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Performance characteristics of the IS-95 standard for CDMA spread spectrum mobile communication systems

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Dedicated To

My Father

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Access Channel: A Reverse CDMA Channel used by mobile stations for communicating to the base station. The Access Channel is used for short signaling message exchanges such as call originations, responses to pages, and registrations. The Access Channel is a slotted random access channel.

Active Set: The set of pilots associated with the CDMA Channels containing Forward Traffic Channels assigned to a particular mobile station.

Analog Voice Channel: An analog channel on which a voice conversation occurs and on which brief digital messages may be sent from a base station to a mobile station or from a mobile station to a base station.

AWGN: Additive White Gaussian Noise.

Base Station: A station in the Domestic Public Cellular Radio Telecommunications Service, other than a mobile station, used for communicating with mobile stations. Depending upon the context, the term base station may refer to a cell, a sector within a cell, an MSC, or other part of the cellular system.

BERSIM: Bit Error Rate Simulator.

bps: Bits per second.

CDMA: See Code Division Multiple Access.

CDMA Channel: The set of channels transmitted between the base station and the mobile stations within a given CDMA frequency assignment. See also Forward CDMA Channel and Reverse CDMA Channel.

CDMA Channel Number: An 11-bit number corresponding to the center of the CDMA frequency assignment.

CDMA Frequency Assignment: A 1.23 MHz segment of spectrum centered on one of the 30 kHz channels of the existing analog system.

Cellular Communication System: As defined by the Federal Communication Commission (FCC): A high capacity land mobile system in which assigned spectrum is divided into discrete channels which are assigned in groups to geographic cells covering a cellular geographic service area. The discrete channels are capable of being reused in different cells within the service area.

Code Channel: A subchannel of a Forward CDMA Channel. A Forward CDMA Channel contains 64 code channels. Code channel zero is assigned to the Pilot Channel. Code channels 1 through 7 may be assigned to the either Paging Channels or the Traffic Channel. Code channel 32 may be assigned to either a Sync Channel or a Traffic Channel. The remaining code channels may be assigned to Traffic Channels.

Code Symbol: The output of an error-correcting encoder. Information bits are input to the encoder and code symbols are output from the encoder. See Convolutional Code.

Convolutional Code: A type of error-correcting code. A code symbol can be considered as the convolution of the input data sequence with the impulse response of a generator function.

CRC: See Cyclic Redundancy Code.

Cyclic Redundancy Code (CRC): A class of linear error detecting codes which generate parity check bits by finding the remainder of a polynomial division.

Data Burst Randomizer: The function that determines which power control groups within a frame are transmitted on the Reverse Traffic Channel when the data rate is lower than 9600 bps. The data burst randomizer determines, for each mobile station, the pseudorandom position of the transmitted power control groups in the frame while guaranteeing that every modulation symbol is transmitted exactly once.

Direct Sequence Spread Spectrum: See Spread Spectrum Signals.

dBc: The ratio (in dB) of the sideband power of a signal, measured in a given bandwidth at a given frequency offset from the center frequency of the same signal, to the total inband power of the signal. For CDMA, the total inband power of the signal is measured in a 1.23 MHz bandwidth around the center frequency of the CDMA signal.

dBm: A measure of power expressed in terms of its ratio (in dB) to one milliwatt.

dBm/Hz: A measure of power spectral density. dBm/Hz is the power in one Hertz of bandwidth, where power is expressed in units of dBm.

dBW: A measure of power expressed in terms of its ratio (in dB) to one Watt.

Deinterleaving: The process of unpermuting the symbols that were permuted by the interleaver. Deinterleaving is performed on received symbols prior to decoding.

DSSS: See Spread Spectrum Signals.

E_b: The energy of an information bit.

Effective Radiated Power (ERP): The transmitted power multiplied by the antenna gain referenced to a half-wave dipole.

Electronic Serial Number (ESN): A 32-bit number assigned by the mobile station manufacturer, uniquely identifying the mobile station equipment.

Encoder Tail Bits: A fixed sequence of bits added to the end of a block of data to reset the convolutional encoder to a known state.

ERP: See Effective Radiated Power.

ESN: See Electronic Serial Number.

FHSS: See Spread Spectrum Signals.

Forward CDMA Channel: A CDMA Channel from a base station to mobile stations. The Forward CDMA Channel contains one or more code channels that are transmitted on a CDMA frequency assignment using a particular pilot PN offset. The code channels are associated with the Pilot Channel, Sync Channel, Paging Channels, and Traffic Channels. The Forward CDMA Channel always carries a Pilot Channel and may carry up to one Sync Channel, up to seven Paging Channels, and up to 63 Traffic Channels, as long as the total number of channels, including the Pilot Channels, is no greater than 64.

Forward Traffic Channel: A code channel used to transport user and signaling traffic from the base station to the mobile station.

Frame: A basic timing interval in the system. For the Access Channel, Paging Channel, and Traffic Channel, a frame is 20 ms long. For the Sync Channel, a frame is 26.666... ms long.

Frame Category: A classification of a received Traffic Channel frame based upon transmission data rate, the frame contents (primary traffic, secondary traffic, or signaling traffic), and whether there are detected errors in the frame.

Frame Offset: A time skewing of Traffic Channel frames from System Time in integer multiples of 1.25 ms. The maximum frame offset is 18.75 ms.

Frequency Hopped Spread Spectrum: See Spread Spectrum Signals.

Global Positioning System (GPS): A US government satellite system that provides location and time information to users. See Navstar GPS Space Segment / Navigation User Interfaces ICD-GPS-200 for specifications.

GPS: See Global Positioning System.

Handoff: The act of transferring communication with a mobile station from one base station to another.

Hard Handoff: A handoff characterized by a temporary disconnection of the Traffic Channel. Hard Handoffs occur when the mobile station is transferred between disjoint Active Sets, the CDMA frequency assignment changes, the frame offset changes, or the mobile station is directed from a CDMA Traffic Channel to an analog voice channel. See also Soft Handoff.

IS-95: Interim Standard - 95, endorsed by the telecommunications Industry Association (TIA) as the "Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System.

Idle Handoff: The act of transferring reception of the Paging Channel from one base station to another, when the mobile station is in the Mobile Station Idle State.

Interleaving: The process of permuting a sequence of symbols.

kHz: Kilohertz (10^3 Hertz).

ksps: Kilo-symbols per second (10^3 symbols per second).

Layering: A method of organization for communication protocols. A layer is defined in terms of its communication protocol to a peer layer in another entity and the services it offers to the next higher layer in its own entity.

Layer 1: See Physical Layer.

Layer 2: Layer 2 provides for the correct transmission and reception of signaling messages, including partial duplicate detection. See also layering and Layer 3.

Layer 3: Layer 3 provides the control of the cellular telephone system. Signaling messages originate and terminate at layer 3. See also Layering and Layer 2.

Long Code: A PN sequence with period 2^{42} -1 that is used for scrambling on the Forward CDMA Channel and spreading on the Reverse CDMA Channel. The long code uniquely identifies a mobile station on both the Reverse Traffic Channel and the Forward Traffic Channel. The long code provides limited privacy. The long code also separates multiple Access Channels on the same CDMA channel. See also Public Long Code Mask, and Private Long Code.

Long Code Mask: A 42-bit binary number that creates the unique identity of the long code. See also Public Long Code and Private Long Code Mask.

LSB: Least significant bit.

Maximal Length Sequence (m-sequence): A binary sequence of period $2^n - 1, n$ a positive integer, with no internal periodicities. A maximal length sequence can be generated by a tapped n-bit shift register with linear feedback.

Mcps: Megachips per second (10^6 chips per second).

Message: A data structure that conveys control information or application information. A message consists of a length field (MSGLENGTH), a message body (the part conveying the information), and a CRC.

MHz: Megahertz (10^6 Hertz).

MIN: See Mobile Station Identification Number.

Mobile Station: A station in the Domestic Public Cellular Radio Telecommunications Service intended to be used while in motion or during halts at unspecified points. Mobile stations include portable units (e.g., hand-held personal units) and units installed in vehicles.

Mobile Station Identification Number (MIN): The 34-bit number that is a digital representation of the 10-digit directory telephone number assigned to a mobile station.

Mobile Switching Center (MSC): A configuration of equipment that provides cellular radiotelephone service. Also called the Mobile Telephone Switching Office (MTSO).

Modulation Symbol: The output of the data modulator before spreading. On the Reverse Traffic Channel, 64-ary orthogonal modulation is used and six code symbols are associated with one modulation symbol. On the Forward Traffic Channel, each code symbol (when the data rate is 9600 bps) or each repeated code symbol (when that data rate is less than 9600 bps) is one modulation symbol.

ms: Millisecond.

Multiplex Option: The ability of the multiplex sublayer and lower layers to be tailored to provide special capabilities. A multiplex option defines such characteristics as the frame format and the rate decision rules. See also Multiplex Sublayer.

Multiplex Sublayer: One of the conceptual layers of the system that multiplexes and demultiplexes primary traffic, secondary traffic, and signalling traffic.

ns: Nanosecond.

Null Traffic Channel Data: One or more frames of 16 ‘1’s followed by eight ‘0’s sent at the 1200 bps rate. Null Traffic Channel data is sent when no service option is active and no signaling message is being sent. Null Traffic Channel data serves to maintain the connectivity between the mobile station and the base station.

Paging: The act of seeking a mobile station when a call has been placed to that mobile station.

Paging Channel (Analog): See Analog Paging Channel.

Paging Channel (CDMA): A code channel in a Forward CDMA Channel used for transmission of control information and pages from a base station to a mobile station.

Physical Layer: The part of the communication protocol between the mobile station and the base station that is responsible for the transmission and reception of data. The physical layer in the transmitting station is presented a frame by the multiplex sublayer and transforms it into an over-the-air waveform. The physical layer in the receiving station transforms the waveform back into a frame and presents it to the multiplex sublayer above it.

Pilot Channel: An unmodulated, direct-sequence spread spectrum signal transmitted continuously by each CDMA base station. The Pilot Channel allows a mobile station to acquire the timing of the Forward CDMA Channel, provides a phase reference for coherent demodulation, and provides a means for signal strength comparisons between base stations for determining when to handoff.

Pilot PN Sequence: A pair of modified maximal length PN sequences with period 2^{15} used to spread the Forward CDMA Channel and the Reverse CDMA Channel. Different base stations are identified by different pilot PN sequence offsets.

Pilot PN Sequence Offset Index: The PN offset in units of 64 PN chips of a pilot, relative to the zero offset pilot PN sequence.

Pilot Strength: The ratio of receive pilot energy to overall received energy. See also E_c/I_0.

PN Chip: One bit in the PN sequence.

PN Sequence: Pseudonoise sequence. A periodic binary sequence.

Power Control Bit: A bit sent in every 1.25 ms interval on the Forward Traffic Channel to signal the mobile station to increase or decrease its transmit power.

Power Control Group: A 1.25 ms interval on the Forward Traffic Channel and the Reverse Traffic Channel. See also Power Control Bit.

PPM: Parts per million.

Primary CDMA Channel: A CDMA Channel at a preassigned frequency assignment used by the mobile station for initial acquisition. see also Secondary CDMA Channel.

Primary Paging Channel (CDMA): The default code channel (code channel 1) assigned for paging on a CDMA Channel.

Primary Traffic: The main traffic stream carried between the mobile station and the base station, supporting the active primary service option, on the Traffic Channel. See also Secondary Traffic, Signaling Traffic, and Service Option.

Private Long Code: The long code characterized by the private long code mask. See also Long Code.

Private Long Code Mask: The long code mask used to form the private long code. See also Public Long Code Mask and Long Code.

Public Long Code: The long code characterized by the public long code mask.

Public Long Code Mask: The long code mask used to form the public long code. The mask contains the ESN of the mobile station. See also Private Long Code

Mask and Long code.

Reverse CDMA Channel: The CDMA Channel from the mobile station to the base station. From the base station's perspective, the Reverse CDMA Channel is the sum of all mobile station transmissions on a CDMA frequency assignment.

Reverse Traffic Channel: A Reverse CDMA Channel used to transport user and signaling traffic from a single mobile station to one or more base stations.

Secondary CDMA Channel: A CDMA Channel at a preassigned frequency assignment used by the mobile station for initial acquisition. See also Primary CDMA Channel.

Secondary Traffic: An additional traffic stream that can be carried between the mobile station and the base station on the Traffic Channel. See also Primary Traffic and Signaling Traffic.

SIRCIM: Simulation of Indoor Radio Channel Impulse Response Models.

Soft Handoff: A handoff occurring while the mobile station is in the Mobile Station Control on the Traffic Channel State. This handoff is characterized by commencing communications with a new base station on the same CDMA frequency assigned before terminating communications with the old base station. See also Hard Handoff.

Spread Spectrum Signals: Signals used for transmission of digital information that are distinguished by the characteristic that their bandwidth W is much greater than the information rate R in bits per second [6]. When the PN (pseudo-noise) sequence employed to spread the information bits is used in conjunction with PSK modulation to shift the phase of the PSK signal pseudo-randomly, the resulting modulated signal is called direct-sequence spread spectrum (DSSS) signal. When the

PN sequence is used in conjunction with FSK to select the frequency of the transmitted signal pseudo-randomly, the resulting signal is called frequency-hopped spread spectrum (FHSS) signal.

sps: Symbols per second.

Symbol: See Code Symbol and Modulation Symbol.

Sync Channel: Code channel 32 in the Forward CDMA Channel which transports the synchronization message to the mobile station.

Sync Channel Superframe: An 80 ms interval consisting of three Sync Channel frames (each 26.666...ms in length).

System: A system is a cellular telephone service that covers a geographic area such as a city, metropolitan region, county, or group of counties. See also Network.

System Time: The time reference used by the system. System time is synchronous to UTC time (except for leap seconds) and uses the same time origin as GPS time. All base stations use the same System Time (within a small error). Mobile stations use the same System Time, offset by the propagation delay from the base station to the mobile station.

Time Reference: A reference established by the mobile station that is synchronous with the earliest arriving multipath component used for demodulation.

Traffic Channel: A communication path between a mobile station and a base station used for user and signaling traffic. The term Traffic Channel implies a Forward Traffic Channel and Reverse Traffic Channel pair. See also Forward Traffic Channel and Reverse Traffic Channel.

Voice Channel: See Analog Voice Channel.

Voice Privacy: The process by which user voice transmitted over a CDMA

Traffic Channel is afforded a modest degree of protection against eavesdropping over the air.

Walsh Chip: The shortest identifiable component of a Walsh function. There are 2^N Walsh chips in one Walsh function where N is the order of the Walsh function. On the Forward CDMA Channel, one Walsh chip equals 1/1.2288 MHz, or 813.802...ns. On the Reverse CDMA Channel, one Walsh chip equals 4/1.2288 MHz, or 3.255...μs.

Walsh Function: One of 2^N time orthogonal binary functions (note that the functions are orthogonal after mapping '0' to '1' and '1' to '-1').

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CHAPTER 1. INTRODUCTION

1.1 Overview

Mobile communication systems provide access to the capabilities of the global network at any time, irrespective of the location or mobility of the user. A cellular mobile communication system overcomes the limitations of its conventional counterpart such as limited service capability, poor service performance and inefficient frequency spectrum utilization.

The IS-95 "Mobile-Station Base-Station Compatibility Standard For Dual-Mode Wideband Spread Spectrum Cellular System" endorsed by the US Telecommunications Industry Association / Electronic Industry Association (TIA/EIA) based on CDMA technology describes one such system underway in North America [1].

The dual-mode operation of IS-95 facilitates the coexistence of analog and digital cellular systems. This is necessary since the North American cellular system has no additional spectrum allocated for the digital system.

CDMA direct sequence spread spectrum technique, incorporated into this system, enables the accommodation of a large number of users in one radio channel depending on the voice activity level [2]. This feature also provides immunity to jamming signals and enables resolution of multipath components in a time-dispersive radio propagation channel [3]. Chapter 3 provides a description of the standard.

A simulation-based approach to performance evaluation is adopted here. A communication system based on the IS-95 standard is simulated using SIMULINK® in MATLAB®. Power delay profiles in various mobile radio propagation channels are used to obtain measurement-based channel models for urban, suburban, indoor and open area environments. Statistics of the path loss characteristics are then used to estimate the number of taps and tap gains. These are then used in an optimum combining RAKE receiver structure for signal detection.

Performance comparison of the simulated system with regard to bit error rate (BER) for four-way and optimum combining RAKE receivers is presented. Various multipath propagation channels are characterized based on the number of discrete paths and average delay spreads.

The need for simulation is described as follows. The performance of a communication system can be evaluated using formula-based calculations, waveform level simulation or through hardware prototyping and measurements [4].

Formula-based techniques are based on the analysis of simplified models of the system using analytical methods. Hence the degree of accuracy of system model and performance evaluation decreases with the complexity of communication systems.

Hardware prototyping is an accurate and credible method, but with a loss of flexibility. It is also time consuming and expensive.

A simulation-based approach, on the other hand, can model systems with any level of detail and the design space can be explored more efficiently than the above methods. Moreover, mathematical and empirical models can be combined and measured characteristics incorporated into the system model in a better way. Simulation waveforms obtained can be used for rapid prototyping using a Real-time Workshop®.

1.2 Motivation and Scope of Research

As the demand for digital wireless communication systems grows, the accurate prediction of average and instantaneous BER in multipath channels becomes increasingly important. These predictions enable the determination of acceptable modulation methods, coding techniques and receiver implementations in the operating environments. However, such predictions become extremely difficult when there are numerous system and channel parameters involved (e.g. SNR, data rate, impulse noise and mobile speed). Moreover, the time-varying nature of mobile-radio channels complicates the optimization of these parameters using analytical techniques. Hence the performance of a complex mobile communication system based on IS-95 is evaluated using a simulated system model.

Multipath fading is the major cause of communication impairments in a microwave radio link [5]. It is mainly caused by multipath reflections of a transmitted wave by local scatterers such as houses, buildings and forests surrounding the mobile station. When a direct wave is present in the fading signal along with the reflected waves, the channel is described as a Rician fading environment, otherwise it is called a Rayleigh fading environment. Various measurement based channel models with multipath fading are developed and presented to the system.

Also, optimum combining RAKE receiver structures are developed from the characteristics of various propagation channels obtained from [5-11], and the overall performance of the system is presented.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Computer-based modeling and simulation is a relatively new dimension in the performance evaluation of communication systems. Though it has developed only over the past two decades, a variety of modeling and simulation techniques have been developed since. The current generation software simulation packages (BOSS [12], SPW [13],COSSAP [14]) offer interactive, graphical and user-friendly frameworks for simulation [4].

2.2 Previous Work on System Simulation

The simulation methodology implemented in the bir error rate simulator (BERSIM) allows subjective evaluation of link quality between a source and a sink via real-time bit-by-bit error simulation for mobile radio systems. In this package, communication system parameters like modulation scheme, data rate, SNR and receiver speed may be specified permitting performance comparisons. Indoor and outdoor multipath fading channels, AWGN and cochannel interference effects are also simulated here [15]. BERSIM uses the measurement-based statistical indoor channel model in Simulation of Indoor Radio Channel Impulse Response Models (SIRCIM) described in [16].

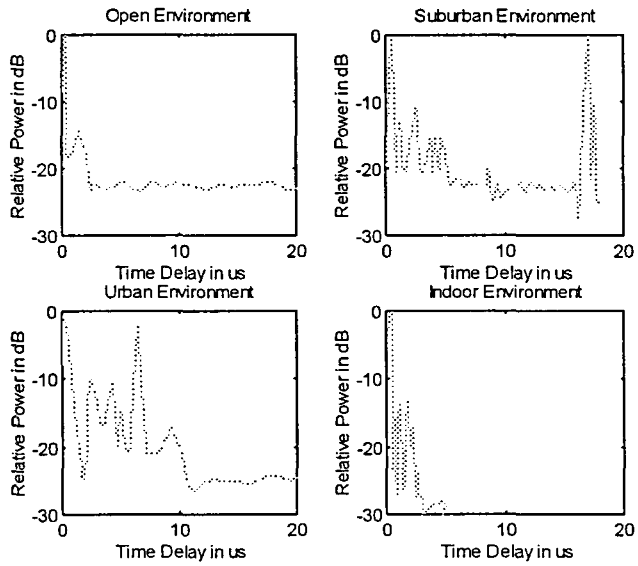


Figure 2.1: Typical Power Delay Profiles for various propagation channel environments.

2.3 Previous Work on Channel Impulse Response Measurements

The performance of a communication system is lower-bounded under the worst-case operating conditions. A reasonable sample of worst case multipath profiles and typical wideband path loss characteristics (for urban, suburban, open area and indoor environments, see Figure 2.1) were obtained from the measurements presented in the following papers. The measurements were restricted to those of RF signals in the range of 800 MHz to 910 MHz. This is because the Federal Communication Commission (FCC) has allocated a 50-MHz bandwidth in the 825-890 MHz frequency range for high-capacity mobile radio telephone use. This bandwidth is equally divided between transmit and receive bands with mobile transmit channels in the 825-845 MHz range and mobile receive channels in the 870-890 MHz range [17]. Systems based

Table 2.1: Radio Channel Allocation

Transmitter	Channel No. N	Center Frequency (MHz)	Range
Mobile	$1 \leq N \leq 799$	0.03N + 825.000	825.030 - 848.970
	$990 \leq N \leq 1023$	0.03(N - 1023) + 825.000	824.010 - 825.000
Base	$1 \leq N \leq 799$	0.03N + 870.000	870.030 - 893.970
	$990 \leq N \leq 1023$	0.03(N - 1023) + 870.000	869.010 - 870.000

on the IS-95 standard conform to these regulations. The distribution of channels between the mobile and base station are given in Table 2.1.

Statistical descriptions of the time delays and Doppler shifts associated with multipath propagation in a suburban mobile radio environment obtained from bandpass impulse response measurements are presented in [6]. These provided average power delay profiles made up of over 200 individual profiles for 910 MHz radio signals.

Distributions of delay spread for 910 MHz Gaussian wide-sense stationary uncorrelated scattering (GWSSUS) channels at different locations in New York City are presented in [5]. The regions are representative of heavily built-up areas of many large cities in US. Over 10 percent of the areas covered here exhibited more than 2.5 μs for rms delay spread.

Experimental propagation loss measurements taken in the Ottawa region at 910 MHz are presented in [7]. In addition, a comparative study of these profiles with statistical models described by Hata-Okumura, Egli, Edwards and Durkin, Blomquist and Ladell, Allsebrook and Parsons under applicable conditions are also presented.

Time delay spread and signal level measurements of 850 MHz radio waves in indoor propagation channels are presented in [8]. Average delay spreads of 420 ns were obtained in residential environments.

Measurements and cumulative probability distributions of power delay profiles for suburban, dense suburban, urban and dense urban radio propagation environments at different locations in the city of Leeds, UK are presented in [9]. Also, the number of discrete paths and their corresponding time delays are deduced from the distributions.

Microcellular radio measurements at 900 MHz undertaken at University of Liverpool are presented in [10]. These were representative of power delay profiles of urban propagation channels.

Typical and worst case rms delay spreads, excess delay spreads and mean channel path loss at 900 MHz in four European cities are presented in [11]. Path loss changes as a function of the distance between base-station and mobile-station are also determined here using a power law propagation model.

Data obtained from measurements described above are used in developing mobile propagation channel models as described in Section 2.5.

2.4 Previous Work on RAKE Receivers

The RAKE tropospheric scatter technique is described in [18]. Propagation measurements were carried out using this technique with an RF carrier of 900 MHz, pseudorandomly phase-shift modulated at 100 ns intervals. This provided a multipath resolution of 100 ns. Scattering functions thus obtained were one of the first set of presentations for tropospheric-scatter transmission paths.

Noncoherent combining of the outputs of the taps of the RAKE receiver in a CDMA DSSS system with binary DPSK modulation is presented in [19]. This study showed that RAKE receivers are more appropriate for DS systems with smaller number of chips (50) per data symbol while a correlation receiver is preferred in systems with large number of chips (400) per data symbol.

2.5 Relevance to Research

Comprehensive software packages described in [4] are expensive in terms of resources and infrastructure required to install them. Signal Processing Workstation (SPW) requires a Sun workstation. BERSIM AND SIRCIM system simulation softwares, described in [15] and [16] can be used to simulate modulation, filtering, propagation and detection aspects of communication systems in general. In order to study the performance characteristics of an IS-95 based system, a specific system that met all the required specifications (e.g. chip rate, encoder structure, PN sequence length etc.), needed to be simulated.

Propagation channel impulse responses for radio signals in the UHF range (850-910 MHz) are described in Section 2.3. Power delay profiles which represent the probability density function (pdf) of the average power of the received signal with respect to time for the four multipath channels were obtained from these data. Through appropriate analysis of their statistics, delay spread, average delay, number of discrete paths and excess delay are obtained. This type of analysis is called direct data reduction. The parameters and the bounds on their variability provide a good means of assessing the performance of the system.

The number of taps and the tap gains to be provided in the RAKE receiver are obtained from the number of discrete paths, their time delays and the amplitude distributions of the multipath channel. The RAKE receiver makes a binary decision based on a real-valued decision statistic which is obtained by the noncoherent combination of the individual tap outputs. A comparison of the BER versus signal-to-noise (SNR) characteristics for four-way and optimum combining RAKE receivers for a suburban environment is presented.

CHAPTER 3. OVERVIEW OF THE IS-95 STANDARD

3.1 Introduction

This chapter describes the IS-95 standard for digital cellular systems. Forward (base station to subscriber) and reverse (subscriber to base station) CDMA channel structures and signals, power control, message encryption and privacy, call processing and handoff procedures are the topics discussed here.

3.2 Forward CDMA Channel Structure

The forward CDMA channel consists of four code channels : the pilot channel (always required), the sync channel, paging channels (1 to 7) and traffic channels (55 to 63)(see Figure 3.1) [1].A pilot channel is transmitted at all times by the base station on each active forward CDMA channel. It is an unmodulated spread spectrum signal used for synchronization by a mobile station operating within the coverage area of the base station. The sync channel is a modulated spread spectrum signal used by mobile stations to acquire initial time synchronization. The paging channel is also a modulated spread spectrum signal used to transmit system overhead information by the base station and specific messages by the mobile station. The forward traffic channel is used for the transmission of user and signaling information to a specific mobile station during a call.

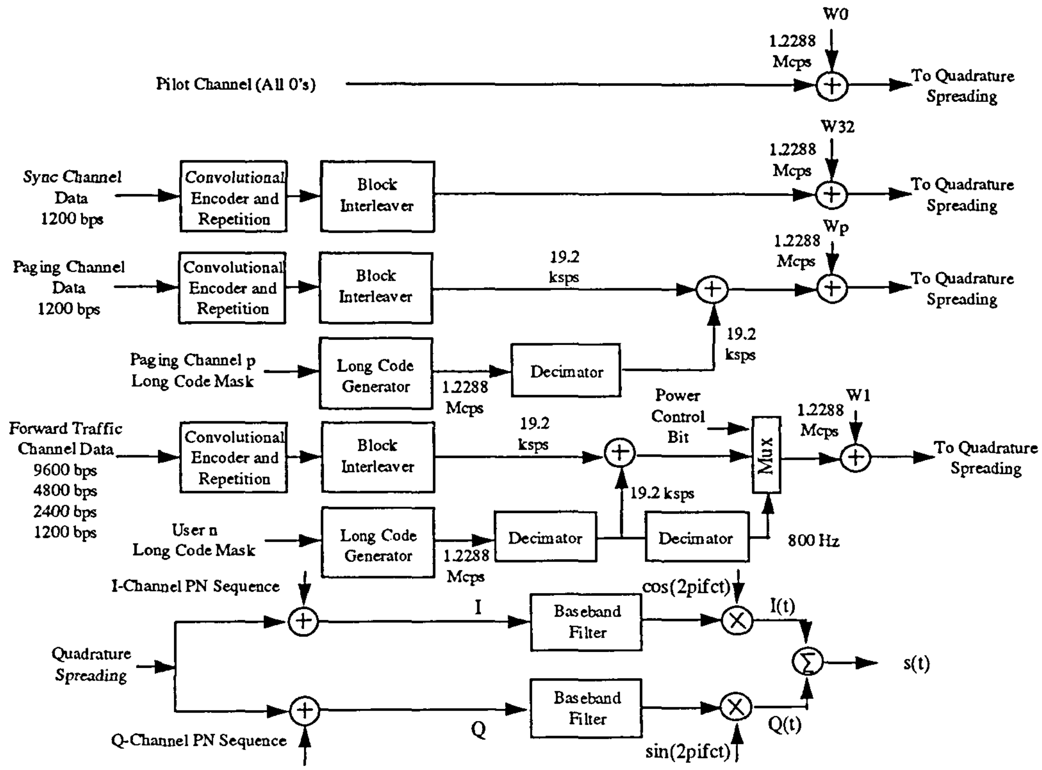


Figure 3.1: Forward CDMA Channel Structure

Data rates at the input are : Pilot channel (all 0's) at 19.2 kbps; Sync channel at 1.2 kbps; Paging channel (fixed data rate) at 9.6, 4.8 or 2.4 kbps; Traffic channel (variable data rate) at 9.6, 4.8, 2.4 or 1.2 kbps. The sync, paging and traffic channel data are then convolutionally encoded using rate 1/2, constraint length 9 code with generator functions 753 (octal) and 561 (octal). This generates two code symbols for each input data bit. The sync channel encoded symbols are repeated twice to achieve a modulation symbol rate of 4.8 ksps. While for paging and traffic channels, the number of repetitions is such that the modulation symbol rate is 19.2 ksps. The modulation parameters are listed in Tables 3.1, 3.2, 3.3.

Table 3.1: Sync Channel Modulation Parameters

Parameter	Data Rate (bps) 1200	Units
PN Chip Rate	1.2288	Mcps
Code Rate	1/2	bits/code sym
Code Repetition	2	mod sym/code sym
Modulation Symbol Rate	4800	sps
PN Chips/Modulation Symbol	256	PN chips/mod sym
PN Chips/Bit	1024	PN chips/bit

Table 3.2: Paging Channel Modulation Parameters

	Data Rate (bps)		
Parameter	9600	4800	Units
PN Chip Rate	1.2288	1.2288	Mcps
Code Rate	1/2	1/2	bits/code sym
Code Repetition	1	2	mod sym/code sym
Modulation Symbol Rate	19200	19200	sps
PN Chips/Modulation Symbol	64	256	PN chips/mod sym
PN Chips/Bit	128	1024	PN chips/bit

After symbol repetition, block interleaving (of span 20ms equivalent to 384 modulation symbols) is performed to avoid burst errors while data is being transmitted through a multipath fading environment. Data scrambling of the interleaved symbols is done using the first of every 64 bits of a long-code (of length 2^{42}-1) at the PN chip rate for paging and traffic channels. A long code mask that modulates the long code in traffic channels is used for voice privacy (see Section 3.5).

Each code channel transmitted on the forward CDMA channel is spread with a Walsh function at a fixed chip rate of 1.2288 Mcps to provide orthogonal channelization among all code channels. One of sixty-four time orthogonal Walsh functions is used. A code channel spread using Walsh function n is assigned to code channel number n (n = 0 to 63). Code channel number zero (64 0's) is always assigned to

Table 3.3: Forward Traffic Channel Modulation Parameters

	Data Rate (bps)				
Parameter	9600	4800	2400	1200	Units
PN Chip Rate	1.2288	1.2288	1.2288	1.2288	Mcps
Code Rate	1/2	1/2	1/2	1/2	bits/code sym
Code Repetition	1	2	4	8	mod sym/code sym
Modulation Symbol Rate	19200	19200	19200	19200	sps
PN Chips per Modulation Symbol	64	64	64	64	PN chips/mod sym
PN Chips/Bit	128	256	512	1024	PN chips/bit

Table 3.4: I and Q Mapping

I	Q	Phase
0	0	$\pi/4$
1	0	$3\pi/4$
1	1	$-3\pi/4$
0	1	$-\pi/4$

the pilot channel. If the sync channel is present, it is assigned code channel number 32. Paging channels, if present, are assigned code channel numbers 1 through 7 and the rest are assigned to the forward traffic channels.

After orthogonal spreading, each of these code channels are spread by a quadrature pair of maximal-length PN sequences (length 2^{15}) at a fixed chip rate of 1.2288 Mcps. The spread polynomials of the I and Q channel PN sequences are

$$P_I(x) = x^{15} + x^{13} + x^9 + x^8 + x^7 + x^5 + 1 \tag{3.1}$$

$$P_Q(x) = x^{15} + x^{12} + x^{11} + x^{10} + x^6 + x^5 + x^4 + x^3 + 1 \tag{3.2}$$

The binary (0's and 1's) I and Q at the output of quadrature spreading are baseband filtered and mapped into phase according to Table 3.4.

The resulting signal constellation and phase transitions are shown in Figure 3.2.

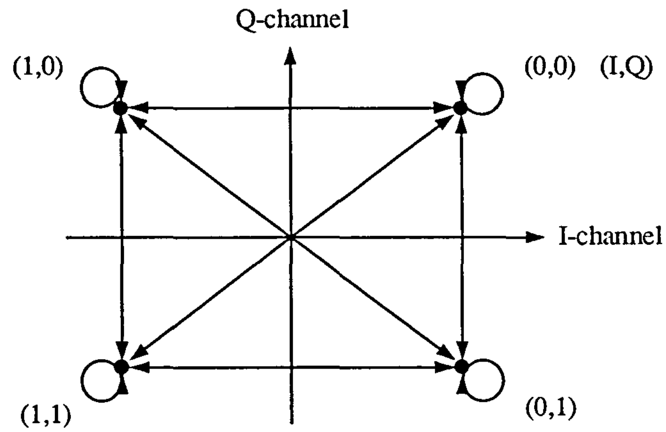


Figure 3.2: Forward CDMA Channel Signal Constellation and Phase Transition

PN sequence time offsets are used in code channels for synchronization by a mobile station. The pilot PN sequence time offset is used to identify a forward CDMA channel. Time offsets may be reused within a CDMA cellular system. The I and Q channel PN sequences for the sync, paging and forward traffic channels use the same offset as the pilot channel for a given base station.

The base station transmits the forward CDMA channel signal at 870.030 MHz with a channel spacing of 30 kHz. The corresponding dual-mode mobile station transmit channel is at 825.030 MHz. This is termed channel number 1. The maximum effective radiated power (ERP) and antenna height above average terrain (HAAT) is coordinated locally on an ongoing basis. A typical forward CDMA channel transmitted by a base station is shown in Figure 3.3.

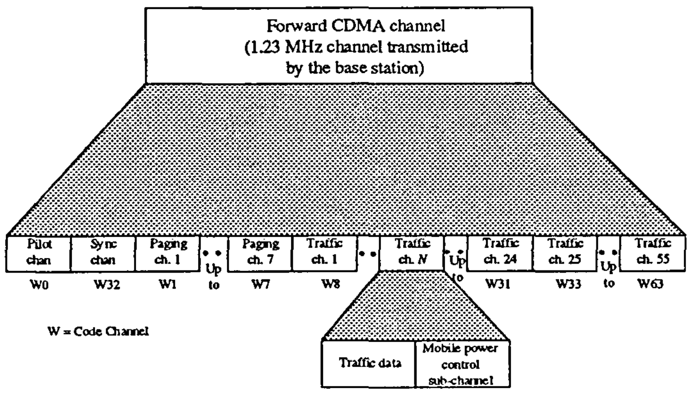


Figure 3.3: Example of a forward CDMA channel transmitted by a base station.

3.2.1 Receiver at Mobile Station

The mobile station demodulation process involves complimentary operations to the base station modulation process. The mobile station also performs tracking and demodulation of multipath components of the forward CDMA channel in addition to scanning and estimation of the signal strength at each pilot PN sequence offset. This is used during the idle or initialization stage and to determine when and from which base station handoff needs to be requested.

3.3 Reverse CDMA Channel Structure

The reverse CDMA channel is composed of access channels and reverse traffic channels. The mobile station does not establish a system time as at the base station. Hence the reverse channel signal does not use coherent detection. The modulation characteristics for the forward and reverse channels are different. The reverse channel is 64-ary orthogonal modulated at data rates of 9.6, 4.8, 2.4 or 1.2 kbps as shown in Figure 3.4 at point A. The actual burst transmission rate is fixed at 28800 code symbols per second. This results in a fixed Walsh chip rate of 307.2 thousand chips per second. Each Walsh chip is spread by four PN chips. The rate of the spreading PN sequence is fixed at 1.2288 Mcps (million chips per second). The reverse traffic channel and access channel modulation parameters are listed in Tables 3.4 and 3.5 respectively.

The reverse traffic channel is used for the transmission of user and signaling information to the base station during a call. The access channel is used by the mobile station to initiate communication with the base station and to respond to

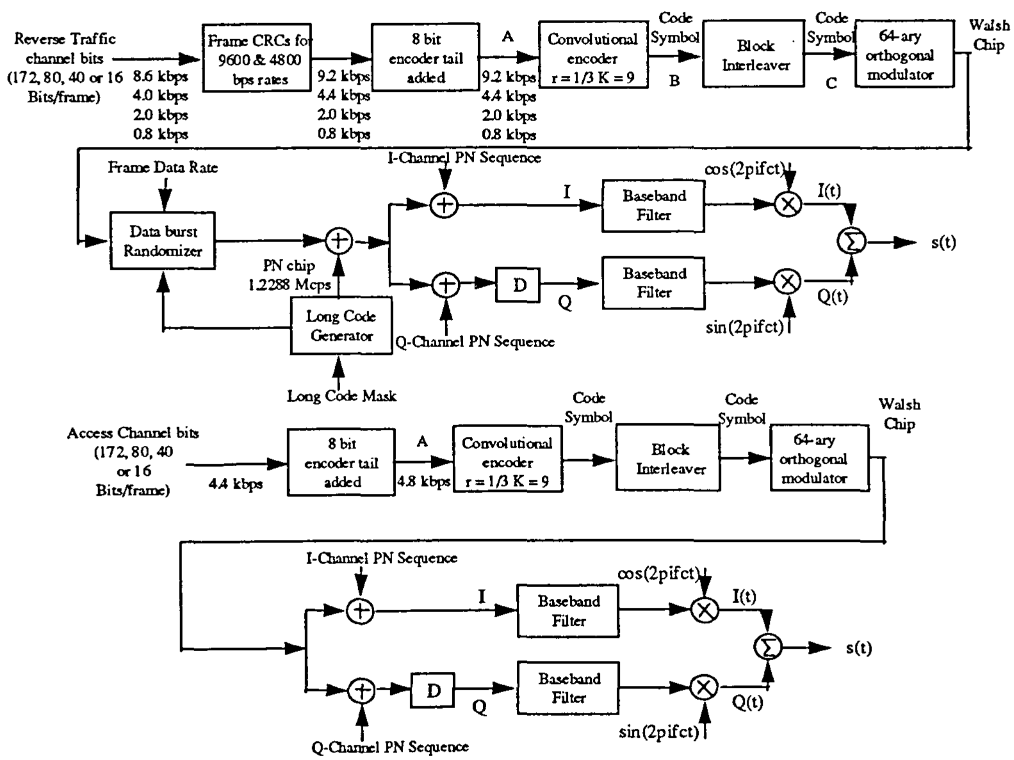


Figure 3.4 Reverse CDMA Channel Structure

Table 3.5: Reverse Traffic Channel Modulation Parameters

Parameter	Data Rate (bps) 9600	4800	2400	1200	Units
PN Chip Rate	1.2288	1.2288	1.2288	1.2288	Mcps
Code Rate	1/3	1/3	1/3	1/3	bits/code sym
Transmit Duty Cycle	100.0	50.0	25.0	12.5	%
Code Symbol Rate	28800	28800	28800	28800	sps
Modulation	6	6	6	6	code sym/mod sym
Modulation Symbol Rate	4800	4800	4800	4800	sps
Walsh Chip Rate	307.20	307.20	307.20	307.20	kcps
Modulation Symbol	64	64	64	64	PN chips/mod sym
Duration	208.33	208.33	208.33	208.33	μs
PN Chips/Code Sym	42.67	42.67	42.67	42.67	PN chips/code sym
PN Chips/Mod. Sym	256	256	256	256	PN chips/mod. sym
PN Chips/Walsh Chip	4	4	4	4	PN chips/Walsh chip

Table 3.6: Access Channel Modulation Parameters

Parameter	Data Rate (bps) 4800	Units
PN Chip Rate	1.2288	Mcps
Code Rate	1/3	bits/code sym
Code Symbol Repetition	2	symbols/cod sym
Transmit Duty Cycle	100.0	%
Code Symbol Rate	28800	sps
Modulation	6	code sym/mod sym
Modulation Symbol Rate	4800	sps
Walsh Chip Rate	307.20	kcps
Modulation Symbol Duration	208.33	μs
PN Chips/Code Symbol	42.67	PN chips/code sym
PN Chips/Modulation Symbol	256	PN chips/mod. sym
PN Chips/Walsh Chip	4	PN chips/Walsh chip

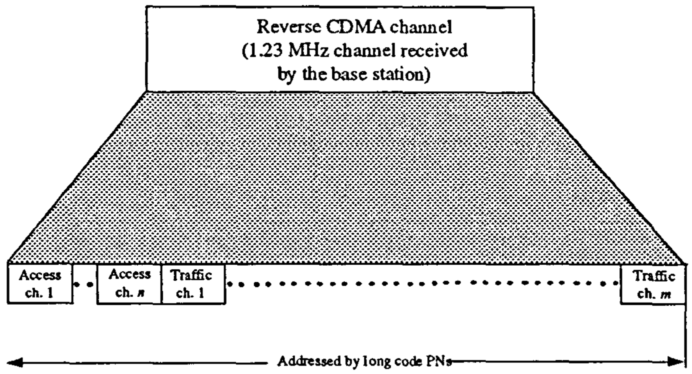


Figure 3.5 Example of a reverse CDMA channel received by a base station.

paging channel messages. The mobile station transmits information on the reverse traffic channel at variable data rates of 9.6, 4.8, 2.4 or 1.2 kbps and on the access channel at a fixed data rate of 4.8 kbps. These are then convolutionally encoded by rate 1/3, constraint length 9 codes with code generators 557, 663 and 711 (octal). The code symbols are then block-interleaved with a span of 20 ms (576 code symbols) and modulated by a 64-ary orthogonal modulator using 64 Walsh functions. The reverse traffic channel and the access channel are then direct sequence spread by the long code (with period = 2^{42} -1 chips) satisfying the linear recursion specified by the polynomial

$$\begin{aligned} p(x) &= x^{42}+x^{35}+x^{33}+x^{31}+x^{27}+x^{26}+x^{25}+x^{22}+x^{21}+x^{19}+x^{18}+ \\ &\quad x^{17}+x^{16}+x^{10}+x^{7}+x^{6}+x^{5}+x^{3}+x^{2}+x+1 \end{aligned} \tag{3.3}$$

The subscriber address is contained in the long code mask which modulates the long code before spreading. Furthermore, the waveform is spread by a pair of

PN codes (identical to the ones used in the forward traffic channel), common to all subscribers and to the access channel in an OQPSK arrangement. The final waveform is then filtered to generate a spectrum with 1.2288 MHz double-sided 3 dB bandwidth.

The mobile station transmits the reverse CDMA channel signal at 825.030 MHz with a channel spacing of 30 kHz. The corresponding dual-mode base station transmit channel is at 870.030 MHz. This is termed channel number 1. The maximum effective radiated power (ERP) with respect to a half wave dipole for any class mobile transmitter is 8 dBW (6.3 Watts).

3.4 Power Control

CDMA power control is essential in a cellular CDMA system for the reverse link transmission in order to reduce near-far interference. The mobile station receives a signal that has undergone log-normal and Rayleigh fading from the forward link. Also, the Rayleigh fading on the forward channel and the reverse channel are not the same since CDMA uses duplex channels. Hence, the desired average transmit power needs to be sent back to the base station on the reverse link. At the base station (or cell site), the available information on the instantaneous value versus the expected value of frame error rate (FER) (1 frame = 192 bits) of the received signal is examined to determine whether to command a particular mobile to increase or decrease its transmit power. This mechanism is called CDMA closed-loop power control.

The base station reverse traffic channel receiver estimates the received signal strength of the particular mobile station it is assigned to over a 1.25 ms period (1/16 of 20 ms). The estimate is used to determine the value of the power control bit ('0' or '1') corresponding to an indication of increase or decrease in the mean output power to the mobile station) to be transmitted on the corresponding forward traffic channel. Each power control bit replaces two consecutive modulation symbols of the forward traffic channel after data scrambling. The change in mean output power for every power control bit is 1 dB nominal within ± 0.5 dB of the nominal change.

3.5 Voice Privacy

Voice privacy is provided in the CDMA system by means of the private long-code mask used for PN spreading. Voice privacy control is provided on the traffic channels only. All calls are initiated using the public long-code mask. To initiate a transition to the private long-code mask, the base station or the mobile station sends a long-code transition request order on the traffic channel.

3.6 Call Processing

The mobile station call processing consists of the following states:

Initialization state : The mobile station selects the base station corresponding to the highest signal strength in its coverage area. It then acquires the pilot channel of the CDMA system within 20 ms and obtains the system configuration and timing information. The mobile station synchronizes its timing to that of the CDMA system.

Idle state : The mobile station performs paging channel monitoring procedures. Unless otherwise specified, it transmits an acknowledgement in response to any message received from the base station addressed to the mobile station. It also maintains active registration timers like the power-up, power-down, timer-based, distance and zone-based registrations.

System access state : The mobile station sends messages to the base station on the access channel and receives messages from the base station on the paging channel. Response messages and request messages are sent on the access channels.

Traffic channel state : The mobile station communicates with the base station using the forward and reverse traffic channels. The mobile station verifies its reception of the forward channel and transmits on the reverse traffic channel.

3.7 Handoff Procedures

Handoff or transfer of communication with a mobile station from one base station to the other is soft when it occurs at the same CDMA frequency. Hard handoff occurs when the transfer is between disjoint active sets, when the CDMA frequency changes, the frame offset changes, or when the mobile station is directed from a CDMA traffic channel to an analog voice channel.

The mobile station supports four handoff procedures:

Soft handoff: The mobile station commences communication with a new base station without interruption in communication with the old base station.

Softer handoff: Handoffs between sectors within a cell.

CDMA-to-CDMA hard handoff: The mobile station transmits between two base stations with different frequency assignments.

CDMA-to-analog handoff: The mobile station is directed from a forward traffic channel to an analog channel with different frequency assignment.

CHAPTER 4. COMMUNICATION SYSTEM MODEL

4.1 Introduction

A communication system based on the IS-95 standard is developed from a software-representable description or a block diagram of the system. Each block represents a subsystem that can be described using signal-processing operations. An explicit model viz., the equations and algorithms or methodologies followed in the implementation of each operation is presented here.

4.2 Forward CDMA Channel Structure

The forward CDMA channel structure can be broadly divided into the discrete channel and the analog channel (see Figure 4.1). The discrete channel consists of the following blocks.

4.2.1 Code Channel Data Generator

Pilot, sync, paging and forward traffic channels comprise the forward CDMA channel structure. Input information bits in these channels are in the form of digital signals containing embedded digital sequences. Such a digital signal can be represented as :

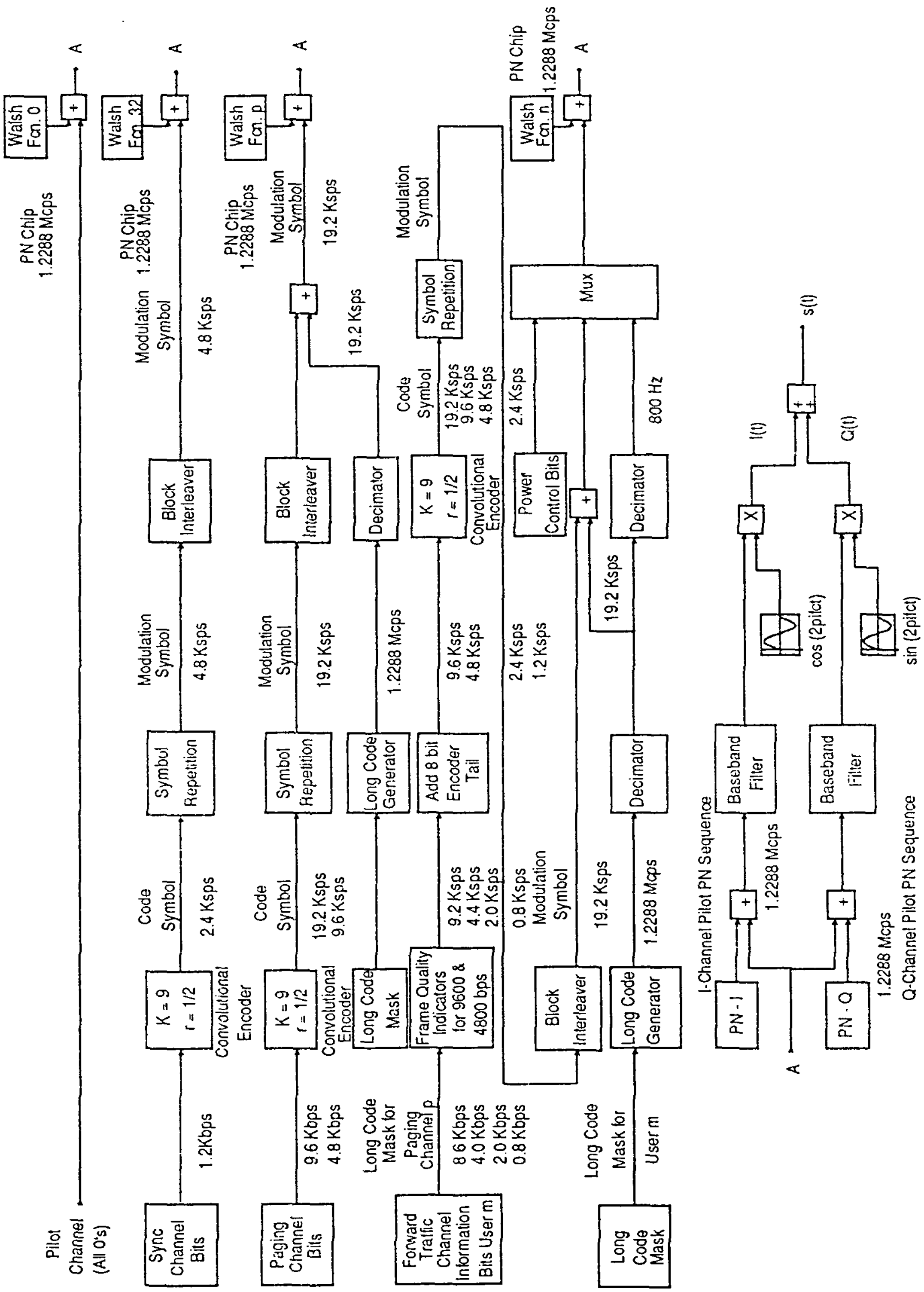


Figure 4.1 Forward CDMA Channel Structure

$$X(t) = \sum_{k=-\infty}^{\infty} A_k p(t - kT_b - D) \tag{4.1}$$

where $\{A_k\}$ is a digital sequence, T_b is the bit period, D is a random delay and p(t) is a suitable pulse waveform.

A general subblock to implement (4.1) is developed using the random number block in SIMULINK, which is a pseudo-random, normally distributed (Gaussian) number generator. The pulse waveform and delay are incorporated into the subblock as shown in Figure 4.2.

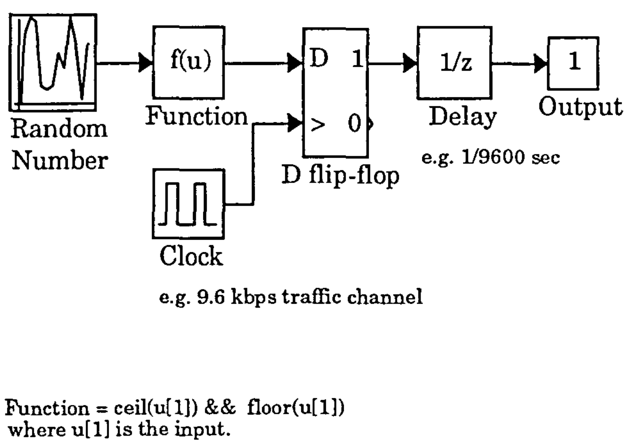


Figure 4.2 Random Data Generator (SIMULINK Block Representation)

The user interface to this subsystem has controls for specifying the time period or the data rate, random delay and the seed for the random number generator. Different seeds are used to distinguish between the code channels. Initial delays are set to zero and the data rates are given as follows.

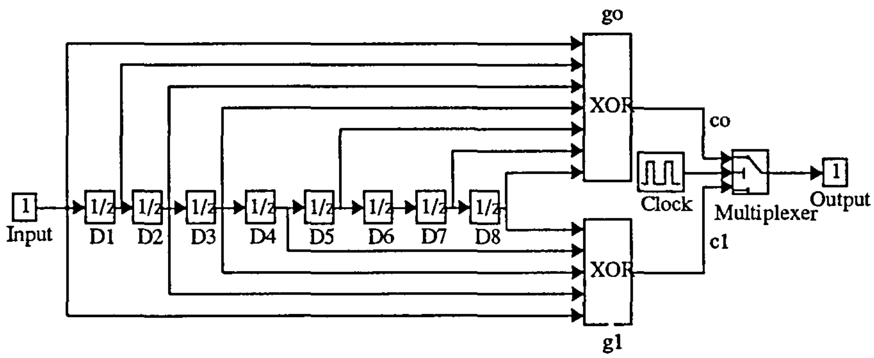
$$
T_b = \begin{cases} 9.6\,\text{kbps for pilot channel data,} \\ 1.2\,\text{kbps for sync channel data,} \\ 9.6 \textit{ or } 4.8\,\text{kbps for paging channel data and} \\ 9.6,\ 4.8,\ 2.4 \textit{ or } 1.2\ \text{kbps for traffic channel data.} \end{cases}
$$

4.2.2 Convolutional Encoder

A convolutional encoder accepts binary input in sets of k bits and outputs sets of n bits corresponding to n generator polynomials. These polynomials represent the finite discrete impulse response that the input is convolved with to produce the convolutional code. Convolutional codes are characterized by a rate, $R = k/n$ and constraint length, $K = Lk$ bits where each set of n output bits is determined by the current input set and $L - 1$ preceding input sets. These codes are also characterized by the free distance, d_f, which is the minimum distance between all pairs of codeword sequences in the code and is related to the error-correcting capability of the code.

Sync, paging and forward traffic channels are convolutionally encoded prior to transmission. The convolutional code of rate 1/2 and constraint length 9 is generated using the encoder given in Figure 7.1.3.1.3-1 of [1] (see Figure 4.3). The generator functions of the code are 753 (octal) for g_o and 561 (octal) for g_1. These are chosen to have the maximum free distance (minimum data bit errors) of 12 for the given constraint length and rate [20]. Two code symbols are generated for each data bit. These code symbols are output such that code symbol (c_o) encoded with generator function g_o is output first and code symbol (c_1) encoded with generator function g_1 is output last.

The convolutional code is generated by passing the information sequence from



D : Unit delay block used as a shift register.
XOR gates are used for Modulo-2 Adders
c_0 : 753 (octal); c_1 : 561 (octal)

E.g. Input data rate = 9600 kbps for traffic channel
Clock = 19200 KHz

Figure 4.3 Convolutional Encoder, K = 9, Rate = 1/2

the data generator through a linear shift register made up of 1 bit delays. The modulo-2 adders are implemented using XOR gates and the outputs of g_o and g_1 multiplexed to form the output sequence of code symbols at twice the input data rate.

4.2.3 Symbol Repetition

Symbol repetition is performed to achieve a uniform data rate of 19.2 ksps at the input to the orthogonal spreading blocks of paging and forward traffic channels and 4.8 ksps in the case of sync channel. In SIMULINK, the clock and data streams are represented by column vectors whose elements are samples of the clock pulse or data bits, the sampling rate being the highest clock (or data) rate in the system simulation. This is also the integration step in the simulation [21]. The highest clock

Table 4.1: Block Interleaver Parameters

	M	N	End-to-end Delay (in symbol periods)	Buffer Size (bytes)
Sync	16	8	256	65536
Traffic	24	16	768	98304

rate in this system is 1.2288 Msps which is the chip rate. Thus a digital signal at 9.6 kbps rate with a given data sequence and another digital signal at 4.8 kbps rate with each bit in the data sequence repeated once are identical and symbol repetition is not required.

4.2.4 Block Interleaver

A block interleaver accepts the coded symbols in blocks from the encoder, permutes the symbols and feeds the rearranged symbols to the modulator. The permutation of the block is accomplished by filling the columns of an M x N array, with the encoded sequence. The symbols are output in a specific row order after the array is completely filled. The array size required for forward CDMA channel block interleaver is 24 x 16.

The purpose of a block interleaver is to avoid burst errors while transmitting data through a multipath environment. But the time lag introduced into the system due to end-to-end delay is large. The simulation methodology adopted here causes one data bit at 9.6 kbps to be represented by $1.2288 \times 10^{-6} / 9600 = 128$ elements of a vector thus requiring $768 \times 128 = 98304$ bytes of storage while the maximum buffer size on SIMULINK is 8192 bytes. This results in buffer overflow.

The values of M, N, end-to-end delay and memory requirement of approximately 2MN symbol periods and 2MN bytes [20] are shown in Table 4.1.

All the above factors cause information to be lost and the performance of the system can no longer be validated. Hence block interleavers are not implemented.

4.2.5 Walsh Code Generator

Each code channel transmitted on the forward CDMA channel is spread with a Walsh function at a fixed chip rate of 1.2288 Mcps to provide orthogonal channelization among all code channels. One of sixty-four time-orthogonal Walsh functions is used for the purpose. The code channel spread with Walsh function n is assigned to code channel number n. The 64 x 64 matrix of Walsh functions is generated by means of the following recursive procedure:

$$H_1 = 0 \qquad H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

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

where N is a power of 2 and $\overline{H_N}$ denotes the binary complement of H_N. The Walsh function spreading sequence repeats with a period of 52.083 μs (=64/1.2288 Mcps) which is the duration of one modulation symbol.

The Repeating Sequence block in SIMULINK calls the MATLAB m-file called walshfun.m. This routine uses the built-in MATLAB function hadamard.m. A 64 x 64 Hadamard matrix is first generated using the recursive procedure described above. The elements of the Walsh function are then obtained by mapping the binary alphabet of {-1,1} of the Hadamard matrix into the binary alphabet of {1,0} of the Walsh function matrix. The walshfun.m routine takes in as input the Walsh function number and outputs the corresponding Walsh function. The Walsh function waveform is then obtained as in Figure 4.4.

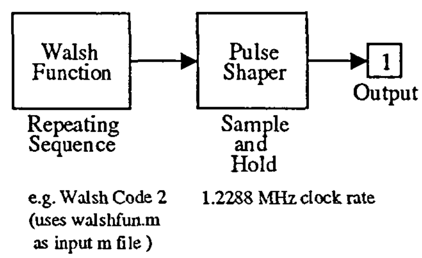


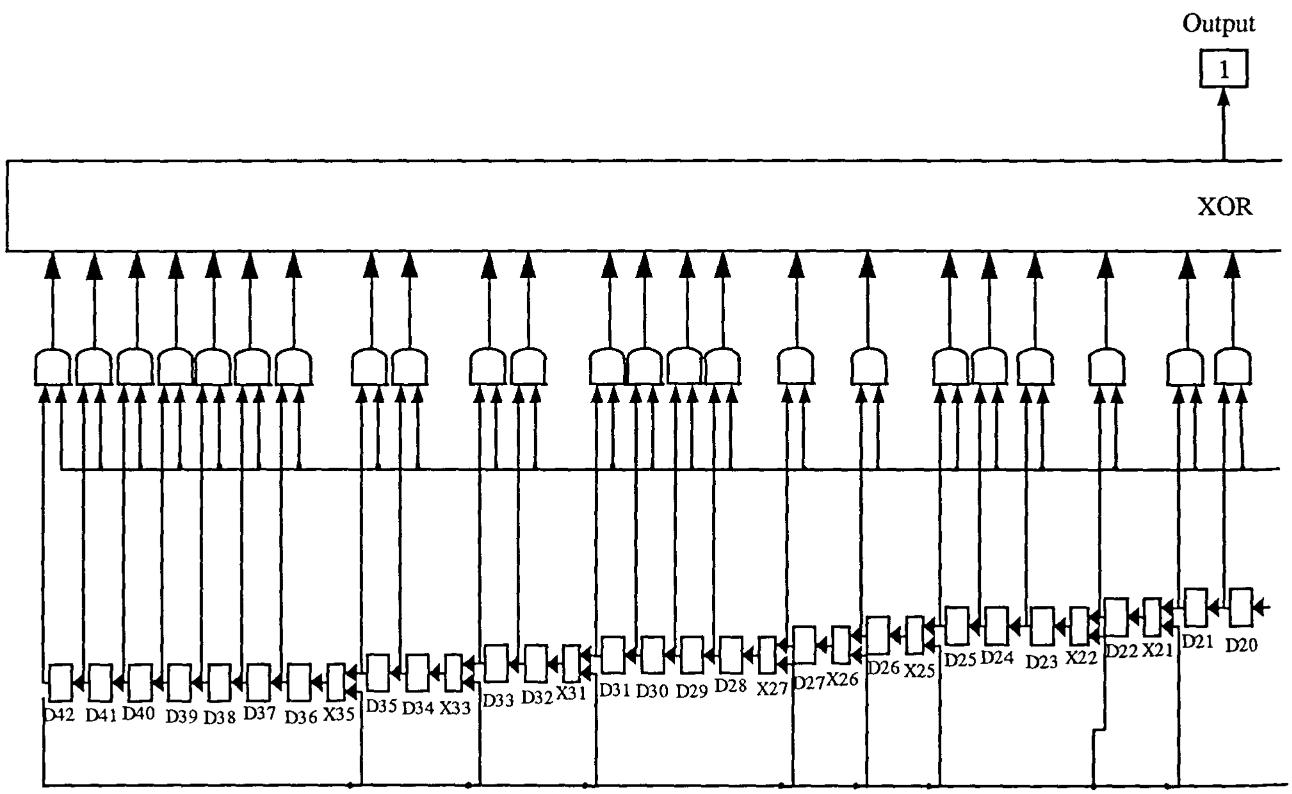
Figure 4.4 Walsh Function Waveform Generator (SIMULINK Block Representation)

The chip rate of 1.2288 Mcps is input as the time period to the Repeating Sequence block. This is the required Walsh Chip rate. The Sample and Hold block is the Unit Delay block used to obtain the Walsh function as digital signals or waveforms.

4.2.6 Long Code Generator

Prior to transmission, The paging and forward traffic channels are direct sequence spread by the long code which has a period of 2^{42} -1 chips. The long code satisfies the linear recursion specified by the characteristic polynomial given by (3.3). The code is generated by the modulo-2 inner product of a 42-bit mask and the 42-bit state vector of the sequence generator as shown in Figure 4.5.

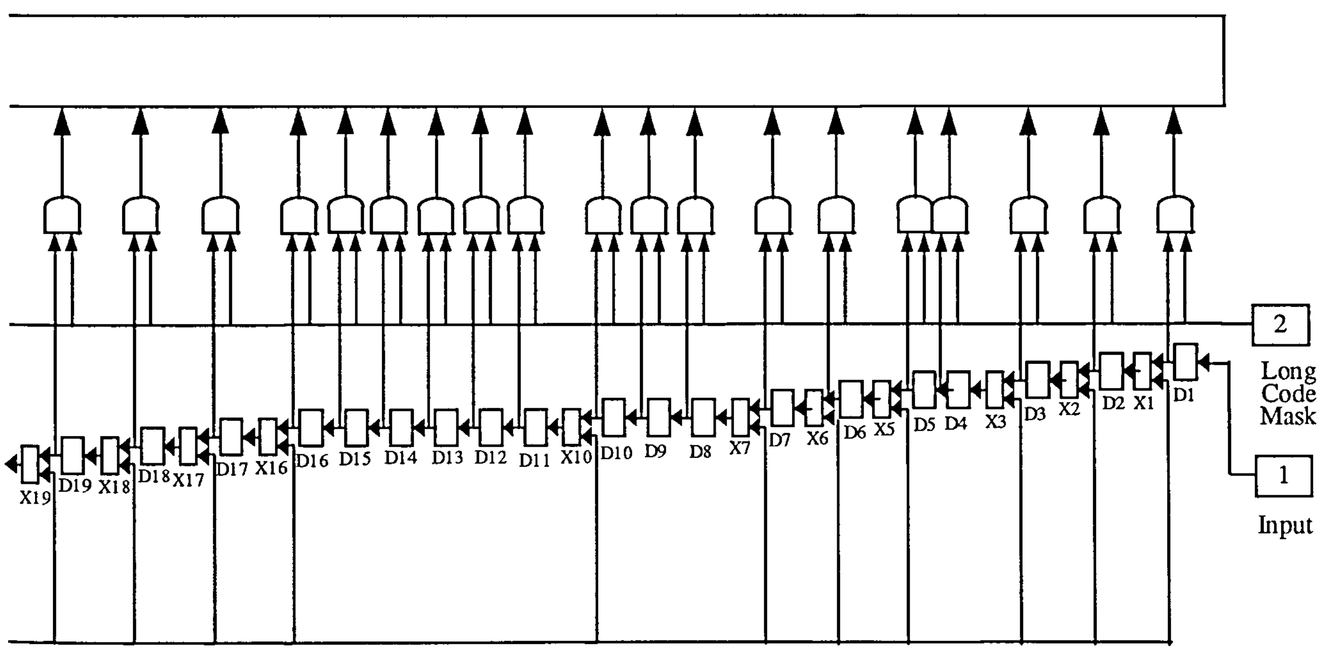
The paging channel long code mask incorporates the paging channel number and the pilot PN sequence offset index for the corresponding forward CDMA channel. The forward traffic channel public long code mask incorporates a permuted form of the ESN or electronic serial number, which is a 32-bit identification number provided by



D : Unit Delay used as shift register

X : XOR gate used as Modulo-2 adder

Figure 4.5 Long Code Generator (SIMULINK Block Representation)


2
Long Code Mask
1
Input
D1 X1 D2 X2 D3 X3 D4 D5 X5 D6 X6 D7 X7 D8 D9 D10 X10 D11 D12 D13 D14 D15 D16 X16 D17 X17 D18 X18 D19 X19

the mobile station manufacturer. (The information on private long code mask which is used for message encryption and voice privacy is distributed by TIA as a part of the Technology Transfer Plan and is not available). Since these masks are not required to evaluate the system level performance, 42-bit random repeating sequences were used instead.

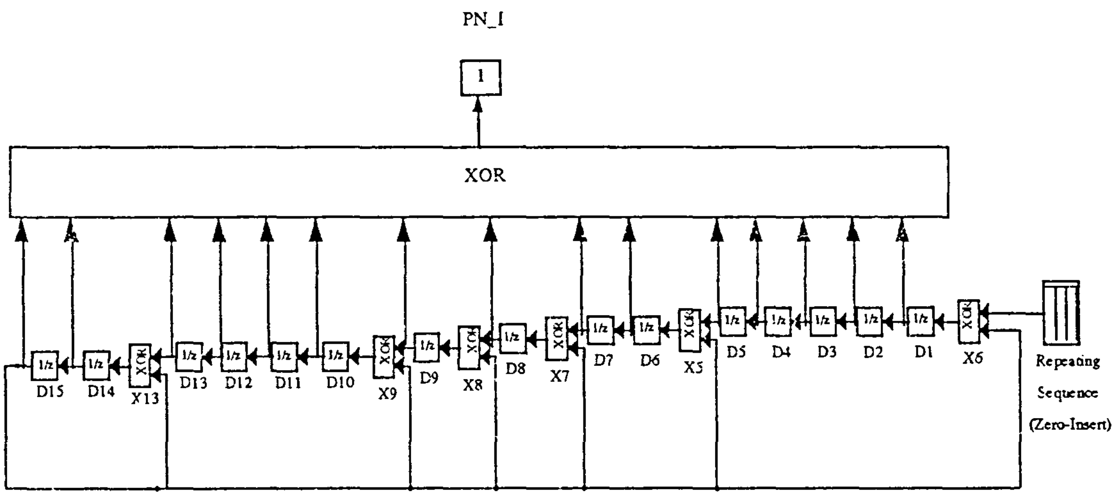
4.2.7 PN Sequence Generators

Following orthogonal spreading, each code channel is spread in quadrature. The spreading sequence is of length 2^{15} and is also called the pilot PN sequence. The maximum length linear feedback shift register sequences i(n) and q(n) are based on the polynomials of length 2^{15} -1 given by (3.1) and (3.2). Unit delays are used for shift registers and XOR gates for modulo-2 adders and the sequences are generated as in Figure 4.6 and Figure 4.7.

The I and Q pilot PN sequences are obtained by inserting a '0' in i(n) and q(n) after 14 consecutive '0' inputs (this occurs once in each period). This is achieved using a repeating sequence block that inserts a zero appropriately. Chip rate for the pilot PN sequence is 1.2288 Mcps which is the input in the user interface to the PN_I and PN_Q subblocks.

4.2.8 Baseband Filter

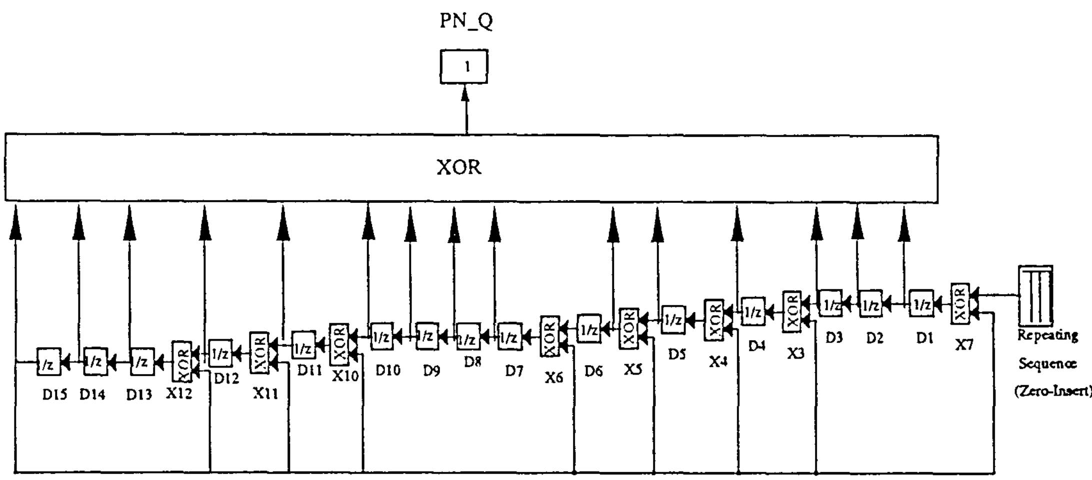
After the spreading operation, the I and Q impulses are applied to the inputs of the I and Q baseband filters. These filters are derived from the filter coefficients specified in Table 7.1.3.1.10.1-1 of [1]. The normalized frequency response of the filter is contained within $\pm\delta_1$ in the passband $0 \leq f \leq f_p$ and is less than or equal to -δ_2 in



D : Unit Delay used as shift register
X : XOR gate used as modulo-2 adder

Figure 4.6 I Channel PN Sequence Generator (SIMULINK Block Representation)

the stopband f $\geq$ f_s. The numerical values for the parameters are δ_1 = 1.5 dB, δ_2 = 40dB, f_p = 590 kHz and f_s = 740 kHz. The baseband filters are implemented using the Discrete Filter block in SIMULINK. The numerator and denominator coefficients are derived from the specified filter coefficients.



D : Unit Delay used as shift register
X : XOR gate used as modulo-2 adder

Figure 4.7 Q Channel PN Sequence Generator (SIMULINK Block Representation)

4.2.9 QPSK Modulator

RF modulation forms the analog part of the forward CDMA channel. The filtered and quadrature spread I and Q channel sequences phase-shift modulate in-phase and quadrature phase carriers in a pseudo-random fashion. This is called Direct Sequence Spread Spectrum Modulation. All the four code channels are QPSK modulated resulting in phase mapping of the I and Q channel sequences as given in Table 3.4. The output signal can be expressed as

$$S(t) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t) \tag{4.2}$$

where I(t) and Q(t) are the filtered waveforms with embedded I and Q channel digital sequences respectively represented as

$$\begin{aligned} I(t) &= \sum_{k=-\infty}^{\infty} Ip(t - kT_c) \\ Q(t) &= \sum_{k=-\infty}^{\infty} Qp(t - kT_c). \end{aligned}$$

f_c is the transmit frequency (870.030 MHz) and T_c is one chip period (813.802 ns). S(t) can also be expressed as

$$S(t) = \mathrm{Re}\{\tilde{S}(t)e^{j2\pi f_c t}\}$$

where $\tilde{S}(t)$ is the complex envelope or the low-pass equivalent representation given by

$$\tilde{S}(t) = [I(t) + jQ(t)].$$

The RF carriers required for the modulation process are implemented using the Sine blocks in SIMULINK with frequency f_c, phase 0 and $\pi/2$ and unit amplitudes. The output waveforms are continous (or analog). The product and difference operations in (4.2) are implemented using suitable blocks as shown in Figure 4.8.

4.2.10 Data Scrambler and Frame Quality Indicators

Data scrambling is achieved by performing modulo-2 addition of the interleaver output symbol with the binary value of the long-code PN chip (2^{42} -1). Frame Quality

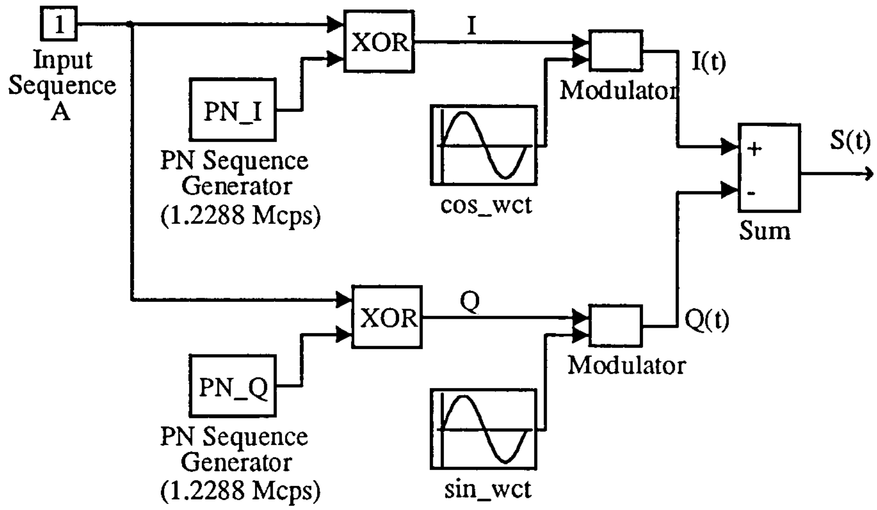


Figure 4.8 Forward CDMA Channel QPSK Modulator

Indicators are Cyclic Redundancy Codes used to determine if a frame is in error. It also assists in the determination of the data rate of the received frame. These functions form parts of the encoder. Explicit simulation of a codec is not necessary for purposes of system performance evaluation since adequate approximation or bounds on the codec performance can be applied. The performance of the encoders and decoders are not being studied here. Hence data scramblers and descramblers, frame quality indicators and the decimators required for their implementation were not simulated. The power control bits were not simulated since the effect of estimation of the power control bits based on the received signal strength (and their position) on the evaluation of system performance is not of interest here.

4.3 Reverse CDMA Channel Structure

The reverse CDMA channel structure also consists of the digital and analog channels. The general block diagram is shown in Figure 4.9. It is composed of access channels and reverse traffic channels that form the code channels.

4.3.1 Code Channel Data Generators

The access channel has a fixed data rate of 4.8 kbps and the reverse traffic channels, a variable data rate of 9.6, 4.8, 2.4 or 1.2 kbps. The corresponding digital waveforms required for performance estimation are obtained using the data generators described in Section 4.2.1.

4.3.2 Convolutional Encoder

Access and reverse traffic channels undergo convolutional encoding prior to transmission. The convolutional code of rate 1/3 and constraint length 9 is generated using the encoder given in Figure 6.1.3.1.3-1 of [1] (see Figure 4.10). The generator functions of the code are g_o equals 557 (octal), g_1 equals 663 (octal) and g_2 equals 711 (octal). These are chosen to have the maximum free distance (minimum data bit errors) of 18 for the given constraint length and rate [20]. Three code symbols are generated for each data bit. These code symbols are output such that code symbol (c_o) encoded with generator function g_o is output first, (c_1) encoded with generator function g_1 is output second and code symbol (c_2) encoded with generator function g_2 is output last.

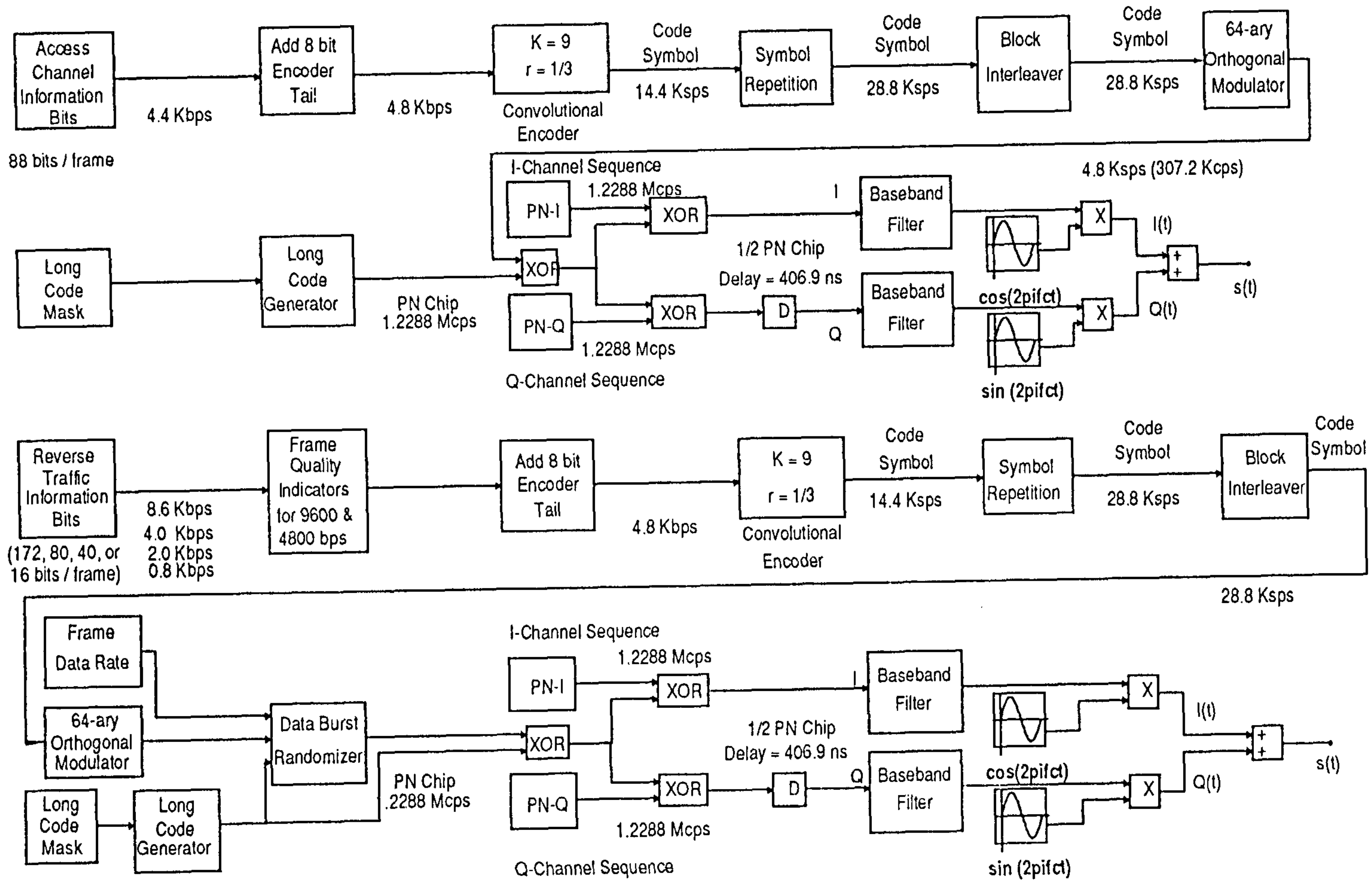
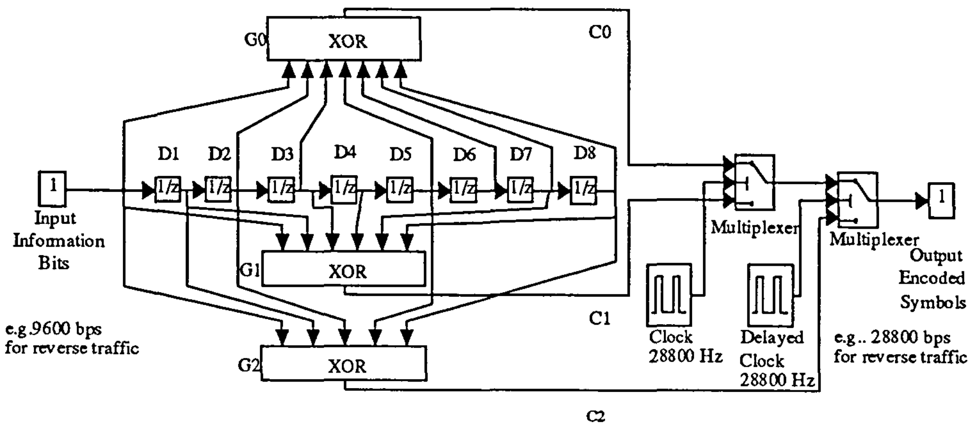


Figure 4.9 Reverse CDMA Channel Structure



D : Unit Delay used as shift register
X : XOR Gate used as modulo-2 adder
c_0: 557 (octal)
c_1: 663 (octal)
c_2: 711 (octal)

Figure 4.10 Convolutional Encoder K = 9, rate = 1/3

The convolutional code is generated by passing the information sequence from the data generator through a linear shift register made up of 1 bit delays. The modulo-2 adders are implemented using XOR gates and the outputs of g_o, g_1 and g_2 multiplexed to form the output sequence of code symbols at three times the input data rate.

4.3.3 Symbol Repetition

Symbol repetition is not required based on reasons described in Section 4.2.3. The code symbol after convolutional encoding is at 28.8 ksps data rate.

4.3.4 Block Interleavers

In the case of reverse CDMA channel, the block interleaver forms an array of size 32 x 18 requiring a memory capacity of 576 symbols for 9600 bps data rate. This amounts to a storage requirement of 73728 bytes. Hence, for reasons stated in Section 4.3.4, the block interleaver was not implemented.

4.3.5 Walsh Code, Long Code, PN Sequence Generators and Baseband Filter

The Walsh code, long code, I and Q channel PN sequence generators and the baseband filter implemented for the forward CDMA channel structure were used for the reverse CDMA channel structure as well. These are described in Sections 4.2.5, 4.2.6, 4.2.7 and 4.2.8 respectively.

4.3.6 OQPSK Modulator

RF modulation forms the analog part of the reverse CDMA channel. The data spread by the Q pilot PN sequence is delayed by half a PN chip time (406.901 ns) with respect to the data spread by the I pilot PN sequence. The filtered and quadrature spread I and Q channel sequences phase-shift modulate in-phase and quadrature phase carriers in a pseudo-random fashion. This is called Direct Sequence Spread Spectrum Modulation. Access and reverse traffic channels are OQPSK modulated resulting in phase mapping of the I and delayed Q channel sequences as given in Table 3.4. The output signal can be expressed as

$$S(t) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t) \tag{4.3}$$

where I(t) and Q(t) are the filtered waveforms with embedded I and Q channel digital sequences respectively represented as

$$
\begin{aligned}
I(t) &= \sum_{k=-\infty}^{\infty} Ip(t-kT_c) \\
Q(t) &= \sum_{k=-\infty}^{\infty} Qp(t-kT_c-T)
\end{aligned}
$$

f_c is the transmit frequency (870.030 MHz), T_c is the chip period (813.802 ns) and T is the offset (409.901 ns). S(t) can also be expressed as

$$S(t) = \mathrm{Re}\{\tilde{S}(t)e^{j2\pi f_c t}\}$$

where $\tilde{S}(t)$ is the complex envelope or the low-pass equivalent representation given by

$$\tilde{S}(t) = [I(t) + jQ(t)].$$

The RF carriers required for the modulation process are implemented using the Sine blocks in SIMULINK with frequency f_c, phase values 0 and $\pi/2$ and unit amplitudes. The output waveforms are continous (or analog). The product and difference operations in (4.2) are implemented using suitable blocks as shown in Figure 4.11.

4.3.7 Data Burst Randomizer and Frame Quality Indicators

The data burst randomizer generates a masking pattern of '0's and '1's that randomly masks out redundant data generated by the code repetition. Frame Quality Indicators are Cyclic Redundancy Codes used to determine if a frame is in error.

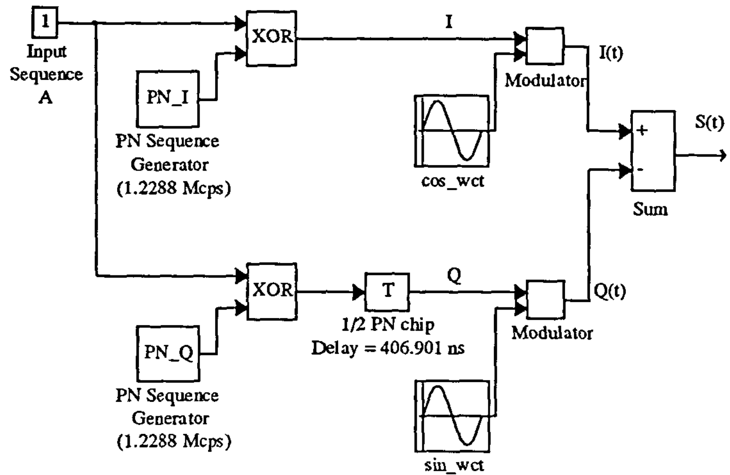


Figure 4.11 OQPSK Modulator (SIMULINK Block Representation)

It also assists in the determination of the data rate of the received frame. These functions form parts of the encoder. Explicit simulation of a codec is not necessary for purposes of system performance evaluation since an adequate approximation or bounds on the codec performance can be applied. The performance of the encoders and decoders are not being studied here. Hence data burst randomizer and frame quality indicators were not implemented.

4.4 Receiver Structure

The mobile station receiver performs the demodulation process comprising of complimentary operations to the base station modulation process. Similarly, the base station receiver performs demodulation process consisting of complimentary operations to the mobile station modulation process. The general receiver block diagram is shown in Figure 4.12.

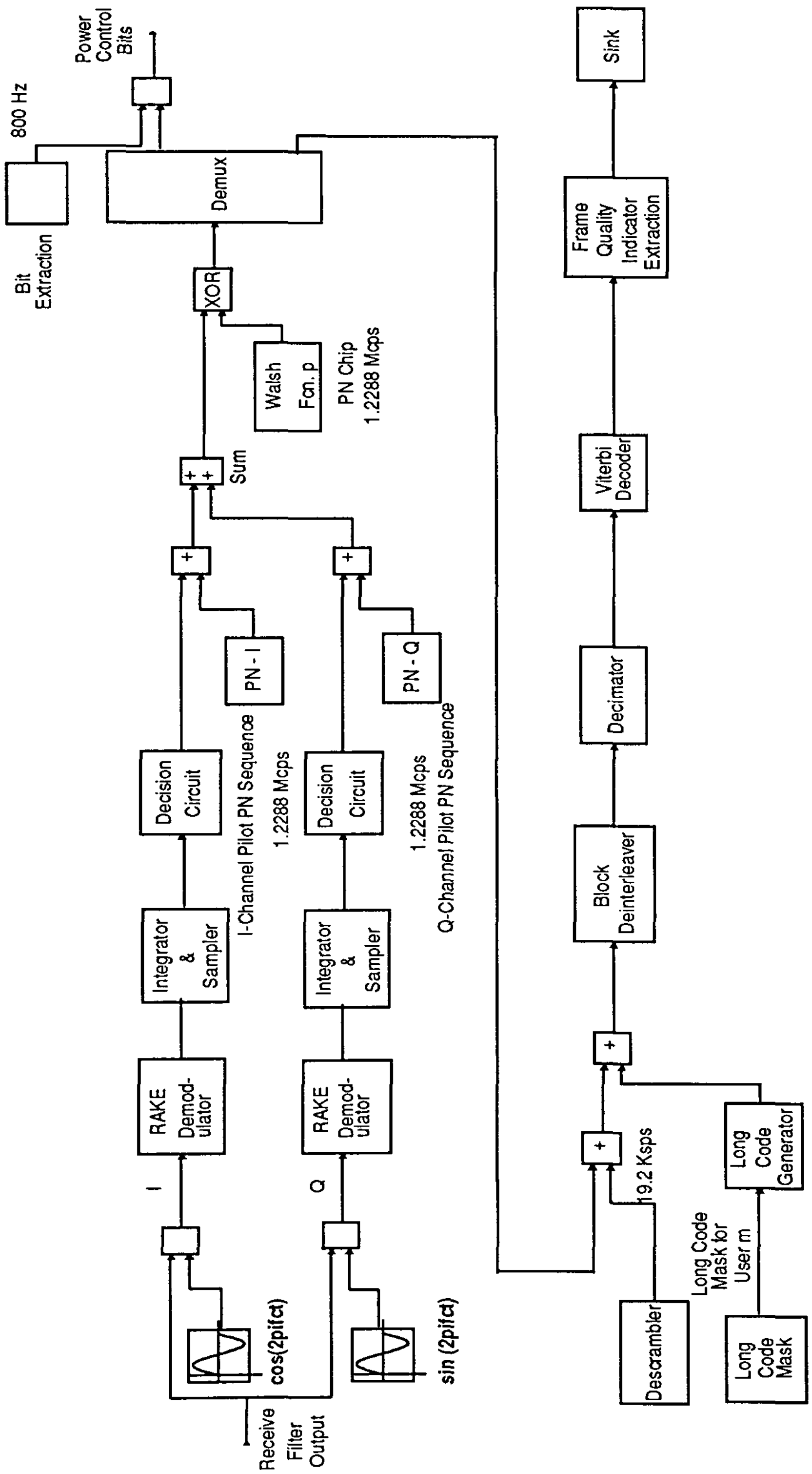


Figure 4.12 Receiver Structure

The power control bit extraction process in the mobile station receiver replaces the complimentary operation of data burst randomization in the base station receiver. The subsystems forming the receiver are described as follows.

4.4.1 Integrator and Sampler

The Integrator and Sampler block performs integration of the input waveform over one chip period and outputs this value at the end of the chip period. The integrator is reset after every chip period, T_c (=813.802 ns). This is implemented using the Integrator, Sample and Hold blocks in SIMULINK as shown in Figure 4.13.

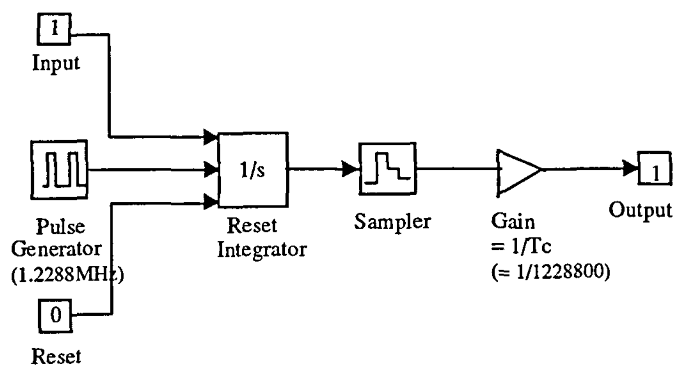


Figure 4.13 Integrator and Sampler (SIMULINK Block Representation)

4.4.2 RF Demodulators

QPSK and OQPSK demodulation can be carried out using local carrier references as shown in Figure 4.14. For simulation purposes, perfect carrier recovery and time synchronization are assumed. Hence the local references are assumed to be of the same frequency as the RF carriers and there is no phase error (since $\theta = \hat{\theta}$). The complex low-pass equivalent of the received signal can be derived as follows. Since

$$S(t) = I(t)\cos(2\pi f_c t + \theta) - Q(t)\sin(2\pi f_c t + \theta),$$

the demodulated outputs $I_o(t)$ and $Q_o(t)$ are given by

$$\begin{aligned}
I_o(t) &= \frac{1}{T_c}\int_0^{T_c}\left[2I(t)\cos^2(2\pi f_c t + \theta) - 2Q(t)\sin(2\pi f_c t + \theta)\cos(2\pi f_c t + \theta)\right]dt \\
&= \frac{1}{T_c}\int_0^{T_c}\left[I(t)\left\{1 + \cos 2(2\pi f_c t + \theta)\right\} - Q(t)\sin 2(2\pi f_c t + \theta)\right]dt \\
&\simeq I(t) \qquad (4.4)
\end{aligned}$$

$$\begin{aligned}
Q_o(t) &= \frac{1}{T_c}\int_0^{T_c}\left[-2I(t)\cos(2\pi f_c t + \theta)\sin(2\pi f_c t + \theta) + 2Q(t)\sin^2(2\pi f_c t + \theta)\right]dt \\
&= \frac{1}{T_c}\int_0^{T_c}\left[-I(t)\sin 2(2\pi f_c t + \theta) + Q(t)\left\{1 - \cos 2(2\pi f_c t + \theta)\right\}\right]dt \\
&\simeq Q(t) \qquad (4.5)
\end{aligned}$$

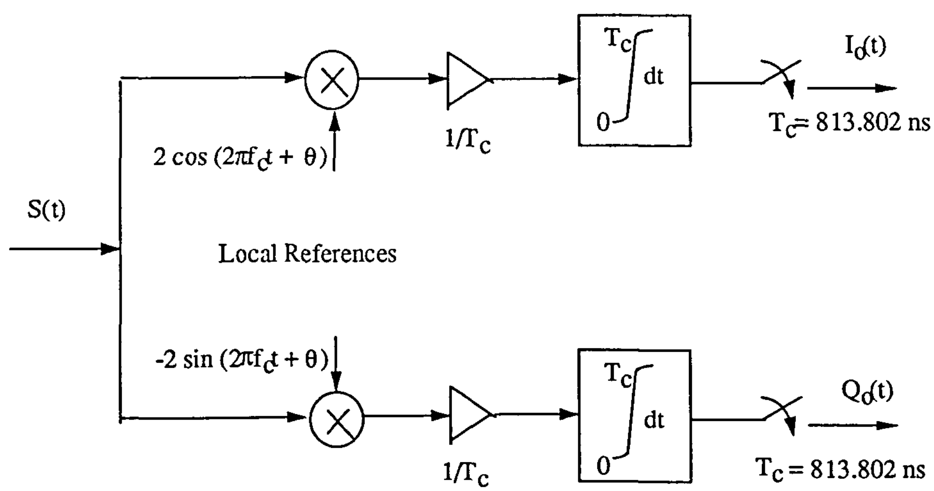


Figure 4.14 Typical QPSK Demodulator

Thus the embedded I and Q sequences are demodulated. The local references are implemented using the Sine blocks in SIMULINK and the integrate and sample operations were implemented using the Integrator and Sampler subsystem described above.

4.4.3 RAKE Receiver

The problem of digital signaling over frequency-selective channel can be modeled by a tapped delay line with statistically independent time-variant tap weights $\{c_n(t)\}$. This tapped delay line model provides L replicas of the same transmitted signal at the receiver. A receiver that processes the received signal in an optimum manner will achieve the performance of an equivalent L-th order diversity communications system. This is comparable to a multipath channel. Hence, a tapped delay line receiver that attempts to collect the signal energy from all the received signal paths that fall within the span of the delay line and carry the same information is an optimum receiver for processing wideband signals that suffer from multipath fading effects. Since the action of such a receiver is analogous to the garden rake, it has been named "RAKE receiver" by Price and Green (1958) [3].

The RAKE receiver is implemented using the Transport Delay blocks for the delays and Gain blocks for the tap gains in SIMULINK as shown in Figure 4.15. The taps on the RAKE receiver are synchronized to the detected paths in the received signal using the Delay blocks. The decision variable is obtained from the noncoherent combination of the matched filter (integrater and sampler) outputs. This is achieved by delaying these outputs and synchronizing them at a time equal to $(T+\Delta w)$ where T is the estimated time from the symbol synchronization and Δw is the maximum

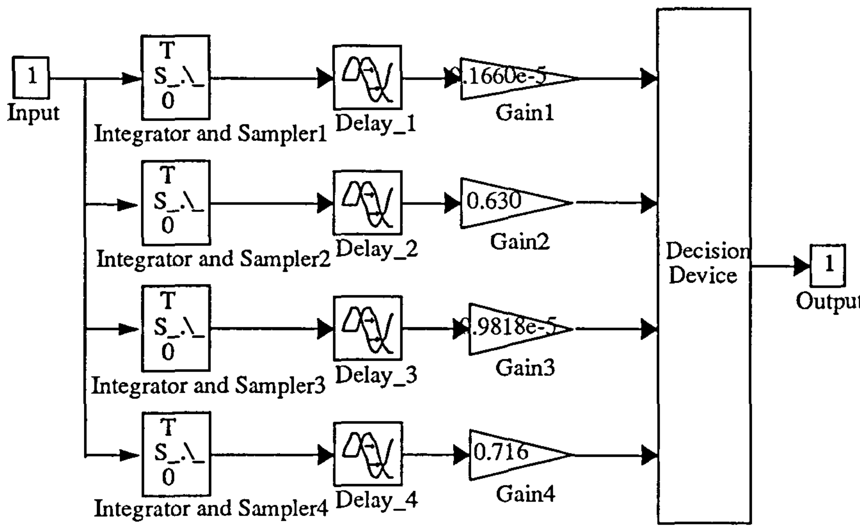


Figure 4.15 RAKE Receiver Structure (SIMULINK Block Representation)

delay of the radio channel. If the correlator outputs are represented as $\xi(T - \tau_i)$, $i = 1, 2..K$ where τ_i is the ith time delay and K is the number of paths, the decision variable can be expressed as

$$\varsigma = \sum_{i=1}^{K} \beta_i \xi_i (T + \Delta w) \tag{4.6}$$

where β_i is the normalized tap gain corresponding to the strength of the ith path. The decision block outputs a '1' for $\varsigma < 0$ and '0' for $\varsigma \geq 0$.

CHAPTER 5. MULTIPATH CHANNEL MODEL

5.1 Introduction

A wave propagation mechanism is closely affected by wavelengths of the propagation frequencies. In man-made environments, buildings ranging from 18 to 30 m in width and 12 to 30 m in height form natural wave scatterers. The dimensions of such scatterers are equivalent to many wavelengths of a propagation frequency, creating reflected waves. Assuming that the antenna height of a mobile unit is much lower than the height of an average building, it can be assumed that all buildings are scatterers. Under these conditions, an RF signal propagating at frequencies above 30 MHz forms multipath propagation medium. Since the base station to mobile station link (forward link) is usually less than 24 km, there is no radio-path loss due to the earth's curvature.

The typical dimensions of the base station antenna height for a large cell of radius 6.5 to 13 km (or 4-8 miles) is between 30 and 50 m in small suburban areas and over 50 to 90 m in large cities. While the average height of a mobile station antenna is around 2-3m. Hence the base station has comparatively noise free surroundings while the mobile station antenna is embedded in a noisy environment. The terrain configuration as well as the man-made environment in which the communication link lies, determine the overall propagation path loss.

The above description of a mobile radio propagation channel indicates that the mobile station receives one relatively strong direct wave and many reflected waves from different angles, uniformly spaced over 0 to 2π radians [22]. Hence the channel is called multipath channel. Depending on the presence or absence of the direct wave (as in the case of urban environments), the channel can be described using a Rician or Rayleigh statistical model, respectively.

The nature of multipath and its influence on the characteristics of mobile radio propagation indicates that an exact or deterministic characterization of the channel is not possible [23]. Hence statistical communication theory is used to model the mobile radio propagation channel.

5.2 The Multipath Channel

The combined effect of the direct and reflected waves in a mobile radio propagation channel is called multipath fading. The fading signal has three basic components contributing to the variations in its signal strength described as follows.

5.2.1 Propagation Path Loss

The free space propagation path loss is due to the frequency of transmission and the distance of the mobile from the base station and can be described as,

$$\frac{P_{or}}{P_t} = \left[\frac{1}{4\pi d(f/c)}\right]^2 = \left[\frac{1}{4\pi(d/\lambda)}\right]^2 \tag{5.1}$$

where c is the speed of light, λ is the wavelength, P_t is the transmitted power and P_{or} is the received power in free space. Hence the free-space propagation path loss is 6 dB/octave or 20 dB/decade. Since the radio signal traveling through a

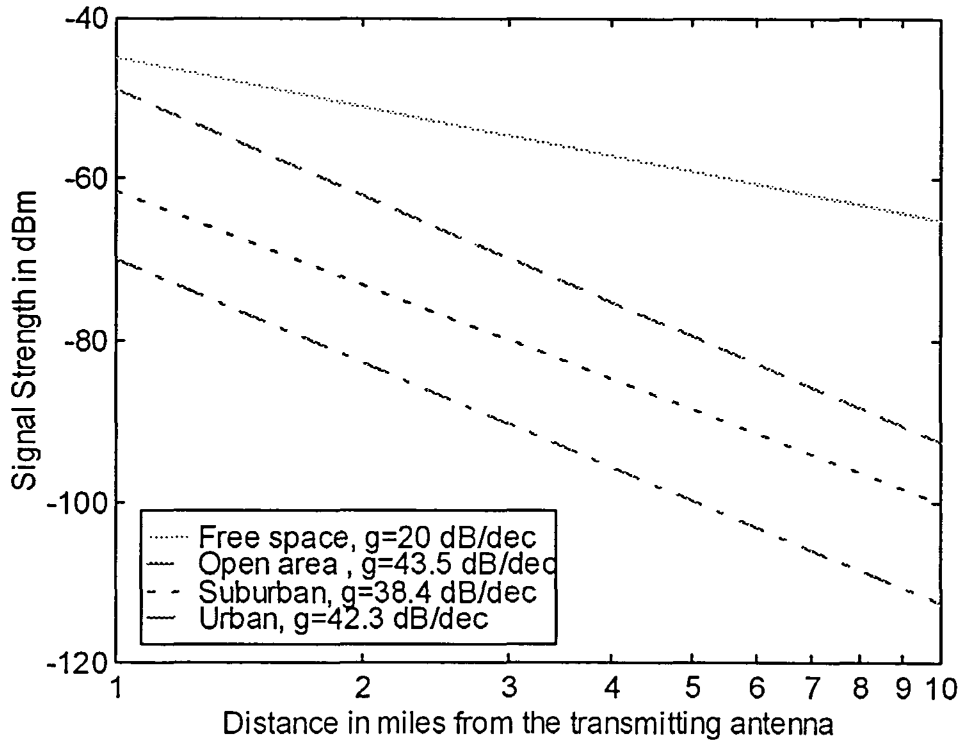


Figure 5.1: Propagation path loss for different environments.

mobile propagation environment undergoes attenuation due to terrain configuration and man-made obstacles, the propagation path loss increases at a much faster rate as can be seen in Figure 5.1. These values were used in the Gain blocks of SIMULINK in the multipath channel model for simulation purposes.

5.2.2 Long-Term Fading

Long-term fading or slow fading is caused by movement of the mobile over distances large enough to produce gross variations in the overall path between the transmitter and receiver. Since the variations are caused due to the mobile moving into

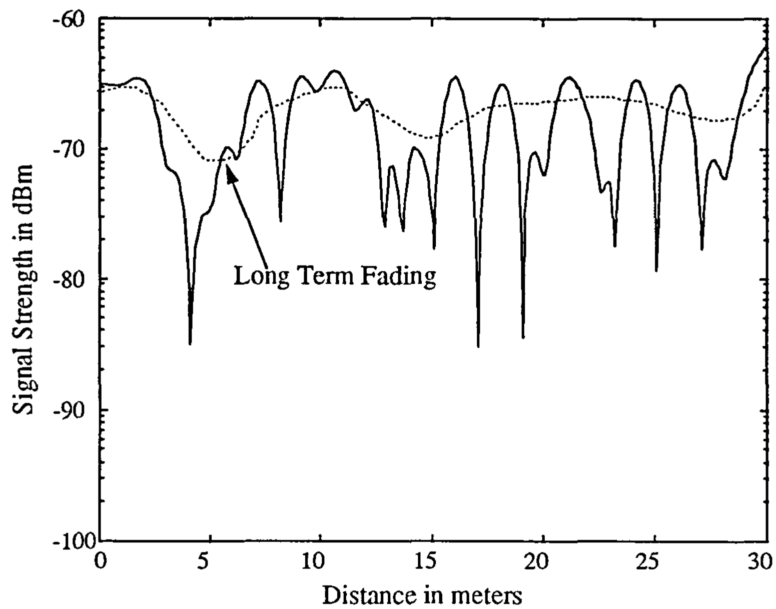


Figure 5.2: Long Term Fading

the shadow of hills or buildings, it is also called shadowing. This results in attenuation and fluctuations in the local-mean of the fading signal as shown in Figure 5.2. Measurements indicate that the mean path loss closely fits a log-normal distribution with a standard deviation that depends on the frequency and environment [4]. Okumura's measurements in Tokyo showed that when the median signal strength was computed over 20 m sectors and the standard deviation determined over areas of diameter 1 to 1.5 km, the values all lay in the range 3 to 7 dB. These proportionally increased with the cell size. Typical values of standard deviation were 7 dB at 200 MHz rising to 10 dB at 3000 MHz for suburban areas. In urban areas, values were 2 dB lower. Since the frequency of interest here is between 825 and 900 MHz, standard deviations of 8 dB and 6 dB were used for suburban and urban environment models. The lognormal pdf can be represented as

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left[-\frac{(y-m)^2}{2\sigma_y^2}\right] \tag{5.2}$$

where the lognormal variable y, its mean m, and its standard deviation σ_y are in dB scales[22]. Lognormal variations in the local mean of the signal were brought about using the random number generator and the logarithm function blocks as in Figure 5.5.

5.2.3 Short-Term Fading

Short-term fading is caused by multipath reflections of a transmitted wave by local scatterers such as buildings and forests surrounding a mobile unit. A typical received signal is shown in Figure 5.3. Amplitude variations of such a signal transmitted over a mobile propagation channel shows occasional deep fades and quasiperiodic occurrence of minima. Many researchers have shown that the envelope of the mobile radio signal is Rayleigh distributed when measured over distances of a few tens of wavelengths where the mean signal is sensibly constant. This suggests that at any point, the received field is made up of a number of horizontally traveling plane waves with random amplitudes and angles of arrival for different locations. The phases of the waves are uniformly distributed from 0 to 2π. The amplitudes and phases are assumed to be statistically independent. Other models have also been proposed but they lead to comparable statistical properties of the field for large numbers of constituent waves.

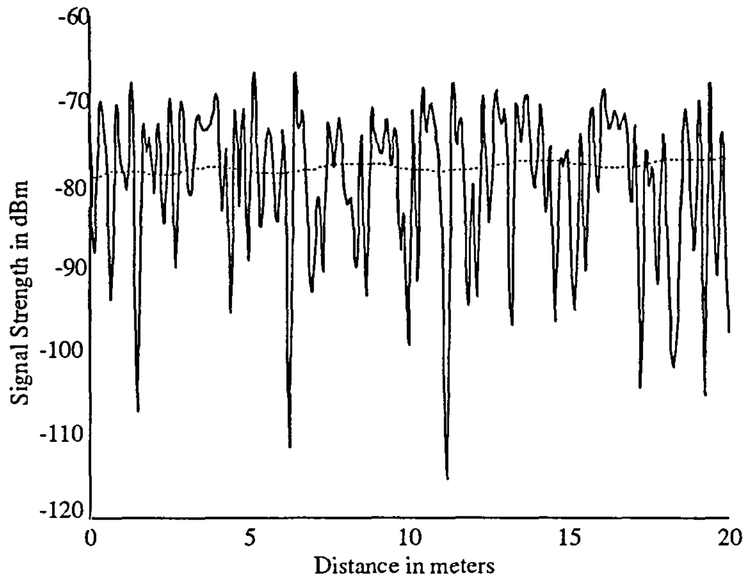


Figure 5.3: Experimental record of received signal envelope in an urban area.

The Rayleigh pdf is represented as

$$p(r) = \frac{r}{\frac{\sqrt{\overline{r^2}}}{2}} \exp\left(-\frac{r^2}{\overline{r^2}}\right) \tag{5.3}$$

where $\overline{r^2}$ is the average power of the short-term fading signal, or $\sqrt{\overline{r^2}}$ is the rms value of r. The standard deviation σ_r is

$$\sigma_r = \frac{\sqrt{4-\pi}}{2}\left(\sqrt{\overline{r^2}}\right) \tag{5.4}$$

and the mean of r is

$$m = \frac{\sqrt{\pi}}{2}\left(\sqrt{\overline{r^2}}\right) \tag{5.5}$$

When the direct wave and the reflected waves form the received signal, the fading signal has a Rician pdf given by

$$p(r) = \frac{r}{\frac{\sqrt{\overline{r^2}}}{2}} \exp\left(-\frac{r^2 + a^2}{\overline{r^2}}\right) I_0\left(\frac{r}{\sqrt{\overline{r^2}/2}} . \frac{a}{\sqrt{\overline{r^2}/2}}\right) \tag{5.6}$$

where r is the envelope of the fading signal, $\overline{r^2}$ is the average power of the fading signal, a is the amplitude of the direct wave and $\mathrm{I}_0\,(.)$ is the modified Bessel function of zero order which can be represented as

$$I_0\,(z) = \sum_{n=0}^{\infty} \frac{z^{2n}}{2^{2n} n! n!}$$

When the direct wave does not exist, a is zero, the pdf becomes Rayleigh and (5.6) becomes (5.3) [22].

5.2.4 Simulated Multipath Channel Model

Experimental evidences such as those described above gave rise to a three-stage model to describe mobile radio propagation, an inverse n-th power law with range from the transmitter to the receiver, (the path loss values are read off from the graph shown in Figure 5.1), lognormal variations of the local mean and superimposed fast fading which follows a Rayleigh distribution. Since Rayleigh fading is caused by the combined effect of time delayed components of the radio signal reaching the receiver, a discrete model based on the channel impulse response was developed as follows. (Since Doppler effects in the multipath channel required complex computations which SIMULINK could not handle [21], the implemented model was based on the static characteristics of a channel).

The effects of the multipath channel on the transmitted radio signal can be described using the concept of the complex envelope of the signal and the corresponding response of the channel [9]. The transmitted signal can be represented as

$$s(t) = \mathrm{Re}[u(t)\exp(j\omega_c t)] \tag{5.7}$$

where $u(t)$ is the complex low-pass envelope of the signal. If there are multiple propagation paths the received band-pass signal for a time-invariant channel can be written as

$$x(t) = \sum_{n=0}^{N} \alpha_n s(t - t_0 - \tau_n) + n(t) \tag{5.8}$$

where t_0 is the propagation time delay for the first arriving component of the multi-path signal, α_n and τ_n are the attenuation and additional propagation delay for the nth path, and $n(t)$ is the additive Gaussian noise. Substituting for $s(t)$ from (5.7) (ignoring t_0) gives for the received signal

$$x(t) = \mathrm{Re}\left[\left\{\sum_{n=0}^{N} \alpha_n \exp(-j\omega_c\tau_n)u(t-\tau_n)\right\}\exp(j\omega_c t)\right] + n(t) \tag{5.9}$$

The equivalent low-pass received signal is then given by (ignoring the noise term)

$$r(t) = \sum_{n=0}^{N} \alpha_n \exp(-j\omega_c\tau_n)u(t-\tau_n) \tag{5.10}$$

The impulse response of the equivalent low-pass channel is

$$c(\tau) = \sum_{n=0}^{N} \alpha_n \exp(-j\omega_c\tau_n)\delta(t-\tau_n) \tag{5.11}$$

The term $\omega_c\tau_n$ is the phase associated with the nth path. In the limit, when there is a continuum of multiple paths, the received signal, i.e. x(t) in (5.8), is

$$x(t) = \int_0^{\infty} \alpha(\tau)s(t - t_0 - \tau)d\tau + n(t) \tag{5.12}$$

and the impulse response is then

$$c(\tau) = \alpha(\tau)\exp(-j\omega_c\tau) \tag{5.13}$$

The path delay t_0 is suppressed so that the impulse response is represented relative to the first arrival of the signal at the receiver. Since there are many paths, the received signal can be modelled as a zero-mean complex Gaussian random process. The autocorrelation function of $c(\tau)$ can then be defined as

$$R_c(\tau_1, \tau_2) = \frac{1}{2}E[c^*(\tau_1)c(\tau_2)] \tag{5.14}$$

For a wide sense stationary uncorrelated scattering channel (WSSUS), the attenuation and phase shift of the channel at the delay τ_1 are uncorrelated with those at the delay τ_2. The autocorrelation function can then be expressed as

$$R_c(\tau_1, \tau_2) = P_c(\tau_2)\delta(\tau_1 - \tau_2) \tag{5.15}$$

where the delta function implies uncorrelated scatterers. But the function $P_c(\tau_2)$ in a general form $P_c(\tau)$ is the average power received as a function of delay time τ for an impulse input. The function $P_c(\tau)$ is called the 'multipath intensity profile' or 'power delay profile' of the channel and can be regarded as the scattering function averaged over all Doppler shifts [24]. $P_c(\tau)$ can also be considered as the probability density function of the average power as a function of time and is obtained as the average of several individual profiles [11] as in (5.16). A typical power delay profile is shown in Figure 5.4.

$$P_m(\tau_k) = \frac{1}{M}\sum_{i=1}^{M} p_i(\tau_k) \tag{5.16}$$

A measure of the width of an average power delay profile that is relevant in assessing the impact on a communications system performance is delay spread, s_m, defined as the square root of the second central moment of a profile m and expressed as

$$s_m \triangleq \left[\frac{\sum_{k=1}^{K}(\tau_k - d_m - \tau_A)^2 P_m(\tau_k)}{\sum_{k=1}^{K} P_m(\tau_k)}\right]^{1/2} \tag{5.17}$$

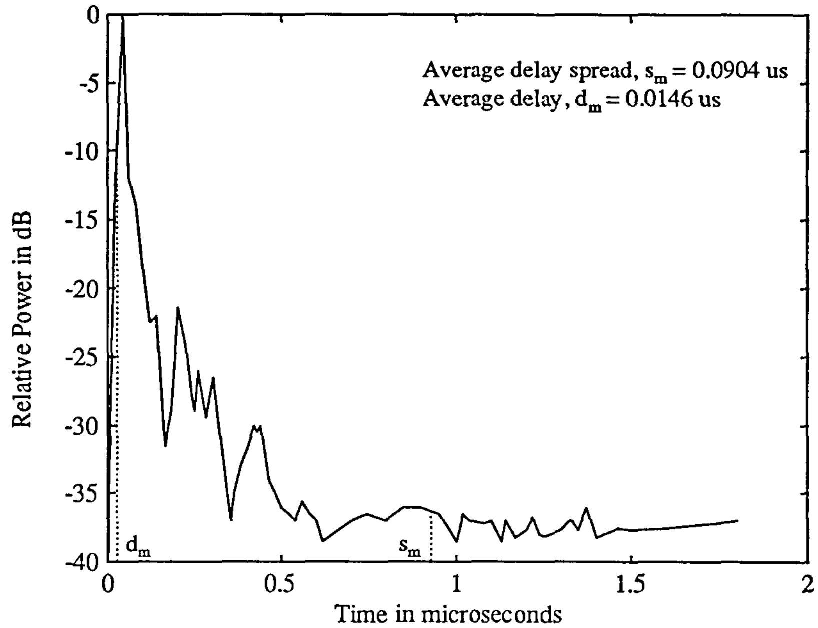


Figure 5.4: Sample Power Delay Profile

where k ranges over the entire time duration of the measuring window, τ_k is the time delay of the kth sample and d_m is the average delay, the first moment of the profile with respect to the first arrival delay τ_A, defined as

$$d_m \triangleq \frac{\sum_{k=1}^{K} \tau_k P_m(\tau_k)}{\sum_{k=1}^{K} P_m(\tau_k)} - \tau_A. \tag{5.18}$$

The delay of the last significant component above -10 dB in the power delay profile is called the average excess delay, E_d. The energy of the signal outside the window between τ_A and E_d is negligible and is set to zero for computations of the tap gains and tap delays in the RAKE receiver.

Measurements of power delay profiles from [5-11], described in Chapter 2, were

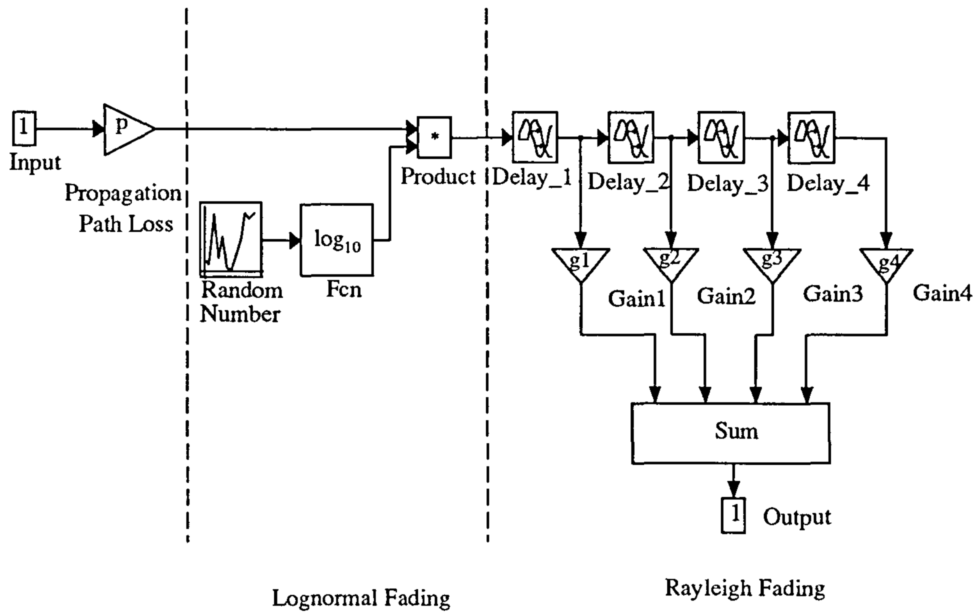


Figure 5.5 Multipath Channel Model

incorporated into the discrete model for the multipath channel (see Figure 5.5). This provided measurement based channel models for performance evaluation of the communication system. Multipath channel impulse responses or power delay profiles were divided into four categories; open area, suburban, urban and indoor environments, based on the description of the locations where the measurements were made. Values of parameters α_n, the attenuation along the path arriving after a time delay, τ_n were estimated from the power delay profiles. These were then used in the Gain and Transport Delay blocks of the simulated overall multipath channel model.

CHAPTER 6. SIMULATION RESULTS

6.1 Introduction

Simulation of a complex communication system requires the reduction of block diagrams to simpler equivalents. This can be done by replacing processes passed through chains of equipment by an equivalent process or the judicious combination of analysis with simulation. The latter requires the adoption of a suitable simulation methodology which is discussed in Section 6.2. The performance of any communication system is governed by two important factors: signal-to-noise ratio (SNR) and the accumulated signal distortions in terms of the bit error rate (BER). Functional descriptions are used to estimate these factors for the simulated communication system model.

6.2 BER Estimation

For a digital communication system, the relevant measure of performance is related to the system's error-producing behavior. This behavior may be characterized in different ways. The most common aspect considered, however, is the case where a system transmits symbols and the average production of errors in an indefinitely long sequence is measured as the bit error rate (BER) [4]. Three of the simulation-based approaches for estimating the BER are described as follows.

6.2.1 Monte Carlo Simulation

Monte Carlo is the name for implementation of a sequence of Bernoulli trials where the number of 'successes' (errors) are divided by the number of trials. This method requires no assumption about the input processes or the system as shown in Figure 6.1. Since the source output is known it is compared with a delayed version of the decision device output to obtain an empirical basis for the error rate. The knowledge of this relative delay is implied since perfect carrier and symbol synchronization are assumed. The BER can be written as

$$b = \int_{\nu \in D_0} f_V(\nu) d\nu \qquad (6.1)$$

where f_V is the pdf of sampled zeros at sampling epoch τ. D_0 is the region of ν

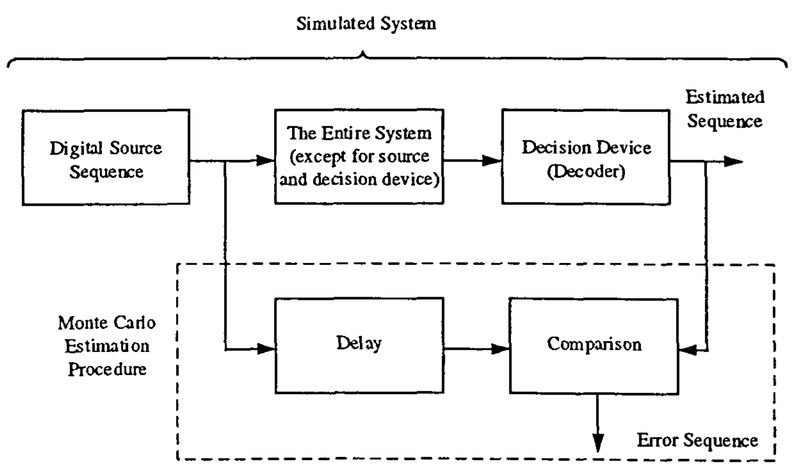


Figure 6.1: Schematic representation of Monte Carlo estimation procedure

that corresponds to an error. An *error indicator function* can be defined such that

$$H(\nu) = \begin{cases} 1, & \nu \in D_0 \\ 0, & \nu \notin D_0 \end{cases} \tag{6.2}$$

and (6.1) can be rewritten as

$$b = \int_{-\infty}^{\infty} H(\nu) f_V(\nu) d\nu \tag{6.3}$$

which is equivalent to

$$b = E[H(V)] \tag{6.4}$$

where E is the expectation operator. Since a natural estimator $\hat{b}$ of the expectation is the sample mean, it can be expressed as

$$\hat{b} = \frac{1}{N_0} \sum_{i \in I_0} H(V_i) \tag{6.5}$$

where $\mathrm{V}_i \triangleq V(t_i)$ is the sequence of symbol-spaced samples of the decision voltage, I_0 is an integer set that contains all i such that t_i corresponds to sampling a 'zero,' and N_0 is the number of elements in the set. Hence $H(V_i)$ acts as an error detector, the summation is an error counter and $1/N_0$ is the normalizing factor. Assuming all symbols have the same probability of occurrence, (6.5) can be extended to apply irrespective of the symbol, namely,

$$\hat{b} = \frac{n(N)}{N} \tag{6.6}$$

where N is the total number of symbols processed and n is the total number of errors observed. As $N \to \infty$, $\hat{b}$ converges to b by the law of large numbers.

$H(V_i)$ is implemented using an XOR gate since the transmitted alphabet consists of {0,1}. The summation and normalization are done on the MATLAB workspace after the simulation run is completed. Thus, (6.5) is implemented as the BER Estimator block.

A closed form for the confidence interval is obtainable for the estimator distribution in the Monte Carlo method in terms of the cumulative beta distribution [4]. Moreover the Monte Carlo estimator is unbiased and its variance goes to zero when $N \rightarrow \infty$. Hence this simulation methodology was adopted though the relevant equations needed to be solved iteratively.

6.2.2 Importance Sampling

Importance sampling is a form of Monte Carlo simulation in which the statistical properties of the noise processes driving the system are altered such that many more errors are produced per unit time. Since a known change is introduced, it can be corrected for. The net effect is the reduction in simulation runtime. If the system is assumed to have a single zero-mean Gaussian noise source, the mean and variance are the parameters that can be altered. Since the system under consideration has various noise sources with varying distributions (Lognormal, Rayleigh and Rician), alteration and correction of their parameters become computationally intensive. Moreover the BER estimator is biased. Hence this simulation methodology was not adopted.

6.2.3 Extreme Value Theory

Extreme value theory is based on the fact that the limiting distribution of the largest value of any random variable falls into one of three classes, and that the area under the tails of all the densities within a class converge to a common form. The class of interest in the context of communication system includes exponential type distributions like Rayleigh, Gaussian, etc. This simulation methodology estimates the parameters underlying these distributions. Though it offers a runtime advantage, extreme value theory is an asymptotic theory (valid, in the limit, as the sample size becomes indefinitely large) and assumes that the underlying distribution of the noise source is completely known. Since this is not the case with multipath effects, this simulation methodology was not adopted.

6.2 SNR Estimation

The standard measure of performance for a noisy signal is the signal-to-noise ratio (SNR). Assuming that output of the decision block after the RAKE receiver is a signal corrupted by additive noise, the combined signal can be represented as

$$x = s_0 + n_0 \tag{6.7}$$

where the s_0 is the signal and n_0 is the noise component. Then can be expressed as

$$s_0 = As_\tau \tag{6.8}$$

where

$$s_\tau = \begin{cases} s(t-\tau), & 0 \le t \le T \quad or \quad s(iT_s - \tau), \quad i = 1, 2, ...N \\ 0 & elsewhere \end{cases} \tag{6.9}$$

and A is the amplitude of the signal. The average squared error is then defined as

$$\varepsilon^2 = \left\langle (x - As_\tau)^2 \right\rangle \tag{6.10}$$

which is minimized over all A and τ. It can be shown that [2] (6.10) is minimized when

$$u(\tau, A) = A^2 \left\langle s_\tau^2 \right\rangle - 2AR_{xs}(\tau) \tag{6.11}$$

is minimized, where

$$\left\langle s_\tau^2 \right\rangle = \frac{1}{N}\sum_{k=1}^{N} s^2(kT_s - \tau) \tag{6.12}$$

is the N-point average power, and

$$R_{xs}(\tau) = \frac{1}{N}\sum_{k=1}^{N} x(kT_s)s(kT_s - \tau) \tag{6.13}$$

Assuming there exists a unique $A = A_*$ and $\tau = \tau_*$ which minimizes (6.11), for the applicable τ_* it can be shown that [4]

$$A_* = R_{xs}(\tau_*)/\left\langle s_{\tau_*}^2 \right\rangle \tag{6.14}$$

which indicates that A_* can be determined once τ_* is known. Hence for such a measurement, the SNR estimate $\hat{\rho}$ is given by

$$\hat{\rho} = \left\langle s_0^2 \right\rangle / \varepsilon^2 \tag{6.15}$$

In the system under consideration, s_0 is a pulse waveform with amplitude, $A = 1$ and ε^2 is obtained from (6.10) as the time average of the square of difference in the source and output digital waveforms as shown in Figure 6.1. Thus the SNR is estimated.

6.3 Transmitter Characteristics

Modulation is an important part of the transmitter in any communication system. There are several criteria that must be considered in choosing a modulation technique for a digital cellular system such as spectral efficiency, adjacent-channel interference, BER performance, applicability to cellular environment and implementation capabilities. These factors determine the overall performance of a communica-

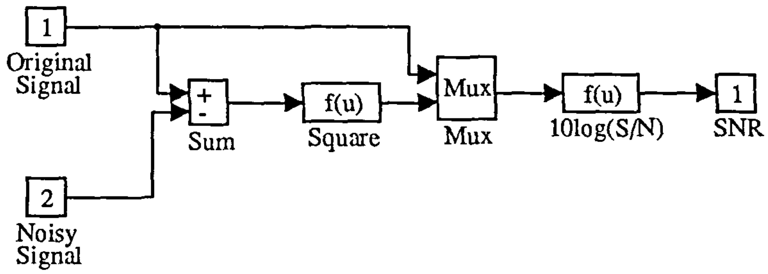


Figure 6.2: SNR Estimation

tion system and are dependent on the characteristics of the baseband and broadband data signals.

Baseband data for the simulated IS-95 based communication system at 1.2, 2.4, 4.8 and 9.6 kbps rates were generated. The convolutional encoder was implemented and tested in terms of its impulse response by observing its output for a single '1' bit input [20]. Walsh functions are used to modulate the code symbols to form the code channels. The orthogonality property ($P = 0$) of the implemented Walsh codes or functions were tested using the correlation relation

$$P = \frac{1}{N}(N_s - N_d) \tag{6.16}$$

where $N = 64$, N_s is the number of $S's$ and N_d is the number of $D's$ in the following comparison of two Walsh codes [25]:

$$\begin{array}{cccccccccc} 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ D & S & S & D & D & S & D & S & D & D \end{array}$$

Direct sequence spreading is achieved using the modified maximal length PN sequence. Since the information rate on the traffic channel is 9.6 kbps and the chip rate of the PN sequence is 1.2288 Mcps, the processing gain can be computed from the following expression,

$$PG = 10\log\frac{B_{ss}}{B}(\text{in dB}) \tag{6.17}$$

where the information bandwidth, $B = 9.6kHz$ and the direct sequence bandwidth, $B_{ss} = 1.2288MHz$ yielding a processing gain of $21dB$. Data modulation on the forward link is Quadrature Phase Shift Keying and on the reverse link is Offset Quadrature Phase Shift Keying.

The performance characteristics of the communication system in multipath cellular environment is of interest here. Hence the 2^{15} long PN sequence was QPSK modulated with a carrier frequency of 870 MHz, passed through the multipath channel and detected using a RAKE demodulator. The BER and SNR were estimated and the performance characteristics of the system determined. It was sufficient to evaluate the performance for forward link since the propagation path for forward and reverse links are identical as given by the reciprocity principle for the multipath channels considered here [22].

6.4 Receiver Characteristics

The prime function of a receiver is to detect the signal, input to the communication system, as closely as possible. This is achieved by compensating for the channel effects in addition to performing all the complimentary operations of the transmitter. The complimentary operations include symbol synchronization (which is assumed) and QPSK demodulation. A 6 dB degradation in performance was included to compensate for the convolutional encoder and block interleaver [4]. However, the fading effects of the multipath channel was modified to provide a sophisticated method for obtaining diversity. This was possible due to the wideband nature of the DSSS signal. The optimum receiver that follows the above description is called a RAKE correlator [20].

A four-way RAKE receiver to demodulate the four strongest multipath components received on two diversity antennas is shown in Figure 6.3 [26]. In this configuration, the decision output from each of the active demodulators is fed to an external microprocessor. The microprocessor combines the individual demodulator decisions, weighing each one by the relative strength of the respective multipath component and generates a single stream of soft-decision inputs to the Viterbi decoder. But this type of diversity combining is sub-optimal since an independent decision on the transmitted orthogonal symbol is being made by each individual demodulator.

Hence an optimum combining diversity receiver was developed where the number of taps are equal to the number of paths in the power delay profile and the tap gains were estimated from the strength of the signal component along the corresponding path. The test setup is shown in Figure 6.4. The noise threshold chosen to distinguish between a signal and noise component was -94 dBm [27]. The multi-

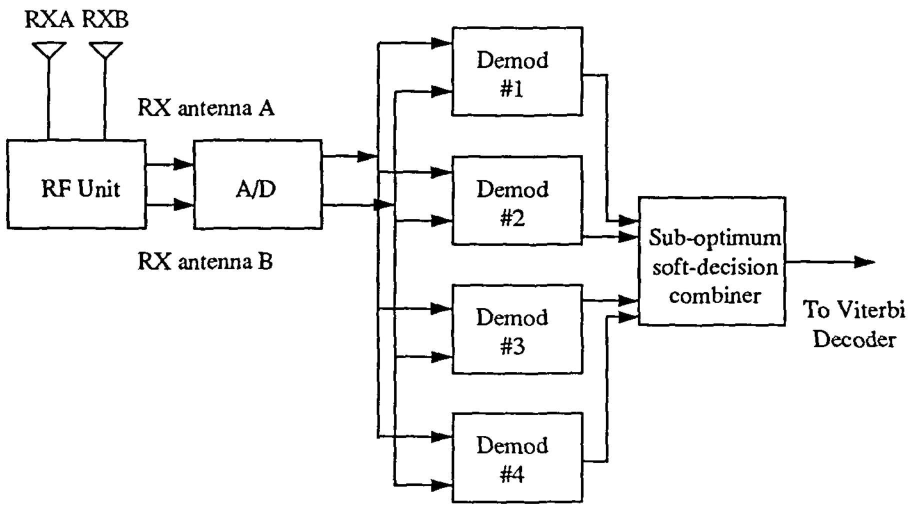


Figure 6.3: Sub-optimal multipath diversity receiver architecture

path channel and RAKE demodulator structures are described in Sections 5.2.4 and 4.4 respectively. Profile 1 is the file containing power delay profile measurements obtained from [28] for a suburban environment. The obtained performance characteristics are shown in Figure 6.5. Optimum combining RAKE receiver shows a 2.5 dB improvement in the required SNR for a BER of 10^{-3}.

6.5 Multipath Channel Characteristics

The distinguishing factor in a multipath channel is the fading due to multiple echoes of the transmitted signal reaching the receiver via different paths. Time-

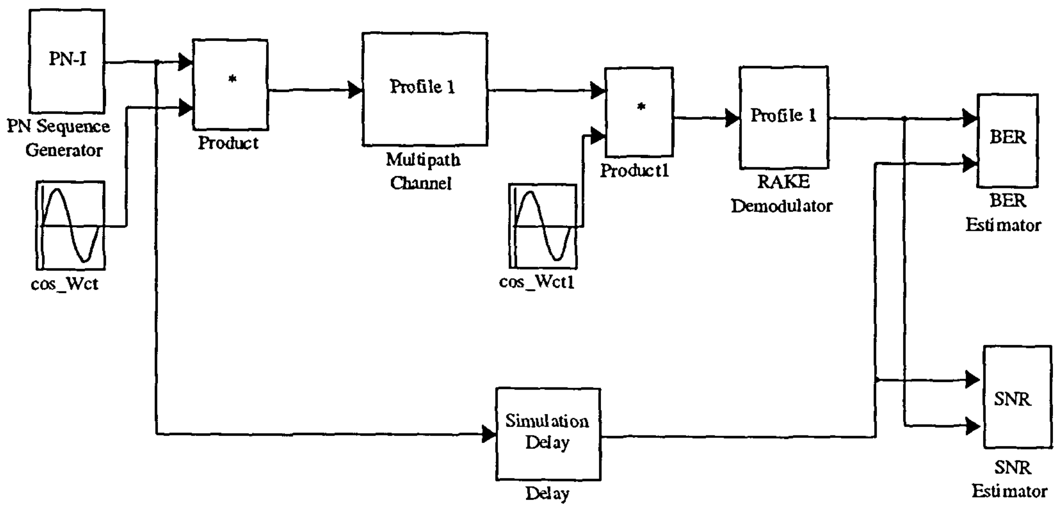


Figure 6.4: Simulation Test Setup.

delayed echoes can overlap causing errors in digital systems due to intersymbol interference. In this case, increasing the signal-to-noise ratio will not cause a reduction in error rate and so the delay spread sets the lower bound on error performance for a specified data rate. This limit is often termed as the irreducible error rate. The performance of the system can however be improved by the use of channel equalization and diversity (RAKE receiver) techniques.

Some of the observed characteristics in the power delay profiles of open area, suburban, urban and indoor environments are tabulated in Table 6.1. A noise threshold of -94 dBm or 35 dB below the strongest component was used to distinguish between

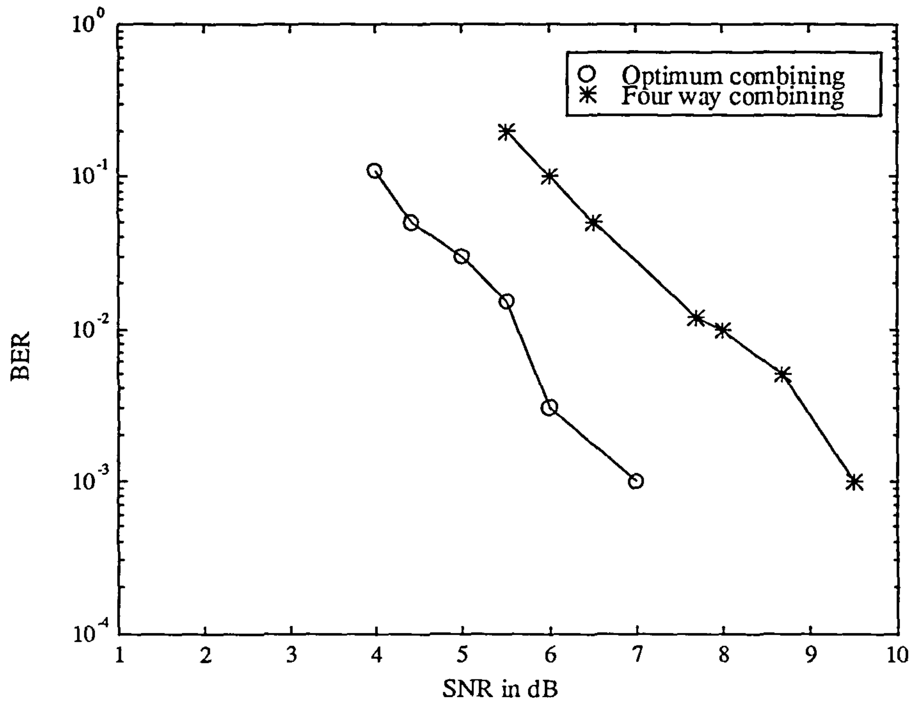


Figure 6.5: Comparison of BER Vs SNR for optimum and four-way combining RAKE diversity receiver.

signal and noise components and to estimate the number of paths and the average (or rms) delay spreads from the power delay profiles in [5-11].

Open area environments are characterized by very small average delay spread values with less than 4 paths. The direct component is almost always present in them and they do not require channel equalization. Suburban environments also provide a good propagation medium when the direct component is present and the reflected components are well above the noise floor. Hence diversity combining proves highly efficient for such environments. Urban and indoor channels, however, have many

Table 6.1: Observed Channel Characteristics

Type of Channel	Number of Paths, K	Average Delay Spread, s_m (in μs)
Open Area	$K < 4$	$0.5 < s_m < 0.9$
Suburban	$5 < K < 8$	$1 < s_m < 5$
Urban	$8 < K < 15$	$s_m \geq 3$
Indoor	$K > 5$	$s_m < 1$

reflected paths and can be differentiated by the fact that the latter have shorter paths and hence considerably smaller average delay spread values.

The delay spreads by themselves do not provide very precise measures for system evaluation. It is therefore more useful to provide statistics about the number of paths and their time delays. These results are then used in designing hardware and software simulators such as diversity combining receivers. However, there are extreme cases in all the four categories of multipath channels which provide the limiting values [9].

CHAPTER 7. CONCLUSIONS

A software simulation technique to implement an IS-95 standard based CDMA spread spectrum communication system was developed. Major subsystems (encoders, modulators, demodulators) required to estimate the performance of the system in a mobile cellular environment were simulated and tested. A multipath channel model consisting of Lognormal and Rayleigh fading simulators and a path loss component was implemented. The performance of the system with regard to BER was determined and compared for 4-way and optimum combining RAKE receivers. The optimum combining RAKE receiver provides $2.5dB$ improvement in SNR for a BER of 10^{-3}. Characteristics of multipath channels for open area, suburban, urban and indoor environments with regard to average delay spread and number of discrete paths were compared based on power delay profile measurements. A simple and straightforward criterion to characterize multipath channels is also suggested.

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APPENDIX

WALSHFUN.M

(NOT INCLUDED IN SIMULINK)

```
function [b]=walshfun(c);
h = hadamard(64);
for i = 1:64
for j = 1:64
if h(i,j) == 1
a(i,j) = 0;
else a(i,j) = 1;
end
end
end
b = zeros(1,64);
b = a(c,1:64);
return;
```

HADAMARD.M

(NOT INCLUDED IN SIMULINK)

```
function H = hadamard(n);
[f,e] = log2([n n/12 n/20]);
k = find(f==1/2 & e > 0);
if isempty(k)
error(['N, N/12 or N/20 must be a power of 2.']);
end
e = e(k)-1;
if k == 1
H = [1];
elseif k == 2
H = [ones(1,12); ones(11,1) ...
toeplitz([-1 -1 1 -1 -1 -1 1 1 1 -1 1],[-1 1 -1 1 1 1 -1 -1 -1 1 -1])];
elseif k == 3
H = [ones(1,20); ones(19,1) ...
hankel([-1 -1 1 1 -1 -1 -1 -1 1 -1 1 -1 1 1 1 1 -1 -1 1], ...
[1 -1 -1 1 1 -1 -1 -1 -1 1 -1 1 -1 1 1 1 1 -1 -1])];
end
for i = 1:e
H = [H H H -H];
end
return;
```