible with a sequence of length ‘n’. However, the sequence of all zeros is not considered as it causes a saturation of the shift register and hence the total number of periods is limited to $2^n$-1. These PN sequences are referred to as maximal length sequences (m-sequences) and are used in the IS-95 system. With any particular initial loading of the ‘n’ states of the shift register, one particular version (phase shift) out of $2^n$-1 possible sequence of length $L = 2^n$-1 is produced [12].

Normally, the bits are represented in the bipolar form; with a logical one represented as -1 and a logical zero represented as +1. With this representation, the modulo-2 addition operation gets translated to multiplication. Generally, the correlation value is normalized with respect to the length of the PN sequence. Hence the autocorrelation of a PN sequence in the bipolar form yields a value of 1 and its cross correlation with a phase shifted version of itself gives $1/L$. Therefore, if the length of the PN sequence is long, this value becomes approximately zero. This feature is exploited in a multiple access system employing CDMA.
The reference time for the CDMA system clock is maintained by global positioning system (GPS) and the reference PN code shift is synchronized to this time. A decimated sequence of the PN sequence is used in the channels of the forward link by selecting the first chip of every 64 chips of the sequence to scramble the data sequence at that rate. This decimated sequence is also pseudorandom with all the desired attributes of a PN sequence [12].

As a note, the orthogonal sequences like Walsh codes that are used for modulation are not PN sequences because they do not possess good correlation properties which are the essence of PN sequences.

2.5.2 Features of the IS-95 standard

Frequency allocations [12]

The dual-mode compatibility requirement dictates that the IS-95 equipment be capable of operating in both the analog band digital modes. Thus, the cellular frequency allocations for the IS-95 system overlays the spectrum for the analog AMPS system. The frequency assignment in the forward link is from 824 MHz to 849 MHz and in the reverse link from 869 MHz to 894 MHz. The total bandwidth is 50 MHz in both the links. The underlying AMPS channel carriers occupy the same spectrum. The chip rate is set to 1.2288 Mcps and the nominal bandwidth of the CDMA waveform is 1.25 MHz.

System time [12]

The maintenance of the system time is critical component of the IS-95 CDMA system. Because each base station in a cellular service area transmits at the same center frequency and uses the same PN sequence, the forward link waveforms are distinguished at the mobile stations by their unique code offset. Each base station maintains a clock synchronized with the GPS time signals and thus the different base stations are synchronized with respect to each other. The phase shift of the PN sequence of a particular base station is determined at the mobile station by decorrelating the received sequence with each possible phase shift and selecting the one that gives the highest correlation. Owing to the properties of the PN sequences as described in Section 2.5.1, any other PN sequence but the PN sequence used at the base station will give the minimum value of correlation.
Multiple access [12], [20]

In the forward link, mutually orthogonal Walsh code sequences modulate the channel data. This helps keep the channels orthogonal and minimizes interference. The discrimination of signals from the different base stations is possible due to the different phase offsets for the PN sequences that each of the base station uses. In the reverse link, channel separation is achieved with a user distinct offset of the PN code sequence.

Modulation [12]

The modulation of the forward link waveform using I (cosine) and Q (sine) RF carriers yields two waveforms of the binary phase shift keying (BPSK) form. Addition of the two BPSK waveform gives the quaternary phase shift (QPSK) waveform. In the reverse link, every six symbols at the input of the modulator determine which Walsh code of length 64 is to be used. This waveform is then quaternary modulated as in the forward link except that the Q-quadrature is delayed by half a PN chip, thus generating a form of offset quaternary phase-shift keying (OQPSK).

Pulse shaping [12]

The digital pulses in the I and the Q channels are shaped using FIR filters to minimize the Inter-Symbol Interference (ISI) while constraining the bandwidth. The raise cosine filter is used which yields error free transmission at the sampling rates. To achieve the effect at the receiving end, square root of raised cosine filters are used at both the transmitter and the receiver.

Voice Coding and error control [12]

The IS-95 system can provide variable data rate transmissions at 1.2 kbps, 2.4 kbps, 4.8 kbps and 9.6 kbps using variable-rate vocoder. Error control is done by convolutional encoding and interleaving to prevent against data burst errors.

Demodulation

Coherent demodulation is employed in the forward link of IS-95 due to the presence of the unmodulated pilot channel which provides the phase reference at the receiver in the mobile station. However, in the reverse link, non-coherent modulation is employed as the channels in the reverse link do not have a pilot channel to serve as the phase reference.
2.6 Third generation mobile systems

The second generation digital technology was developed to replace and enhance the capabilities of the first generation analog systems. The goal of the next generation systems is to make wideband communications available anywhere and to anyone. This necessitates a standard that can be accepted worldwide as a single global system. With this objective in mind, the UMTS/IMT-2000 body is conferred with the task of defining the 3G mobile systems.

2.6.1 System Requirements of the 3G systems

The main requirements put forth by IMT-2000/UMTS for the air interface of the third generation systems are [22]:

- Full coverage and mobility for 144 kbps, preferably 384 kbps;
- Limited coverage and mobility for 2 Mbps;
- High spectrum efficiency compared to existing 2G systems
- Flexibility to operate in any propagation environment, such as indoor, outdoor to indoor and vehicular scenarios
- High flexibility to introduce new services and to handle both circuit switched and packet switched mode services.
- Maintain quality of service comparable to that of the current network with affordable cost.

Of the many proposals made by 3GPP and 3GPP2 for the air interface scheme, two proposals made it to the final selection process for the 3G systems air interface technique. They are wideband CDMA and a combination of TDMA and CDMA in both time division duplexing (TDD) and frequency division duplexing (FDD) modes. As of now, the wideband CDMA technique, which provides a much higher bandwidth than the existing narrowband CDMA networks, has been adopted for the air interface in the 3G systems of both UMTS and IMT-2000. The nominal bandwidth for the proposals is 5 MHz. The data rates that are targeted by the 3G requirements are 144 kbps, 384 kbps and 2 Mbps (under limited conditions). These rates are achievable within the 5 MHz bandwidth. Also, higher bandwidths imply that more multipaths can be resolved thus improving performance.
2.6.2 Characteristics of the UMTS/IMT-2000 radio access:

This section is adapted from [23]. The spectrum allocation proposed by the UMTS terrestrial radio access (UTRA) is shown in Figure 2.3 and that for IMT-2000 is shown in Figure 2.4.

![Figure 2.3: The proposed spectrum allocation in UTRA [23]](image)

<table>
<thead>
<tr>
<th>W-CDMA (TDD)</th>
<th>W-CDMA Reverse link (FDD)</th>
<th>MSA</th>
<th>W-CDMA (TDD)</th>
<th>W-CDMA Forward link (FDD)</th>
<th>MSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td>2170</td>
<td>1980</td>
<td>2025</td>
<td>2200</td>
<td>2010</td>
</tr>
</tbody>
</table>

MSA – Mobile Satellite Applications

![Figure 2.4: The proposed spectrum allocation in IMT-2000 [23].](image)

<table>
<thead>
<tr>
<th>W-CDMA Reverse link (FDD)</th>
<th>MSA</th>
<th>W-CDMA (TDD)</th>
<th>W-CDMA Forward link (FDD)</th>
<th>MSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920</td>
<td>1980</td>
<td>2025</td>
<td>2170</td>
<td>2200</td>
</tr>
</tbody>
</table>

MSA – Mobile Satellite Applications

2.6.3 W-CDMA and cdma2000

W-CDMA is the system proposed by UTRA and cdma2000 is the systems proposed by IMT-2000. Both the systems use the WCDMA technique for their air interface. However, in order to be compatible with the existing 2G systems, they differ in certain respects; the main differences being in the chip rate, downlink channel structure and network synchronization [25]. A tabulated comparison of W-CDMA and cdma2000 with respect to different aspects is shown in Table 2.2 [25].

2.6.4 3G PCS system in United States based upon WCDMA technology

W-CDMA and cdma2000 are the 3G proposals for the cellular mobile systems. The cellular systems and the PCS systems are basically the same with exceptions of the frequency bands of operation and some call processing features related to the identification of the mobile device. One of the problems with cdma2000 is that the frequency allocation proposed for it has already been allocated for PCS applications in the USA [23] and so it has
Table 2.2: Comparison between cdma2000 and W-CDMA [25]

<table>
<thead>
<tr>
<th></th>
<th>cdma2000</th>
<th>W-CDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channel bandwidth</strong></td>
<td>1.25, 5, 10, 20 MHz</td>
<td>5, 10, 20 MHz</td>
</tr>
<tr>
<td><strong>Downlink RF channel structure</strong></td>
<td>Direct Spread or multicarrier</td>
<td>Direct Spread</td>
</tr>
<tr>
<td><strong>Chip rate</strong></td>
<td>1.2288/3.6864/7.3728/11.0593/14.745 MHz (n=1,3,6,9,12)</td>
<td>4.096/8.192/16.384 MHz</td>
</tr>
<tr>
<td><strong>Roll-off factor for chip shaping</strong></td>
<td>Similar to IS-95</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Frame length</strong></td>
<td>20 ms for data and control / 5 ms for control information on the fundamental and dedicated control channel</td>
<td>10 ms /20 ms (optional)</td>
</tr>
<tr>
<td><strong>Spreading modulation</strong></td>
<td>Balanced QPSK (forward link) Dual channel QPSK (reverse link) Complex spreading circuit</td>
<td>Balanced QPSK (forward link) Dual channel QPSK (reverse link) Complex spreading circuit</td>
</tr>
<tr>
<td><strong>Data modulation</strong></td>
<td>QPSK (forward link) BPSK (reverse link)</td>
<td>QPSK (forward link) BPSK (reverse link)</td>
</tr>
<tr>
<td><strong>Coherent detection</strong></td>
<td>Pilot time multiplexed with power control bits (reverse link) Common continuous pilot and auxiliary pilot (forward link)</td>
<td>User dedicated time multiplexed pilot (forward and reverse links) and no common pilot in forward link</td>
</tr>
<tr>
<td><strong>Channel multiplexing in the reverse link</strong></td>
<td>Control, pilot, fundamental and supplemental code multiplexed I&amp;Q multiplexing for data and control channels</td>
<td>Control and pilot channel time multiplexed I&amp;Q multiplexing for data and control channel.</td>
</tr>
<tr>
<td><strong>Multirate</strong></td>
<td>Variable spreading and multicode</td>
<td>Variable spreading and multicode</td>
</tr>
<tr>
<td><strong>Spreading factors</strong></td>
<td>4 - 256</td>
<td>4 - 256</td>
</tr>
<tr>
<td><strong>Power control</strong></td>
<td>Open and fast closed loop</td>
<td>Open and fast closed loop</td>
</tr>
<tr>
<td><strong>Spreading (forward link)</strong></td>
<td>Variable length Walsh sequences for channel separation, m-sequence $2^{15}$ (same sequence with time shift in different cells, different sequences in I&amp;Q channels)</td>
<td>Variable length orthogonal sequences for channel separation. Gold sequences $2^{18}$ for cell and user separation (truncated cycle 10 ms)</td>
</tr>
<tr>
<td><strong>Spreading (reverse link)</strong></td>
<td>Variable length orthogonal sequences for channel separation, m-sequence $2^{15}$ (same for all users, different sequences in I&amp;Q channels), m-sequence $2^{42}$ -1 with time shifts for user separation</td>
<td>Variable length orthogonal sequences for channel separation, Gold sequences $2^{42}$ for user separation (different time shifts in I&amp;Q channel, truncated cycle 10 ms)</td>
</tr>
<tr>
<td><strong>Handoff</strong></td>
<td>Soft handoff Interfrequency handoff</td>
<td>Soft handoff Interfrequency handoff</td>
</tr>
</tbody>
</table>
to be designed such that its framework coexists with the existing applications. The WCDMA based PCS system given by the specifications in [1], is allocated the frequency bands of 1850-1910 MHz and 1930-1990 MHz and is based upon the IS-95 system of second generation cellular system.

The transmitter and the receiver sections implemented in this thesis are those for the WCDMA technology based PCS system in the USA. The standard referred is the ANSI Joint-Standard-015 (ANSI J-STD-015) published in December 1998 [1]. This standard is a trial usage version that will be revised and submitted to ANSI for approval as an American National Standard. However, at the time this standard was bought (January 2000), it is the latest available from TIA and hence will be used. The reader may refer to any recent version, if available, for the latest updates. It is not clear from [1] why despite being a standard for PCS in the USA, where cdma2000 is proposed as the 3G cellular system, it uses a chip rate (4.096 Mcps) same as that for the W-CDMA system proposed by UMTS (whereas cdma2000 uses a chip rate of 3.6864 Mcps.). Issues about the frequency of transmission, however, will not imply a drastic change in the design. A basic model that can be adapted for other 3G systems as well will be built here. The subtleties concerning the differences from the second generation IS-95 system will be pointed out in the course of the description of the different channels.
CHAPTER 3 REVERSE AND FORWARD LINKS OF WCDMA SYSTEM

3.1 WCDMA system\textsuperscript{3} overview

The WCDMA system air interface for the PCS applications operates from 1.85 GHz to 1.99 GHz. The mobile device is called the personal station in PCS terminology. The reverse link is the communication link from the personal station to the base station and the forward link is the communication link from the base station to the personal station. The reverse link operating between 1.85 GHz to 1.91 GHz and the forward link operating between 1.93 GHz to 1.99 GHz are frequency division duplexed with an 80 MHz spacing. Each link is divided into two band classes, viz. Band class 1 assigned 15 MHz of contiguous spectrum and band class 2 assigned 5 MHz of contiguous spectrum. Band class 1 can hence fit bandwidths higher than 5 MHz and band class 2 can be used for the basic 5 MHz bandwidth. These band classes are designated to different block designators as shown in Table 3.1 [1]. The personal station can operate in either or both of the band classes.

The basic WCDMA system standard supports a bandwidth of 5 MHz with the PN sequence rate, also called the chip rate, at 4.096 Mcps. Higher bandwidths of 10 MHz and 15 MHz can also be supported but will not be implemented here as they differ in their design. The reader may refer to [1] for more details on that. The system capacity of the basic WCDMA system is 128 channels that share the spectrum using DS/CDMA. Power control is provided using a combination of open and closed loop power control. In the open loop scheme, the personal station adjusts its power according to the strength of the measured

\textsuperscript{3} Hereafter, WCDMA system will refer to the PCS system based on WCDMA technology and specified by the ANSI J-STD-015 standard.
signal from the base station on the receiver of the forward link [12]. This scheme is useful when compensating for long-term, median propagation loss [1]. In the closed loop scheme, the base station sends feedback using the power control bits to the personal station to reduce or increase its transmit power level depending upon the measured mobile strength at the receiver of the base station for the reverse link. This scheme is used to rapidly correct output power variations due to short term fading or shadowing [1].

Table 3.1: Block Designators and WCDMA system frequency correspondence [1]

<table>
<thead>
<tr>
<th>Block Designator</th>
<th>Band Class</th>
<th>Personal Station transmit frequency band in MHz</th>
<th>Base Station transmit frequency band in MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1850 – 1865</td>
<td>1930 - 1945</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>1865 – 1870</td>
<td>1945 – 1950</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1870 - 1885</td>
<td>1950 – 1965</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>1885 – 1890</td>
<td>1965 – 1970</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>1890 – 1895</td>
<td>1970 – 1975</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>1895 – 1910</td>
<td>1975 – 1990</td>
</tr>
</tbody>
</table>

The following sections contain the general descriptions of the physical layer of the air interface for the base station i.e., the forward link and the personal station i.e., the reverse link. The data link layer and the protocols for call establishment and processing are not ventured into here. The reader can refer to [1], [20] for details pertaining to that.

3.2 Forward link

The forward link of the WCDMA system from the base station to the personal station consists of the following channels as seen from Figure 3.1:

- Pilot channel – It is transmitted at all the times by the base station when it is active. The pilot channel, similar to IS-95, is an unmodulated spread spectrum signal orthogonally spread using the Walsh code sequence with index zero. The same pilot channel is used for all the frequency assignments of a particular base station.
• Sync channel - It is convolutionally encoded, interleaved, spread and modulated using the same PN offset as for the pilot channel and is used by the personal station for initial frame synchronization.

• Paging channels - It is convolutionally encoded, interleaved, spread and modulated signal and used by the base station to send specific messages to the mobile station. The forward link may have up to eight paging channels.

• Forward traffic channel - It consists of a forward information and forward signaling channel. One forward traffic channel is used per personal station for transmission of user data and signaling information.

![Diagram of Forward Link of WCDMA System]

Figure 3.1: Forward link of WCDMA system

The base station continuously and simultaneously transmits the pilot channel, the sync channel and the paging channel. Each of the channels of the forward link is explained in detail in the following sections [1], [20], [12].

3.2.1 Pilot channel

Every base station in the cellular area uses the same PN sequence generated with the PN sequence generator, as will be discussed in Section 4.10, but with a different phase shift or time offset. As the pilot channel does not carry any data and is modulated by the Walsh code index zero, as shown in Figure 3.2, the receiver of the personal station can easily acquire it. It thus serves as a coherent phase reference for demodulation of the other channels. The pilot channel is always transmitted at a higher power level than the other channels since it plays a crucial role in timing.
All the base stations in a cellular area are synchronized with the GPS signal as mentioned in Section 2.5.1. The pilot PN code generator generates the long code of length $2^{32}$ and will be discussed in Section 4.10.

The modulo-2 addition of this sequence with the Walsh code of index zero that is used for the orthogonal modulation results in a pilot PN sequence of period 81920 chips. The pilot sequence when delayed by 256 chips gives a new pilot PN sequence that can be used by another base station. Hence, a total of 320 ($= 81920/256$) unique values for the time offsets of the PN sequence are possible and each is identified by an index. The same index of the PN sequence is used on all channels when communicating with a particular base station. After spreading by the pilot PN sequence, the waveform is filtered and then transmitted.

### 3.2.2 Sync Channel

The synchronization channel or the sync channel provides the information necessary for the personal station to obtain synchronization with the system timing. It is generated at 16 kbps, error control coded using $\frac{1}{2}$ rate convolutional encoder, interleaved and repeated to provide further protection against possible burst errors that can occur due to fading nature of the channel. It is then spread with the same PN sequence as the pilot channel, modulated with a Walsh code of index 128 and baseband filtered before transmission as shown in Figure 3.3. The convolutional encoding, interleaving, symbol repetition, PN code generation and filtering operations will be discussed in Chapter 4. The length of the sync channel superframe is 20 ms which equals the period of the pilot PN sequence of 81920 chips. As the sync channel is spread by the same PN sequence as the pilot channels, and has its frame timing
aligned with the pilot sequence, all the personal stations assigned to that base station can know the basic timing structure of the channel. This is achieved by correlating the received sync channel signal (after demodulation, deinterleaving and decoding) with each time offset of the PN sequence and choosing one that gives the highest value. This corresponds to the phase shift of the PN sequence for that particular base station.

![Diagram of sync channel structure of WCDMA system]

Figure 3.3: Sync channel structure of WCDMA system

### 3.2.3 Paging Channel

Paging channels alert the personal station to incoming calls, convey channel assignments to personal stations that have not yet been assigned a traffic channel and transmit system overhead information such as mobility management and radio resource management messages. The base station uses multiple paging channels to transmit system information and personal station specific messages. The paging channel information is generated at 16 kbps. The paging information is encoded, repeated, interleaved, as described for the sync channel. Its overall structure is as shown in Figure 3.4. Prior to transmission, it is modulated using one of the seven Walsh codes (indices between 1 and 7), spread using the same PN sequence as used by the pilot channel and filtered using baseband filters.

The paging channel frame has length of 5 ms. The paging channel is divided into page slots of 20 ms duration. The base station can transmit pages for a particular personal station in any of the slots. There are two ways the personal station can monitor the pages on the
paging channel mode: non-slotted mode or slotted mode. In the non-slotted mode, the personal station monitors all paging slots for its page whereas in the slotted mode, the personal station is preassigned a slot [1]. Among other information, the unique long code seed required by the personal station to be used on the reverse channel is also communicated.

![Forward Traffic Channel Diagram](image)

Figure 3.4: Paging channel structure of WCDMA system

### 3.2.4 Forward Traffic Channel

During a call, each personal station is assigned a forward traffic channel that carries digital voice or data at rates of 64, 32 or 16 kbps. The forward traffic channel may also carry signaling bits at the rates of 4 or 2 kbps and power control bits at the rate of 2 kbps. The maximum number of channels that can be simultaneously supported by a forward link is equal to 64 for 64 kbps, 128 for 32 kbps and 256 for 16 kbps. Subtracting the number of pilot, sync, and paging channel, the maximum number of forward traffic channel that can be supported can be found. The PN sequence used by the forward traffic channels of a particular base station is the same as the PN sequence used by the pilot channel of that base station.

The overall channel structure of the forward traffic channel is shown in Figure 3.5. The forward traffic channel consists of the forward information and the forward signaling channel. Addition of power control and the signaling bits are done in the forward information channel sequence by puncturing its rate.
Figure 3.5: Forward traffic channel structure of WCDMA system
A power control bit ‘0’ indicates to the personal station to increase the average output power level and a ‘1’ bit indicates to the personal station to decrease the average power output. A detailed description of the forward traffic channel with its implementation details is provided in Chapter 4.

3.3 Reverse link

The channel structure of the reverse link from the mobile station to the base station is shown in Figure 3.6 and consists of the following channels:

- **Access channel** – It consists of the reverse pilot channel and the reverse access channel. The pilot channel in the access channel provides phase reference for coherent detection of the access channel data at the base station receiver. The reverse access channel is used to respond to pages from the base station.

- **Reverse traffic channel** – It consists of the reverse pilot channel, reverse information channel and reverse signaling channel. The pilot channel serves as the phase reference for coherent detection at the base station receiver.

![Figure 3.6: Reverse link of WCDMA system](image)

3.3.1 Access Channel

The access channel is used by the mobile station to communicate messages when responding to pages from the base station and the overall structure can be seen in Figure 3.7. The access channel consists of two sub channels, the reverse pilot channel and reverse access channel. There exists at least one access channel on the reverse channel for every
paging channel on the forward channel and a maximum of 32 access channels. Each access channel is associated with a single paging channel.

The reverse pilot channel is used by the base station to acquire, track and derive phase reference for reverse access channel; thus providing a way of coherent detection unlike the reverse link of the IS-95 system. Each frame is of length 5 ms. The reverse access channel information bits are convolutionally encoded, interleaved, repeated, spread, filtered before transmission. The same convolutional encoder is used in the channels of the forward link and the reverse link as well and will be dealt in detail in Section 4.3.

![Diagram](image)

**Figure 3.7: Access channel structure of WCDMA system**

### 3.3.2 Reverse Traffic Channel

The reverse traffic channel consists of three channels: reverse pilot channel, reverse information channel and reverse signaling channels as shown in Figure 3.8. The reverse pilot channel is used to provide phase reference for the reverse information and the signaling channel. Hence reverse link of the WCDMA system is a coherent communication system unlike IS-95 systems. The data rate on the reverse information channel is fixed at 64, 32 or 16 kbps. The reverse signaling channel is transmitted at the rate of 4kbps. Convolutional encoding, interleaving, and repeating are applied on the reverse information and the reverse signaling channel only. The reverse pilot channel is unmodulated spread signal transmitted for phase reference for coherent detection.
The information presented so far is the structural description of the different channels on the reverse and forward link of the WCDMA system. In the following chapter, the forward traffic channel of the forward link is described and implemented. The different components like convolutional encoder, interleaver, PN sequence generator, modulator and baseband filter that are mentioned here will be discussed with respect to their implementation details.
CHAPTER 4  SIMULATION OF THE FORWARD TRAFFIC CHANNEL

4.1 Development Environment

The data on the information channel of the forward traffic channel is preprocessed before multiplexing with the power control bits and the signaling bits of the forward signaling channel. It is then scrambled, spread, modulated and filtered before transmitting to the personal station as can be seen from Figure 3.5. In this chapter, we discuss the implementation features of these different blocks.

The forward traffic channel (FTC) transmitter is based upon the specifications in [1]. The receiver implementation structure for the channel is left as a flexible choice for the implementers and hence not discussed in [1]. As the link being modeled is the forward link, the receiver structure is a single user receiver used in multiple access schemes. The front-end of the receiver is a conventional matched filter like that used in IS-95 [12], [19]. The rest of the blocks of the receiver undo the preprocessing done at the transmitting end.

The implementation of both the transmitter and the receiver is done in MATLAB using m-file routines (with extension ‘.m’) and mex (with extension ‘.c’) routines. Mex routines are basically routines in C that interface with MATLAB. The C language references can be found in [34] and [35]. Though MATLAB is a powerful tool for matrix computation, it is inefficient when loop executions are required in large numbers. The processing of each bit in the data sequence by any block requires such loop executions and hence they are implemented as mex routines even if equivalent m-file routines are available. The platform used is UNIX on SGI machines. The files are structured in two directories, mfiles and mex, for the two kinds of files.
4.2 FTC transmitter structure

*FTC_transmit.m:* This is the main script for the forward traffic channel transmitter for data at the rate of 64 kbps and it contains calls to the various functional blocks of the forward traffic channel shown in Figure 3.5. The flow chart of the transmitter *FTC_transmit.m* is shown in Figure 4.1.

**Implementation details:** The different blocks in the transmitter are designed for a data rate of 64 kbps and frame length of 5ms i.e., 320 bits. A random sequence of input bits is generated using the routine *gen01data.c*. Each component block is implemented by a different functional routine. The calls to these functions and the parameters required by them are set in *FTC_transmit.m*. Each of the functional blocks is explained in the following sections.

4.3 Convolutional Encoder

Convolutional encoding is used for the purposes of forward error correction (FEC). Coding reduces the required signal energy to noise density ratio to achieve a specified bit error rate (BER) [12]. A convolutional encoder is conventionally represented as a (n, k, K) encoder or described as an r rate encoder with constraint length K, where

- k = Number of bits that form a block input to the encoder.
- n = Number of bits (symbols) that form the output of the encoder for every k bits at the input.
- K = Constraint length of the encoder which shows how many k-bit stages are considered while generating the output bits.
- r = Rate of the encoder given by \( \frac{k}{n} \)

A (2, 1, 9) convolutional encoder (or a \( \frac{1}{2} \) rate convolutional encoder with constraint length 9) is employed in the forward link. Its structure is shown in Figure 4.2.

It produces two output symbols, \( c_0 \) and \( c_1 \), for each bit input to the encoder and the output symbols are defined by the two generator polynomials

\[
g_0(x) = 1 + x + x^2 + x^3 + x^5 + x^7 + x^8, \text{ and}
\]
\[
g_1(x) = 1 + x + x^2 + x^3 + x^4 + x^8.
\]
START

Generate the input data of given number of spans (64 kbps).
*genOldata.c* *(Section 4.2)*

Convolutionally encode the data using (2,1,9) encoder to give I and Q channels sequences.
*ConvEncoder.c* *(Section 4.3)*

Interleave each span (320 bits) of the data on I and Q channels using the interleaver.
*DataInitSeq_5_64_I.c,*
*DataInitSeq_5_64_Q.c* *(Section 4.4)*

Decimate the long PN code sequence to 64 kbps.
*LCGenerator.m* *(Section 4.9)*

Generate the long PN code sequence at 4.096 kbps.

Multiplex both channels with power and signaling bits.
*FTCMux_64_2_4.c* *(Section 4.8)*

Figure 4.1: Flowchart for the FTC transmitter
Generate the Walsh sequence of length 64. 
*GenWalsh.m (Section 4.10)*

Scramble the channels with the decimated PN sequence. 
*(Section 4.9)*

Modulate the channels with Walsh sequence. 
*ModwWalsh.c (Section 4.10)*

Use long PN sequence to spread the channels. 
*(Section 4.11)*

Convert the digital data (0,1) to bipolar form (1,-1) 
*(Section 4.12)*

Filter using square root of raised cosine filter with roll off = 0.22 and sampling factor = 4. 
*(Section 4.12)*

Figure 4.1: Flowchart for the FTC transmitter (contd.)
The upper taps are considered according to the generator polynomial $g_0(x)$ and the lower taps are considered according to the generator polynomial $g_1(x)$. The output symbol $c_0$ is generated by the modulo-2 addition of the upper taps of the serially time delayed data sequence of length eight ($K-1$) and the input bit. The output symbol $c_1$ is generated by the modulo-2 addition of the lower taps of the same data sequence and the input bit. Each input bit hence affects nine pairs of output symbols.

**Implementation details:** The routine, `ConvEncoder.c`, implements the $\frac{1}{2}$ rate convolutional encoder of constraint length 9. The call to the routine is made as

$$[EncSeq1\_o, EncSeq2\_o] = ConvEncoder(DataSeq\_i);$$

The input to the routine is the data sequence $DataSeq\_i$ and the outputs are the two encoded sequences, $EncSeq1\_o$ and $EncSeq2\_o$, which form the in-phase (I) and the quadrature (Q) channels respectively.

The generator sequences, $g_0(x)$ and $g_1(x)$, are the same for all the encoders used in all the channels and hence are hardcoded in the routine. The register stages of the encoder are initialized with all zeros. After the last input bit, eight zeros are input to the encoder so that the last input bit also affects nine output pairs of symbols. This is referred to as ‘flushing’ of the encoder [26]. The algorithm for the routine can be seen from the flowchart in Figure 4.3.
Input the data sequence.

Initialize the states of all the registers to 0. Set the generator sequences as $g_0 = 0x1EB$ and $g_1 = 0x171$.

For every bit in the input sequence,
- Shift the bits in the registers to the right.
- Set the first register as the input bit.
- Find the two output symbols using the two generator symbols.

Output the two convolutionally encoded sequences.

Figure 4.3: Flowchart for the Convolutional Encoder
4.4 Interleaver

The main purpose of interleaving bits in the data sequence is to disperse bursts of errors over time so that an error control code can correct the errors. The interleaver achieves this by reading out the bits in a different order than which it is so that a burst of error spreads over bits separated from each other.

A block-interleaving span of 5ms is usually used but 10 ms or 20 ms can also be used. The input data to the interleaver is punctured every span for accommodating the signaling bits and the power control bits. The punctured sequence is written columnwise in the interleaver arrays as specified in the WCDMA system specifications in [1]. The bits are read out row wise to give the interleaved sequence. The interleaver arrays are shown in Table 4.1 for the I channel and Table 4.2 for the Q channel. Different interleaver arrays are used for the two channels for different data rates - 64 kbps, 32 kbps, 16 kbps - and different span lengths - 5ms, 10ms and 20 ms [1].

Implementation details: Two different routines, DataIntlSeq_5_64_I.c and DataIntlSeq_5_64_Q.c, are considered as the interleaver arrays for the I and the Q channels are different. The calls to the routines are made as

\[
PunctSeq1_o = DataIntlSeq_5_64_I(EncSeq1_i);
\]
\[
PunctSeq2_o = DataIntlSeq_5_64_Q(EncSeq2_i);
\]

The encoded sequences, EncSeq1_i and EncSeq2_i, of the I and the Q channels are the input to the I and Q interleavers respectively and, PunctSeq1_o and PunctSeq2_o, are the punctured output sequences.

These routines implement the interleaver arrays for data at 64 kbps rate and with span of length 5ms. One span of the data is considered at a time and written into the arrays in Table 4.1 and Table 4.2. For the I channel, the eleventh, sixteenth and the thirty-second bit of every 32 bits is deleted. The span of 320 bits is thus punctured and reduced to give 290 bits. These 290 bits are read out row wise at the output of the interleaver. For the Q channel, the fifth, the twenty-first, and the twenty-sixth bit of every 32 bits is deleted. The 290 punctured bits are written in a different manner in the array than the I channel as seen from Table 4.2. The flow chart for the algorithm of the interleaver routines is shown in Figure 4.4.
Table 4.1: I channel interleaver array for 5 ms span length and 64 kbps data rate.

```
<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>65</td>
<td>97</td>
<td>129</td>
<td>161</td>
<td>193</td>
<td>225</td>
<td>257</td>
<td>289</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>66</td>
<td>98</td>
<td>130</td>
<td>162</td>
<td>194</td>
<td>226</td>
<td>258</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>67</td>
<td>99</td>
<td>131</td>
<td>163</td>
<td>195</td>
<td>227</td>
<td>259</td>
<td>291</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>68</td>
<td>100</td>
<td>132</td>
<td>164</td>
<td>196</td>
<td>228</td>
<td>260</td>
<td>292</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>37</td>
<td>69</td>
<td>101</td>
<td>133</td>
<td>165</td>
<td>197</td>
<td>229</td>
<td>261</td>
<td>293</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>38</td>
<td>70</td>
<td>102</td>
<td>134</td>
<td>166</td>
<td>198</td>
<td>230</td>
<td>262</td>
<td>294</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>39</td>
<td>71</td>
<td>103</td>
<td>135</td>
<td>167</td>
<td>199</td>
<td>231</td>
<td>263</td>
<td>295</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>72</td>
<td>104</td>
<td>136</td>
<td>168</td>
<td>200</td>
<td>232</td>
<td>264</td>
<td>296</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>41</td>
<td>73</td>
<td>105</td>
<td>137</td>
<td>169</td>
<td>201</td>
<td>233</td>
<td>265</td>
<td>297</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>42</td>
<td>74</td>
<td>106</td>
<td>138</td>
<td>170</td>
<td>202</td>
<td>234</td>
<td>266</td>
<td>298</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>43</td>
<td>75</td>
<td>107</td>
<td>139</td>
<td>171</td>
<td>203</td>
<td>235</td>
<td>267</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>44</td>
<td>76</td>
<td>108</td>
<td>140</td>
<td>172</td>
<td>204</td>
<td>236</td>
<td>268</td>
<td>301</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>45</td>
<td>77</td>
<td>109</td>
<td>141</td>
<td>173</td>
<td>205</td>
<td>237</td>
<td>269</td>
<td>302</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>46</td>
<td>78</td>
<td>110</td>
<td>142</td>
<td>174</td>
<td>206</td>
<td>238</td>
<td>270</td>
<td>303</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>47</td>
<td>79</td>
<td>111</td>
<td>143</td>
<td>175</td>
<td>207</td>
<td>239</td>
<td>271</td>
<td>304</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>48</td>
<td>80</td>
<td>112</td>
<td>144</td>
<td>176</td>
<td>208</td>
<td>240</td>
<td>272</td>
<td>305</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>49</td>
<td>81</td>
<td>113</td>
<td>145</td>
<td>177</td>
<td>209</td>
<td>241</td>
<td>273</td>
<td>306</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>50</td>
<td>82</td>
<td>114</td>
<td>146</td>
<td>178</td>
<td>210</td>
<td>242</td>
<td>274</td>
<td>307</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>51</td>
<td>83</td>
<td>115</td>
<td>147</td>
<td>179</td>
<td>211</td>
<td>243</td>
<td>275</td>
<td>308</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>52</td>
<td>84</td>
<td>116</td>
<td>148</td>
<td>180</td>
<td>212</td>
<td>244</td>
<td>276</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>53</td>
<td>85</td>
<td>117</td>
<td>149</td>
<td>181</td>
<td>213</td>
<td>245</td>
<td>277</td>
<td>310</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>54</td>
<td>86</td>
<td>118</td>
<td>150</td>
<td>182</td>
<td>214</td>
<td>246</td>
<td>278</td>
<td>311</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>55</td>
<td>87</td>
<td>119</td>
<td>151</td>
<td>183</td>
<td>215</td>
<td>247</td>
<td>279</td>
<td>312</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>56</td>
<td>88</td>
<td>120</td>
<td>152</td>
<td>184</td>
<td>216</td>
<td>248</td>
<td>280</td>
<td>313</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>57</td>
<td>89</td>
<td>121</td>
<td>153</td>
<td>185</td>
<td>217</td>
<td>249</td>
<td>281</td>
<td>314</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>58</td>
<td>90</td>
<td>122</td>
<td>154</td>
<td>186</td>
<td>218</td>
<td>250</td>
<td>282</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>59</td>
<td>91</td>
<td>123</td>
<td>155</td>
<td>187</td>
<td>219</td>
<td>251</td>
<td>283</td>
<td>316</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>60</td>
<td>92</td>
<td>124</td>
<td>156</td>
<td>188</td>
<td>220</td>
<td>252</td>
<td>284</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>61</td>
<td>93</td>
<td>125</td>
<td>157</td>
<td>189</td>
<td>221</td>
<td>253</td>
<td>285</td>
<td>318</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>62</td>
<td>94</td>
<td>126</td>
<td>158</td>
<td>190</td>
<td>222</td>
<td>254</td>
<td>286</td>
<td>319</td>
<td></td>
</tr>
</tbody>
</table>
```

Table 4.2: Q channel interleaver array for 5 ms span length and 64 kbps data rate.

<p>| | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>177</td>
<td>209</td>
<td>241</td>
<td>273</td>
<td>305</td>
<td>17</td>
<td>49</td>
<td>81</td>
<td>113</td>
<td></td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>178</td>
<td>210</td>
<td>242</td>
<td>274</td>
<td>306</td>
<td>18</td>
<td>50</td>
<td>82</td>
<td>114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>147</td>
<td>179</td>
<td>211</td>
<td>243</td>
<td>275</td>
<td>307</td>
<td>19</td>
<td>51</td>
<td>83</td>
<td>115</td>
<td></td>
<td></td>
</tr>
<tr>
<td>148</td>
<td>180</td>
<td>212</td>
<td>244</td>
<td>276</td>
<td>308</td>
<td>20</td>
<td>52</td>
<td>84</td>
<td>116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>182</td>
<td>214</td>
<td>246</td>
<td>278</td>
<td>310</td>
<td>22</td>
<td>54</td>
<td>86</td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>151</td>
<td>183</td>
<td>215</td>
<td>247</td>
<td>279</td>
<td>311</td>
<td>23</td>
<td>55</td>
<td>87</td>
<td>119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>152</td>
<td>184</td>
<td>216</td>
<td>248</td>
<td>280</td>
<td>312</td>
<td>24</td>
<td>56</td>
<td>88</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>153</td>
<td>185</td>
<td>217</td>
<td>249</td>
<td>281</td>
<td>313</td>
<td>25</td>
<td>57</td>
<td>89</td>
<td>121</td>
<td></td>
<td></td>
</tr>
<tr>
<td>155</td>
<td>187</td>
<td>219</td>
<td>251</td>
<td>283</td>
<td>315</td>
<td>27</td>
<td>59</td>
<td>91</td>
<td>123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>156</td>
<td>188</td>
<td>220</td>
<td>252</td>
<td>284</td>
<td>316</td>
<td>28</td>
<td>60</td>
<td>92</td>
<td>124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>157</td>
<td>189</td>
<td>221</td>
<td>253</td>
<td>285</td>
<td>317</td>
<td>29</td>
<td>61</td>
<td>93</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>158</td>
<td>190</td>
<td>222</td>
<td>254</td>
<td>286</td>
<td>318</td>
<td>30</td>
<td>62</td>
<td>94</td>
<td>126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>159</td>
<td>191</td>
<td>223</td>
<td>255</td>
<td>287</td>
<td>319</td>
<td>31</td>
<td>63</td>
<td>95</td>
<td>127</td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>192</td>
<td>224</td>
<td>256</td>
<td>288</td>
<td>320</td>
<td>32</td>
<td>64</td>
<td>96</td>
<td>128</td>
<td></td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>193</td>
<td>225</td>
<td>257</td>
<td>289</td>
<td>1</td>
<td>33</td>
<td>65</td>
<td>97</td>
<td>129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>162</td>
<td>194</td>
<td>226</td>
<td>258</td>
<td>290</td>
<td>2</td>
<td>34</td>
<td>66</td>
<td>98</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>163</td>
<td>195</td>
<td>227</td>
<td>259</td>
<td>291</td>
<td>3</td>
<td>35</td>
<td>67</td>
<td>99</td>
<td>131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>164</td>
<td>196</td>
<td>228</td>
<td>260</td>
<td>292</td>
<td>4</td>
<td>36</td>
<td>68</td>
<td>100</td>
<td>132</td>
<td></td>
<td></td>
</tr>
<tr>
<td>166</td>
<td>198</td>
<td>230</td>
<td>262</td>
<td>294</td>
<td>6</td>
<td>38</td>
<td>70</td>
<td>102</td>
<td>134</td>
<td></td>
<td></td>
</tr>
<tr>
<td>167</td>
<td>199</td>
<td>231</td>
<td>263</td>
<td>295</td>
<td>7</td>
<td>39</td>
<td>71</td>
<td>103</td>
<td>135</td>
<td></td>
<td></td>
</tr>
<tr>
<td>168</td>
<td>200</td>
<td>232</td>
<td>264</td>
<td>296</td>
<td>8</td>
<td>40</td>
<td>72</td>
<td>104</td>
<td>136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>169</td>
<td>201</td>
<td>233</td>
<td>265</td>
<td>297</td>
<td>9</td>
<td>41</td>
<td>73</td>
<td>105</td>
<td>137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>202</td>
<td>234</td>
<td>266</td>
<td>298</td>
<td>10</td>
<td>42</td>
<td>74</td>
<td>106</td>
<td>138</td>
<td></td>
<td></td>
</tr>
<tr>
<td>171</td>
<td>203</td>
<td>235</td>
<td>267</td>
<td>299</td>
<td>11</td>
<td>43</td>
<td>75</td>
<td>107</td>
<td>139</td>
<td></td>
<td></td>
</tr>
<tr>
<td>172</td>
<td>204</td>
<td>236</td>
<td>268</td>
<td>300</td>
<td>12</td>
<td>44</td>
<td>76</td>
<td>108</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>173</td>
<td>205</td>
<td>237</td>
<td>269</td>
<td>301</td>
<td>13</td>
<td>45</td>
<td>77</td>
<td>109</td>
<td>141</td>
<td></td>
<td></td>
</tr>
<tr>
<td>174</td>
<td>206</td>
<td>238</td>
<td>270</td>
<td>302</td>
<td>14</td>
<td>46</td>
<td>78</td>
<td>110</td>
<td>142</td>
<td></td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>207</td>
<td>239</td>
<td>271</td>
<td>303</td>
<td>15</td>
<td>47</td>
<td>79</td>
<td>111</td>
<td>143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>176</td>
<td>208</td>
<td>240</td>
<td>272</td>
<td>304</td>
<td>16</td>
<td>48</td>
<td>80</td>
<td>112</td>
<td>144</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Input the I and the Q channel sequence to be interleaved.

For every span of the data,
- Write the data in the interleaver array (as per Table 4.1 for I channel and Table 4.2 for Q channel).
- Puncture the appropriate bits.
- Read the sequence out row wise from the arrays.

Output the I and the Q channel interleaved sequences.

Figure 4.4: Flowchart for the Interleaver
4.5 Symbol repetition

To maintain a constant data rate of 64 kbps, each symbol in the sequence at 32 kbps rate is repeated once and those in the sequence at 16 kbps rate is repeated three times. The symbols at 64 kbps need not be repeated.

**Implementation details:** The routine, *RepeatSeq.m*, repeats every bit of the input sequence ‘n’ number of times where ‘n’ can be specified. The call to the routine is made as

\[ \text{ReptSeq}_o = \text{RepeatSeq}(	ext{Seq}_i, \text{no_of_times}); \]

The input *Seq_i* is the sequence that is to be repeated *no_of_times* and *ReptSeq_o* is the output repeated sequence. The flowchart for the routine is shown in Figure 4.5. However, as data at 64 kbps is considered in the forward traffic channel simulator, symbol repetition is not employed.

4.6 Power Control Subchannel

A power control subchannel at the rate 2 kbps is continuously transmitted on the forward traffic channel. The power bit thus transmitted indicates to the mobile station whether to increase or decrease its average output power level. A ‘0’ bit indicates an increase in power is needed whereas a ‘1’ bit indicates a decrease. The value of this power control bit is determined at the base station by its reverse traffic channel receiver.

**Implementation details:** The power control subchannel is needed when the mobile system is to be implemented at the network layer. As we are simulating at the physical layer, power control is not implemented here. Instead, a sequence of logical zeros is assumed for the power channel. For the data at the rate of 64 kbps, ten logical zeros per span length of 5 ms are assumed to form the power control bits sequence.

4.7 Signaling Subchannel

The signaling channel is transmitted at the basic rates of 4 kbps and 2 kbps and can be repeated to give a higher rate. The signaling bits are used to send signaling information to the personal station and are interleaved using a signaling array before multiplexing with the data sequence and the power bits.
Input the number of times 'n' the bits in the sequence have to be repeated and the sequence that is to be repeated.

For every bit in the data sequence,
- Repeat it 'n' more times to give a total of (n + 1) bits.

Output the repeated sequence.

Figure 4.5: Flowchart for the Repeater.
Implementation details: As simulations are done at the physical layer level and not at the network level, the signaling subchannel is not implemented in the model. Instead, a sequence of logical ones at the rate of 4kbps is assumed for the signaling channel. For the data at the rate of 64 kbps, twenty logical ones per span length of 5 ms are assumed to form the signaling bits sequence.

4.8 Multiplexer

One power control bit, two signaling bits and twenty-nine information bits are multiplexed to give thirty-two bits of multiplexed data. Each span at the output of the multiplexer, hence, contains ten power control bits, twenty signaling bits and 290 information bits. The multiplexing is done as per Table 4.3 and explained below.

Table 4.3: Multiplexer table for data at 64 kbps, power bits at 2 kbps and signaling bits at 4 kbps.

<table>
<thead>
<tr>
<th>p</th>
<th>s1</th>
<th>s2</th>
<th>i1</th>
<th>i2</th>
<th>i3</th>
<th>i4</th>
<th>i5</th>
<th>i6</th>
<th>i7</th>
<th>i8</th>
<th>i9</th>
<th>i10</th>
<th>i11</th>
<th>i12</th>
<th>i13</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1</td>
<td>s14</td>
<td>i15</td>
<td>i16</td>
<td>i17</td>
<td>i18</td>
<td>i19</td>
<td>i20</td>
<td>i21</td>
<td>i22</td>
<td>i23</td>
<td>i24</td>
<td>i25</td>
<td>i26</td>
<td>i27</td>
<td>i28</td>
</tr>
<tr>
<td>p2</td>
<td>s3</td>
<td>i30</td>
<td>i31</td>
<td>i32</td>
<td>i33</td>
<td>i34</td>
<td>i35</td>
<td>i36</td>
<td>i37</td>
<td>i38</td>
<td>i39</td>
<td>i40</td>
<td>i41</td>
<td>i42</td>
<td>i43</td>
</tr>
<tr>
<td>p3</td>
<td>s6</td>
<td>i59</td>
<td>i60</td>
<td>i61</td>
<td>i62</td>
<td>i63</td>
<td>i64</td>
<td>i65</td>
<td>i66</td>
<td>i67</td>
<td>i68</td>
<td>i69</td>
<td>i70</td>
<td>i71</td>
<td>i72</td>
</tr>
<tr>
<td>p4</td>
<td>s7</td>
<td>i88</td>
<td>i89</td>
<td>i90</td>
<td>i91</td>
<td>i92</td>
<td>i93</td>
<td>i94</td>
<td>i95</td>
<td>i96</td>
<td>i97</td>
<td>i98</td>
<td>i99</td>
<td>i100</td>
<td>i101</td>
</tr>
<tr>
<td>p5</td>
<td>s9</td>
<td>i107</td>
<td>i108</td>
<td>i109</td>
<td>i110</td>
<td>i111</td>
<td>i112</td>
<td>i113</td>
<td>i114</td>
<td>i115</td>
<td>i116</td>
<td>i117</td>
<td>i118</td>
<td>i119</td>
<td>i120</td>
</tr>
<tr>
<td>p6</td>
<td>s11</td>
<td>i120</td>
<td>i121</td>
<td>i122</td>
<td>i123</td>
<td>i124</td>
<td>i125</td>
<td>i126</td>
<td>i127</td>
<td>i128</td>
<td>i129</td>
<td>i130</td>
<td>i131</td>
<td>i132</td>
<td>i133</td>
</tr>
<tr>
<td>p7</td>
<td>s13</td>
<td>i159</td>
<td>i160</td>
<td>i161</td>
<td>i162</td>
<td>i163</td>
<td>i164</td>
<td>i165</td>
<td>i166</td>
<td>i167</td>
<td>i168</td>
<td>i169</td>
<td>i170</td>
<td>i171</td>
<td>i172</td>
</tr>
<tr>
<td>p8</td>
<td>s15</td>
<td>i192</td>
<td>i193</td>
<td>i194</td>
<td>i195</td>
<td>i196</td>
<td>i197</td>
<td>i198</td>
<td>i199</td>
<td>i200</td>
<td>i201</td>
<td>i202</td>
<td>i203</td>
<td>i204</td>
<td>i205</td>
</tr>
</tbody>
</table>

i denote the information bits
p denote the power control bits
s denote the signaling bits.
Input the interleaved sequence, the power sequence and the signaling sequence.

Verify that the 10 power bits and 20 signaling bits are available every span of the interleaved data (290 bits per span).

For every span (290 bits of data)
- Arrange 10 power bits in single column.
- Arrange 20 signaling bits rowwise in two columns.
- Arrange 290 data bits rowwise in an array of 29 columns by 10 rows.
- Form the output matrix with power column as the first column followed by two signaling columns and the data array.

Read and output the bits out of the array row wise

END

Figure 4.6: Flowchart for the Multiplexer.
Implementation details: The routine, `FTCMux_64_2_4.c`, is used for multiplexing. At the input data rate of 64 kbps, the power bits are at 2 kbps rate and the signaling bits rate is 4 kbps. The call to the routine is made as

\[ \text{MuxSeq}_o = \text{FTCMux}_64_2_4(\text{DataSeq}_i, \text{PowerSeq}_i, \text{SigSeq}_i); \]

The input sequence `DataSeq_i` contains the punctured information bits, `PowerSeq_i` contains the power control bits, `SigSeq_i` contains the signaling bits and `MuxSeq_o` is the multiplexed output sequence. The same routine is used to multiplex the sequences on the I and the Q channels.

The multiplexing array has 10 rows and 32 columns. Every first bit of each row is the power control bit and the second and the third bits are the signaling bits. The rest of the columns of the rows are occupied by the information bits. The bits are multiplexed in Table 4.3 as a 20 by 32 dimension array for convenience. This does not change the output multiplexed sequence which is read out of the table row wise.

4.9 Scrambler

The long PN sequence that is used by the scrambler is generated using the generator polynomial

\[ p(x) = 1 + x^2 + x^{22} + x^{32} \]

The term 'long' is used to denote the PN sequence since it has a long period \((2^{32})\) which extends over several symbols in contrast with the short sequences which repeat every symbol. Such a design is referred to as (pseudo) random CDMA (R-CDMA). The purpose of such a design philosophy is to make multi-user interference look like additive white gaussian noise (AWGN) [29].

The PN code generator is shown in Figure 4.7. Each output bit of the generator is found by the modulo-2 addition of the contents of the 32 registers. The bit in the last register is fed back to those registers that have taps on them. The taps are placed on the registers based upon the generator polynomial \(p(x)\).

The PN code is decimated by selecting the first chip of every 64 chips of the sequence and is used for scrambling the data at 64 kbps.
Implementation details: The routine, \texttt{LCGenerator.m}, is used to generate the long code. The call to this routine is made as

\[ \texttt{LCSeq}_o = \texttt{LCGenerator}\left(\texttt{LCseed}_i, \texttt{TapSeq}_i, \texttt{oplength}_i\right) \]

This routine accepts the seed vector \texttt{LCseed}_i, the tap sequence \texttt{TapSeq}_i or generator sequence and the length of the output long code sequence \texttt{oplength}_I, that is to be generated. The output of the generator is the long code, \texttt{LCSeq}_o.

The generator sequence should be specified as a vector of bits where a ‘1’ specifies the location of the tap. For example, for the generator sequence $1 + x + x^2 + x^4$, the taps are at the first register, after the first register, after the second register and after the fourth register (which is the same as the tap at the first register). Hence the representation for the tap sequence is $[1 1 1 0 1]$. The routine converts this to $[1 1 1 0]$ as the tap at the end of the generator is the same as the one at the input of the generator. The flowchart for the algorithm is shown in Figure 4.8.

This long code is decimated to a rate of 64 kbps by selecting the first of every 64 chips and modulo-2 added with the data sequence to scramble it.
Put the tap sequence with the first and the last tap represented by the same bit '1' at the start of the sequence.

Check if the tap sequence length is same as the seed vector?

The output bit is the modulo-2 addition of all the bits in the registers of the generator.

For every state of the registers,
- Find the output bit by modulo-2 addition of the bits in all the registers.
- Shift the bits circularly to get the next state.
- If the bit in the last register was a 'one', the bit in every register that has a tap before it will be the complement of the bit in it.

Figure 4.8: Flowchart for the PN long code generator.
4.10 Orthogonal Spreading with Walsh codes

Each code channel transmitted on the forward traffic channel is spread with a Walsh code at a fixed chip rate of 4.096 Mcps to provide orthogonal channelization among all code channels on that traffic channel. Data at the rate of 64 kbps is thus spread by 64 (= 4096/64) chips per bit. A channel that is spread using Walsh code ‘n’ is assigned to code index number ‘n’. The total number of Walsh codes available is 64 for 64 kbps data, 128 for 32 kbps data and 256 for 16 kbps data.

Walsh code index 0 is always assigned to the pilot channel of the forward link. The sync channel is assigned code index 128. The paging channels are assigned code indices 1 through 7 in sequence. The remaining indices are assigned to any of the forward traffic channels. Hence, there can be at most 64 channels for 64 kbps, 128 channels for 32 kbps and 256 channels for 16 kbps. If any of the 64 Walsh code sequences is used for a 64 kbps channel, the same code cannot be used for any 32 or 16 kbps channels [1]. Similarly, if one of 128 Walsh codes is used for a 32 kbps channel, the same code cannot be simultaneously used for any 16 kbps channel.
Implementation details: The routine, `GenWalshSeq.m`, generates the Walsh sequences for the input order specified. The call to the routine is made as

```matlab
WalshSeqArray_o = GenWalshSeq(order_i);
```

The order, `order_i`, denotes the order of the Walsh sequence to be generated and is the input to the routine. The output, `WalshSeqArray_o`, is an array with each row a Walsh sequence of length $2^{order}$. For example, for order of 6, the routine generates $64 (= 2^6)$ Walsh sequences of length 64. The Walsh sequences are generated using Hadamard matrices.

`ModwWalsh.c` - This routine spreads the input bits with the Walsh sequence bits. The call to the routine is made as

```matlab
ModSeq_o = ModwWalsh(DataSeq_i, WalshSeq_i);
```

This routine modulates each bit of the input data sequence, `DataSeq_i`, with the Walsh sequence, `WalshSeq_i`, to give the modulated output sequence, `ModSeq_o`. It does that by repeating each data bit a number of times equal to the length of the Walsh sequence and then performs mod-2 addition on the two.

The flowcharts for the two algorithms are shown in Figures 4.9 and 4.10.

### 4.11 Spreading with the long code

The orthogonally spread sequences are modulo-2 added with a unique long code PN sequence for a particular personal station. A sequence of period 81920 chips is obtained on the modulo-2 addition of the long code (pilot PN sequence) and the Walsh code for that channel [1]. The pilot PN sequence for any base station has the same time offset for all the frequency assignments of that base station.

Implementation details: The long code generated by the routine, `LCGenerator.m`, is used as the pilot PN sequence.

### 4.12 Baseband Filtering

The binary pulses of data need to be mapped to a continuous waveform before transmission. Rectangular pulses are not a good choice as they require bandwidth much larger than the minimum bandwidth specified by the Nyquist theory, i.e., $W/2$ for the transmission of $W$ symbols per second without intersymbol interference (ISI). However,
Input the 'order' of the Walsh sequence to be generated.

Walsh = [0]
For 'order' number of times
- Generate the Walsh matrix = \[
\begin{bmatrix}
W_{alsh} & W_{alsh} \\
W_{alsh} & W_{alsh}
\end{bmatrix}
\]

Output the Walsh matrix with each row as one of the 2^{order} Walsh sequences.

Figure 4.9: Flowchart for the Walsh sequence generator.
Input the data sequence and the Walsh sequence to modulate it.

Convert the Walsh sequence to bipolar form.
For every bit in the data sequence,
- Repeat the bit ‘n’ number of times where ‘n’ is the length of the Walsh sequence.
- Multiply the repeated data bits with the Walsh bits.

Output the modulated sequence at the rate = data rate x length of Walsh sequence.

Figure 4.10: Flowchart for the Walsh Modulator.
attaining the Nyquist criteria is not practical as it requires the impulse response of the system to exist infinitely. The approach adopted for confining the spectrum to a required bandwidth and at the same time minimizing the ISI, is to use Nyquist Raised Cosine (RC) filters with different ‘rolloff factor’ [12]. The transfer function of the RC filter with rolloff factor $\alpha$ is given by

$$H_{RC}(f; \alpha) = \begin{cases} 
1, & |fT| \leq \frac{1}{2}(1-\alpha) \\
\cos^2\left\{\frac{\pi}{2\alpha} \left[fT - \frac{1}{2}(1-\alpha)\right]\right\}, & \frac{1}{2}(1-\alpha) < fT \leq \frac{1}{2}(1+\alpha) \\
0, & |fT| > \frac{1}{2}(1+\alpha)
\end{cases}$$

The impulse response of $T \times H(f; \alpha)$ is given as [12]

$$h_{RC}(t; \alpha) = \frac{\cos\left(\frac{\pi\alpha}{2}\frac{t}{T}\right)}{1 - \left(2\alpha\frac{t}{T}\right)^2} \sin\left(\frac{t}{T}\right)$$

The impulse response of the RC filters for different values of $\alpha$ is shown in Figure 4.11. It can be seen that sampling this waveform at $T$ time intervals gives no ISI.
The WCDMA system employs the pulse shaping filters as the baseband filters. Only the frequency response limits as shown in Figure 4.12 are stated as a requirement for the system in [1]. However, as the WCDMA system is based upon the IS-95 system, we use the same roll-off factor (= 0.22) of the RC filter as in the IS-95 system [12], [19].

The magnitude response of the RC filter is split evenly between the transmitter and the receiver so that the overall shape of the pulse is raised cosine. The receiver filter is matched to the transmitting filter to maximize the signal-to-noise ratio (SNR) at the sampling time instances at the receiver. Splitting the RC filter with the impulse response $h_{RC}(t; \alpha)$ gives the square root RC filter defined by the impulse response [30]:

$$g_{T \sqrt{RC}}(t; \alpha) = \begin{cases} 1 - \alpha + \frac{4\alpha}{\pi}, & t = 0 \\ \frac{\alpha}{\sqrt{2}} \left[ \left(1 + \frac{2}{\pi}\right) \sin \left(\frac{\pi}{4\alpha}\right) + \left(1 - \frac{2}{\pi}\right) \cos \left(\frac{\pi}{4\alpha}\right) \right], & t = \pm \frac{T}{4\alpha} \\ \sin \left(\frac{\pi}{T} \left(1 - \alpha\right) + \frac{4}{T} \cos \left(\frac{\pi}{T} \left(1 + \alpha\right) \right) \right) \left(1 - \left(4\alpha \frac{t}{T}\right)^2\right), & \text{for all other } t \end{cases}$$

The receiver lowpass filter $g_{R \sqrt{RC}}(t; \alpha)$ is matched to $g_{T \sqrt{RC}}(t; \alpha)$ and has the same impulse response. If $G_{T \sqrt{RC}}(f; \alpha)$ and $G_{R \sqrt{RC}}(f; \alpha)$ denote the frequency responses of $g_{T \sqrt{RC}}(t; \alpha)$ and $g_{R \sqrt{RC}}(t; \alpha)$ respectively then,

$$G_{T \sqrt{RC}}(f; \alpha) \times G_{R \sqrt{RC}}(f; \alpha) = T \times H_{RC}(f; \alpha)$$

**Implementation details:** Each bit in the I and the Q channel is mapped to the bipolar form using the simple operation $y = 1-2x$ where $x$ is the input (a logical zero or a logical one) and $y$ is the antipodal output (+1 or -1). The impulses corresponding to the digital data are then applied to the transmitter filter.

The IS-95 standard specifies FIR filter coefficients of length 48 and requires any filter designed for the system to be a close fit with these coefficients in terms of the mean squared error [12]. The WCDMA standard [1] does not specify the coefficients or the length of the filter required by the system. Therefore, we base the WCDMA system filter on the IS-95
52

$$20 \log_{10} |S(f)|$$

$$f_s = 2.47 \text{ MHz}$$
$$f_p = 1.96 \text{ MHz}$$
$$d1 = 1.5 \text{ dB}$$
$$d2 = 40 \text{ dB}$$

Figure 4.12: Baseband filters frequency response limits specified in [1].

specifications. As the script for implementation of the FIR filter taken from [31] designs a
symmetrical impulse response, it takes odd lengths for the filter. Hence, the transmitter filter
response $$g_T(\sqrt{RC} t; \alpha)$$ is implemented as a 49 length FIR filter for a rolloff factor $$\alpha = 0.22$$. The sampling time of the filter is taken as $$T/4$$, where $$T$$ is a bit duration, similar to that for
the IS-95 systems [12], [19]. The reader may refer to [31] for design details for the filter. The
impulse response of the square root RC FIR filter employed in the simulator is shown in
Figure 4.13. The cascaded response of the transmitter and the receiver filters is nothing but
the RC filter with zero ISI at the sampling times, i.e, at every four samples, as shown in
Figure 4.14.

In digital operation, for filtering the baseband impulses with a filter with sampling rate
four times higher, three zeros must be padded between the impulses so that the impulse
occurs at the sampling instants of the filter. This sequence is passed through the transmitting
end filter to give shaped pulses for the I and the Q channels.
4.13 Quadrature Phase Shift Keying

The I channel and the Q channel filtered waveforms are then modulated by cosine and sine functions of a high frequency carrier wave to yield two orthogonal binary phase shift keyed waveforms (BPSK). The two BPSK waveforms of the I and the Q channels are added to give the final QPSK waveform of the forward traffic channel [1], [12], [20].

**Implementation details:** As the implementation is inherently digital, modulation with an analog high-frequency carrier wave requires oversampling of the I and Q channel waveforms at a very high rate. The resultant large-sized vectors cause memory issues while implementation. Hence, the step of placing the baseband I and Q channel waveforms on the carriers is omitted in the simulation.

![Normalized FIR filter response for the square root RC filter with $\alpha = 0.22$.](image)

Figure 4.13: Normalized FIR filter response for the square root RC filter with $\alpha = 0.22$. 
Figure 4.14: Normalized FIR filter response of the cascade of the transmitter and the receiver filters with $\alpha = 0.22$. 
4.14 FTC receiver structure

*FTC_receive.m:* This script contains calls to the different functional blocks in the FTC receiver. The parameters required by them are also set here. The receiver structure is shown in Figure 4.15 and the flowchart for the script is shown in Figure 4.16.

**Implementation details:** The different blocks in the receiver are designed for the transmitter at the data rate of 64 kbps and the frame length of 5ms i.e., 320 bits. Each block is implemented by a different functional routine.

A single user receiver is employed in the forward link of any mobile system. In practical CDMA systems, the air channel is considered fading and a RAKE receiver is employed to collect and combine the energy of the received signal along resolvable multipath components. Specifically, the IS-95 system uses a RAKE receiver with three fingers [12].

For the reverse link, when multi-user receiver is employed, sub optimum techniques of detection replace the optimum owing to the complexity issues involved in their practical implementation. Here, we focus on the forward link only. For a good overview of multi-user detectors, the reader can refer to [28].

The basic demodulator structure implemented here consists of a square root RC filter matched to the filter at the transmitting end. The other sub blocks in the receiver, basically, function the exact reverse way than in the transmitter. Each of them are discussed in the following sections.

4.15 Coherent detection

At the personal station receiver, the QPSK signal is first coherently multiplied with the I and the Q channel carriers. The phase reference of the carrier is already known at the receiver by means of the pilot signal; hence coherent demodulation is possible in the forward link channel receiver. The I and the Q channel waveforms thus obtained are then separately demodulated. As the transmitted signal for the simulations is baseband, we do not need to implement this step.
Denotes spreading of every bit with 64 chips

Denotes XOR (modulo-2 addition)

Figure 4.15: Forward traffic channel receiver structure.
Generate the long PN code sequence.

\textit{LC}\texttt{generator.m}  
(Section 4.9)

Convert the PN sequence to bipolar form (1,-1).

(Section 4.18)

Convert the digital data (0,1) to bipolar form (1,-1)

(Section 4.19)

Despread the channels using the PN sequence.

(Section 4.18)

Low pass filter the I and the Q channel data using square root raised cosine filter.

(Section 4.16)

Sample the output of the channels at the filter sampling rate.

(Section 4.17)

Demodulate the channels with the Walsh sequence.

(Section 4.19)

Figure 4.16: Flowchart for the FTC receiver.
Generate the long PN code sequence.

(Section 4.9)

Decimate the long PN code sequence to 64 kbps.

(Section 4.9)

Convert the digital data (0,1) to bipolar form (1,-1)

Decimate sequences to get the unspread I and Q channel sequences.

(Section 4.19)

Descramble the I and the Q channel sequences

(Section 4.20)

Demultiplex the channel data to get the information, power and signaling bits.

FTCDemux_64_2_4.c

(Section 4.20)

Figure 4.16: Flowchart for the FTC receiver (contd.)
Deinterleave the sequences on I and Q channels.

\textit{DeIntSeq\_5\_64\_I.c}
\textit{DeIntSeq\_5\_64\_Q.c}
(Section 4.21)

Decode the I and Q sequences using the hard decision or soft decision Viterbi decoder to give the received sequence of data bits.

\textit{HardDecVD\_K9.c}
(Section 4.22)

END

Figure 4.16: Flowchart for the FTC receiver (contd.)

4.16 Low pass filtering

The low pass filter used is the square root RC filter matched to the one at the transmitting end. This serves as the optimum demodulator in additive white gaussian noise (AWGN) channels in terms of maximizing the output signal-to-noise ratio (SNR) [32]. The cascade of the transmitter and the receiver filters serves as an RC filter.

\textbf{Implementation details:} The filter with response $g_R^{\sqrt{RC}}(t; \alpha)$ is employed at the receiving end. The frequency response of the filter can be seen from Figure 4.17. As seen, it meets the specifications for the filter of Figure 4.11. The filter sampling rate is the same as that at the transmitting section ($= 4$). The conv routine of MATLAB is used to filter the data.
4.17 Sampling the filtered output

The filtered data is sampled every four samples to give the data samples. The cascaded response of the transmitter filter and the receiver filter introduces a delay of 12 chip intervals (= 12x4 = 48 sampling intervals) as can be seen from Figure 4.14. Hence the thirteenth sample at the output of the sampler actually corresponds to the first chip. The filtered samples are normalized by the energy content of the RC pulse resulting from the cascade of the two square root RC filters.

4.18 Decorrelation with the pilot PN sequence

The I and Q channel symbols obtained after filtering are decorrelated with the pilot PN sequence which has a phase shift unique for a particular base station. The synchronization of
the PN sequence is very essential to make use of its correlation properties. Initial acquisition and phase tracking of the PN sequence phase offset is done using the sync signal. Hence, it is appropriate to assume that the phase shift is known at the personal station.

**Implementation details:** The same routine, *LCgenerator.m*, for PN sequence generation, as described in Section 4.9, is used at the receiver for a PN sequence synchronized with the transmitter. The sync channel module that acquires and tracks the phase of the PN code is not implemented in this thesis.

### 4.19 Demodulation using Walsh sequence

The orthogonal Walsh sequence index used for a particular channel is communicated to the personal station using the paging channel. Modulo-2 addition of the input sequence with this Walsh sequence at the receiver and integrating over the bit interval (64 chips) yields the unmodulated sequence.

**Implementation details:** As the Walsh sequence index used for modulating the symbols at the transmitter end is known at the receiver, the same routines for generation of the Walsh sequence viz., *GenWalsh.m*, as described in Section 4.10, is used. The demodulation of the sequence is done using *ModwWalsh_antip.c* (which is similar to *ModwWalsh.c* described in Section 4.10, except that it deals with data in the antipodal form) followed by averaging over the length of the Walsh sequence, i.e., 64 chips.

### 4.20 Descrambling and Demultiplexing

A decimated version of the long code sequence at 64 kbps, as described in Section 4.9, is used for descrambling the symbol sequence. Following this, the symbols are demultiplexed to give the power and the signaling bits.

**Implementation details:** Descrambling is achieved by modulo-2 addition of the sequence with the decimated long code sequence.

*FTCDemux_64_2_4.c* – This routine performs demultiplexing of the sequence by reversing the multiplexing operation at the receiver. The call to the routine is made as

\[
[\text{DataSeq}_o \ \text{PowerSeq}_o \ \text{SigSeq}_o] = \text{FTCDemux}_64_2_4(\text{MuxSeq}_i);
\]
The sequence, $\textbf{MuxSeq}_o$, with information, power and signaling bits multiplexed together forms the input to the routine and the output are the information sequence, $\textbf{DataSeq}_o$, the power control bits sequence, $\textbf{PowerSeq}_o$, and the signaling bits sequence, $\textbf{SigSeq}_o$.

The power bits thus obtained can be used to provide power control for the mobile station. At the transmitting end, the puncturing of the bits resulted in deletion of 30 bits every span. On demultiplexing the sequence, 290 data bits values are obtained in every span of 5ms length for the data at 64 kbps rate.

### 4.21 Deinterleaver

One span of the data of length 5 ms and consisting of 290 bits is considered at a time. Deinterleaving is performed on the data symbols by writing the data row wise into an array of size ten columns by twenty-nine rows. To make up for the bits that were dropped at the transmitting end, a value 1 is inserted in those positions. In digital form, this is equivalent to the logical zeros. The read operation from the arrays is done columnwise. This results in deinterleaving of the interleaved data.

**Implementation details:** Two different routines, $\textbf{DeIntlSeq} \_5 \_64 \_I \_c$, $\textbf{DeIntlSeq} \_5 \_64 \_Q \_c$, are considered for the I and the Q channels as the deinterleaver arrays for both are different. The calls to the routines are made as

\[
\begin{align*}
\textbf{DeIntlSeq1}_o &= \textbf{DeIntlSeq} \_5 \_64 \_I(\textbf{Seq1}_i); \\
\textbf{DeIntlSeq2}_o &= \textbf{DeIntlSeq} \_5 \_64 \_I(\textbf{Seq2}_i); \\
\end{align*}
\]

The descrambled sequences on the I and Q channels, $\textbf{Seq1}_i$ and $\textbf{Seq2}_i$, form the input to the deinterleavers for the two channels respectively. The output sequences, $\textbf{DeIntlSeq1}_o$ and $\textbf{DeIntlSeq2}_o$, are the deinterleaved sequences for the two channels. After arranging the symbols row wise in an array of size 10 columns by 29 rows in the deinterleaver array of the I channel, a row of value 1 is inserted at the eleventh, sixteenth, and thirtysecond row positions. These are the rows that were deleted at the transmitting end (Refer to Table 4.1).

After arranging the symbols row wise in an array of size 10 columns by 29 rows in the deinterleaver array of the Q channel, a row of value 1 is inserted at the fifth, tenth, and twenty-first row positions. These are the rows that were deleted at the transmitting end (Refer to Table 4.2).
4.22 Viterbi decoding

The Viterbi decoding algorithm is used to detect the symbols in the I and the Q channel. It is the optimum decoding algorithm in the sense of maximum likelihood decoding of the entire sequence for convolutional codes [32]. Hard decision Viterbi decoding uses Hamming distance between the received sequence and the trellis path as a metric to detect the sequence.

Implementation details: The routine, HardDecVD_K9.c, has been adapted from the soft decision Viterbi decoder in [26] and implements a hard decision decoder for a ½ rate Convolutional encoder of length 9. For a good description of the Viterbi decoding algorithm in general and its implementation in particular, the reader may refer to the tutorial in [26] and the reference [32]. The call to the routine is made as

\[ \text{DecSeq} = \text{HardDecVD}\_K9(\text{ChanEncSeq}); \]

The input sequence \( \text{ChanEncSeq} \) to the decoder consists of alternate encoded bits of the I and the Q channel encoded sequences and the output sequence \( \text{DecSeq} \) is the decoded sequence.

In practical implementations of the algorithm, the depth of the trellis is usually limited. The loss of performance resulting from the sub optimum detection procedure is negligible if the depth of the trellis is at least \( K \times 5 \) where \( K \) is the length of the Convolutional encoder (= 9 here). We use \( K \times 5 \) depth for the decoding algorithm employed in the simulator. Particularly noteworthy is the time of execution of the algorithm, which takes a few seconds as compared to the m-routine in MATLAB that runs to days.

This chapter provided the routines and highlighted the implementation aspects of the different blocks in the forward traffic channel of the forward link. The results of the simulation tests performed using the transmitter and the receiver model described here are discussed in the next chapter.
CHAPTER 5 SIMULATOR TESTS AND RESULTS

Each component of the transmitter and the receiver section of the simulator was tested and validated with known sequences of data. For verification, the results were crosschecked with those computed manually and in some cases the references [12], [20] were used. Having validated the robustness of each block, simulations were then carried out for verification of the overall operation of the complete simulator under different scenarios. These test cases performed are based on these scenarios typical of any mobile environment. Specifically, tests were carried in the presence of AWGN and fading channel conditions. The properties of the PN sequence were verified. The performance of the system in the presence of interfering signal from another base station was also evaluated. A discussion of these test cases and results obtained is given in this section.

5.1 Summary of parameters set for the simulations

- The baseband I and Q channels sequences are only considered. The carrier modulation is not done (Refer to Section 4.15 for details).
- 5 spans of data at the rate of 64 kbps (corresponding to 320x5 = 1600 data bits) is considered. This translates to 1600x64 = 102400 chips after spreading. Larger amount of data can also be considered at the expense of longer testing times.
- Whenever convolutional encoding is performed the data length is taken eight bits less than the length needed to account for the flushing of the encoder at the end of its operation (Refer to Section 4.3 for details).
- The long code generation seed is set to [1 0 0 1 0 0 1 1 0 0 1 0 1 0 0 1 1 0 1 0 1 1 1 1 0 0 1 1 1 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 1 1 1 0 0 0 1 1] and the tap sequence is set to [1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1] (Refer to Section 4.9 for details).
- Arbitrarily, the eighteenth Walsh code sequence is chosen for the user under test.
The FIR transmitter filter length is chosen to be 49 with the sampling rate 4 times higher than the data rate (Refer to Section 4.12 for details).

For computing the BER, the simulation is run 10 times to find the ensemble average. Higher number of runs result in a smoother performance curve but were not used owing to the longer time of execution for the tests.

5.2 Overall operation of the simulator in the absence of noise

To investigate if the puncturing of data bits in the transmitter to accommodate the signaling and the power bits causes any errors, this test case was carried out in the absence of noise. The BER is found to be 0. Thus the multiplexing of the power and the signaling bits with the information bits has no effect on its BER. This verifies the data handling procedure of the WCDMA system.

5.3 PN sequence synchronization issues

The period of the long code PN sequence used in the WCDMA system is $2^{32}$. For data length of 5 spans, a shorter ($320 \times 5 \times 64 = 102400$ chips) PN sequence is used. To verify its auto correlation properties, the sequence was correlated with its shifted versions. As can be seen from Figure 5.1, the PN sequence’s auto correlation values with phase shifts other than zero are near zero. Figure 5.1 is redrawn in Figure 5.2 with a zoom and it can be clearly seen that the autocorrelation value with zero phase shift of the PN sequence equals 1. This property of the PN sequence is used by the personal station to synchronize with the base station in its cell.

Simulations were carried out with the personal station’s PN sequence unsynchronized with respect to the base station’s PN sequence by 1-100 chips in the absence of noise. The BER of the detected sequence is shown in Figure 5.3. It can be seen that the BER, even in the absence of noise, remains around 0.5 irrespective of the number of chips by which the personal station’s PN sequence is unsynchronized.
Figure 5.1: Auto correlation function for the PN sequence used in the WCDMA system.

Figure 5.2: Autocorrelation value of the PN sequence for zero phase shift.
Figure 5.3: Performance of the receiver when its PN sequence is unsynchronized with the base station’s PN sequence in the absence of noise.

The results obtained when the personal station’s PN sequence is unsynchronized by 20 chips in the presence of AWGN is shown in Figure 5.4 for various values of the SNR. The BER of the detected sequence remains almost constant at 0.5 even with SNR as high as 12 dB.

These results show how critical the synchronization of the PN sequence at the receiver is to keep the BER low. It also illustrates the security the system provides, as without the knowledge of the exact phase shift of the PN sequence it is impossible to detect the information sequence.

5.4 Performance in AWGN channel

The design of the IS-95 system is such that it is inherently robust to interference. The AWGN assumption for multiple user interference is made valid by the use of long sequences [29]. The WCDMA system is similar to the IS-95 system and hence based upon the above assumption, multiple user interference can be modeled as AWGN. Our attempt is to test the design advantages of the system in AWGN channel. AWGN noise is generated using a
Figure 5.4: Performance of the receiver when its PN sequence is unsynchronized with the base station's PN sequence in the presence of AWGN.

Rayleigh random variable which can be easily generated from a uniform random variable. The reader may refer to [32] for more details.

The simulator when employed without encoding and interleaving is equivalent to an antipodal signaling system. If $E_b$ is the energy per bit and $N_0$ is the power spectral density of noise, then the probability of error for an antipodal signaling system is given by,

$$P_{\text{antip}} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right),$$

and that for orthogonal signaling system is given by

$$P_{\text{orthog}} = Q\left(\sqrt{\frac{E_b}{N_0}}\right),$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{t^2}{2}} dt$ and

$$\frac{E_b}{N_0} = \text{Energy per bit to noise power spectral density ratio (i.e., SNR per bit).}$$
In the carrier frequency modulated domain, \( P_{\text{antip}} \) corresponds to \( P_{\text{BPSK}} \), the probability of error in BPSK system and \( P_{\text{orthog}} \) corresponds to \( P_{\text{QPSK}} \), the probability of error in QPSK system. The plots in Figure 5.5 show the curves obtained by these equations and simulated using the simulator.

As can be seen without encoding and interleaving, the simulator functions as a BPSK system. When convolutional encoding is done, performance of the receiver improves, i.e., the SNR per bit (defined as \( E_b / N_0 \)) required to achieve a certain BER is reduced.

![Figure 5.5: Performance comparisons in AWGN channel.](image)

**5.5 Performance in the presence of multiple users**

The base station assigns orthogonal Walsh codes to distinguish between its different forward traffic channels for the personal stations in its cell. Therefore, owing to orthogonality, interference due to multiple users in the same cell is not an issue on the
forward link. This scenario will be an apt test case for the performance of the receiver of the base station on the reverse link when asynchronous users transmit.

A more appropriate situation for the forward link is when the mobile station receives interference from another base station and will be discussed in the next test case.

5.6 Performance in the presence of interfering signal from another BS

The personal station has the ability to distinguish between its own signal and an interfering signal from another base station due to the PN sequence synchronization with the base station in its cell. Here we look at the performance when the interfering signal has comparable power, which can be a situation when the personal station is on the boundary of the cell. The long code of the interfering base station is shifted with respect to the long code of the base station of interest by 256 chips. The interfering signal is assumed to be of the user assigned eighteenth Walsh code in the interfering base station’s cell. That is, we look at a single interfering signal. The performance of the receiver of the personal station is shown in Figure 5.6. The plot shows the performance of the receiver when the ratio of the energies per bit of the intended signal to the interfering signal \( \frac{E_b}{E_{int\,erf}} \) is varied from -25 to 0 dB. It is seen that the BER is 0 when the ratio of the energies per bit of the intended and the interfering signal is greater than -12 dB, that is, when the intended signal energy per bit is at least 0.06 times more than the bit energy of the interfering signal. This can be explained by the fact that the correlation between the PN sequence at the receiver of the personal station is unsynchronized with respect to the PN sequence of the interfering signal and hence it is rejected when its energy is not comparable. In the absence of noise, therefore, the bit error rate at the receiver is 0. For \( \frac{E_b}{E_{int\,erf}} \) less than -12 dB, the intended signal becomes negligible and the situation is equivalent to receiving only the interfering signal and hence the BER increases.
In the presence of AWGN, the performance of the receiver for different values of SNR per bit \((E_b/N_0)\) of the intended signal is shown in Figure 5.7. The plots show curves with \((E_b/E_{\text{interf}})\) varied from -5 to 5 dB. Comparing this with Figure 5.6 we note that the BER increases in the presence of AWGN. This can be explained by the fact that, in the presence of AWGN, the receiver cannot completely reject the interfering signal unless \((E_b/N_0)\) of the intended signal is at least 3-4 dB.

It is useful to compare this graph with Figure 5.5 that shows the performance of the system in the absence of any interfering signal in the AWGN channel. From these graphs we can see that the BER of the receiver is slightly above that in the absence of interfering signal in AWGN channel when \((E_b/E_{\text{interf}})\) is less than 0 dB.
Figure 5.7: Performance of the receiver in AWGN channel in the presence of an interfering signal from another BS.

5.7 Performance in Rayleigh fading channel

The convolutional encoding and 64-ary Walsh coding in the system together provide block coding that is robust to fading channels [29]. Our attempt here is to verify this and also check the performance of the system in fading channels. We are going to assume a flat fading channel and because the forward and the reverse links of the WCDMA system are coherent communication systems, the random phase of the faded signal can be exactly tracked. Hence the model we choose is that of a Rayleigh fading air channel that attenuates the transmitted signal by a factor that is Rayleigh distributed. That is, the transmitted QPSK signal consisting of independent BPSK modulations can be represented as
\[ ftc_{\text{sig}}(t) = RI(t) + RQ(t) + N(t) \]

where,

\[ R = \text{Rayleigh random variable with probability density function (pdf) given by} \]
\[ p_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0 \text{ and } E\{R^2\} = 2\sigma^2 \]

\[ I(t) = \text{The inphase signal component of the transmitted signal} \]
\[ Q(t) = \text{The quadrature signal component of the transmitted signal} \]
\[ N(t) = \text{White gaussian noise.} \]

The probability of error of the BPSK system under conditions of Rayleigh fading is given by [12], [13],
\[ P_{\text{fading}} = \frac{1}{2} \left( 1 - \sqrt{\frac{E\{E_s\}}{N_0}} \right), \]
where \( E\{E_s\} = E\{R^2\} E_b = 2\sigma^2 E_b \).

The plots for the performance of the system under Rayleigh fading conditions with different values of \( E\{R^2\} \) (which represents a measure of the attenuation caused by the channel) are considered in Figure 5.8 through Figure 5.12. The theoretical curves under fading channel conditions in the presence of AWGN, are found using the expression for \( P_{\text{fading}} \) for a BPSK system. The theoretical and simulator curves under non-fading conditions in an AWGN channel are reproduced from Figure 5.5 for easy comparison.

As can be seen from the plots, the BER increases when \( E\{R^2\} \) decreases in an AWGN channel. The performance of the system worsens under extreme conditions of fading ( \( E\{R^2\} \leq 0.6 \)).
Figure 5.8: Performance of the receiver in Rayleigh fading channel with $E\{R^2\} = 1$ in the presence of AWGN.

Figure 5.9: Performance of the receiver in Rayleigh fading channel with $E\{R^2\} = 0.8$ in the presence of AWGN.
Figure 5.10: Performance of the receiver in Rayleigh fading channel with $E\{R^2\} = 0.6$ in the presence of AWGN.

Figure 5.11: Performance of the receiver in Rayleigh fading channel with $E\{R^2\} = 0.4$ in the presence of AWGN.
Figure 5.12: Performance of the receiver in Rayleigh fading channel with $E\{R^2\} = 0.2$ in the presence of AWGN.

The WCDMA receiver performs better than the BPSK system under fading conditions above a certain value of SNR per bit ($E_b/N_0$) for each value of $E\{R^2\}$. The crossover point between the theoretical curve and the simulator curve under fading conditions gives the value of this threshold. Hence, the error correction techniques, like encoding and interleaving, at the transmitting end prove to be an advantage when the personal station is operating above the threshold for the SNR per bit.
CHAPTER 6 CONCLUSIONS

6.1 Summary

The endeavor in this thesis has been to develop a simulator for the transmitter and the receiver of the forward traffic channel of the WCDMA system and also provide a general utility toolbox containing different components that can be used for simulation of mobile communication systems. Efforts have been directed to keep the routines for the various components simple and flexible and yet efficient in terms of their execution time. The literature review of the mobile communication air access techniques of the different generations provided a good start. It also gave a chance to learn and be able to compare the proposals for the third generation mobile systems. Motivation for this research mainly came from the lack of availability of a flexible simulator model with independent modules of the transmitter and the receiver sections that can be used while modeling the air channel of the system. A successful attempt was made in the form of this thesis to provide a stimulator that can be used for study and testing of the mobile communication system air interface.

6.2 Applications of the simulator

- Since the simulator is developed for a 3G WCDMA system based on the IS-95 system, it is easily extensible to other 3G cellular systems compatible with the IS-95 system such as cdma2000.
- The simulator developed here provides the basic structure for the forward traffic channel of the WCDMA system. Its component routines provide a general utility pool that can be used to simulate the reverse link and the other channels of the system as well.
Optimum ways of demodulation and detection for certain air channel conditions are too complex to implement in the receiver of the personal station. Generally, sub optimum techniques are used. In order that this does not compromise on the performance, various preprocessing techniques like encoding, interleaving etc. are employed at the transmitter end of the WCDMA system. Inherently, the system is made robust to different channel conditions. The choice between many sub optimum techniques can be made by testing each with the simulator.

6.3 Recommendations for future work

Some suggestions for making this work fuller are:

- The receiver front end has been implemented as a matched filter here. RAKE structure implementation as in IS-95 systems can be added so as to be able to test the performance under multipath channel conditions. The performance of the system with other air channel models can also be evaluated to be able to judge its robustness in different environments.

- Certain components that were not implemented in this thesis like the power control channel and the signaling channel can be built that can be used to analyze the power requirements for the personal stations in a multi-user environment.

- The reverse link from the personal station to the base station can be implemented using the components in the simulator and the various multi-user receivers can then be employed at the receiving end and the performance of the system in a more practical environment, like multiple users operating in asynchronous mode, can be considered.

- The simulator built here is at the physical level. For performance evaluation of the network as a whole, WCDMA simulators at the link and the system level can be developed.

- At a higher level, a downscaled version of the mobile network can be simulated and other aspects of mobile communications can be explored.
BIBLIOGRAPHY


