GENETIC ALGORITHM ASSISTED OPTIMUM DETECTION FOR BLOCK DATA TRANSMISSION SYSTEMS

by

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Thesis submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy

August 2010

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr.Mohd. Fadzli Mohd. Salleh for his kind and dedication in supervising me, without whom, I would not have completed this research. Secondly I would like to thank my co-supervisor Prof. Farid Ghani, my mentor who gave me an opportunity to work under him in Universiti Sains Malaysia. I would like to thank Dr. Laurel Kimura who corrected English for all my research papers and this thesis. I would like to thank Balan Sinnaih for his help in getting me around USM. I would also like to thank KDU College Penang Campus for allowing to take up part time research program in USM. Last but not least I would like to thank Malaysian government and people for their love and affection they have shown towards me during my stay.

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LIST OF ABBREVATIONS

AWGN	Additive Gaussian White Noise
AP	Access point
ASIC	Application Specific Integrated Circuit
BSS	Base Service Sets
BlER	Block Error Rate
BDTS	Block Data Transmission Systems
BLE	Block Linear Equalizers
BDFE	Block Decision Feedback Equalizer
BGA	Binary GA
BPSK	Binary Phase Shift Keying
BER	Bit Error rate
CIR	Channel Impulse Response
CDMA	Code Division Multiple Access
CU	Control Unit
CP	Cyclic Prefix
dB	Decibel
DFE	Decision Feedback Equalizer
DAB	Digital Audio Broadcasting
D/A	Digital to Analog
DVB	Digital Video Broadcasting
DMT	Discrete Multi Tone Modulation
DDB	Distance to the decision boundary
ETA	Expanding Tree Algorithm

FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
FIR	Finite Impulse Response
1G	First generation
Gbps	Giga Bits per Second
GA	Genetic Algorithms
HDL	Hardware Description Languages
IC	Integrated Circuit
IBI	Inter Block Interference
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
iFFT	Inverse Fast Fourier Transform
KHz	Kilo Hertz
LOS	Line of Sight
LE	Linear Equalizer
LFSR	Linear Feedback Shift Register
LTE	Linear Transversal Equalizer
MAC	Medium Access Layer
MMSE	Minim Mean Square Error
ML	Maximum Likelihood
MLSD	Maximum Likelihood Sequence Detection
MLBD	Maximum Likelihood Block Detection
μGA	Micro Genetic Algorithms
MVA	Modified Viterbi algorithm
MC	Multi Carrier

MCM	Multi Carrier Modulation
N-LOS	Non Line of Sight
NLBE	Non-Linear Block equalizer
OFDM	Orthogonal Frequency Division Multiplexing
P/S	Parallel to Serial
PHY	Physical Layer
PE	Processing Elements
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
QoS	Quality-of-Services
RF	Radio frequency
2G	Second Generation
S/P	Serial to Parallel
SNR	Signal To Noise Ration
SC	Single Carrier
SC-FDMA	Single Carrier - Frequency Division Multiple Access
SISO	Single Input Single Output
SIMD	Single Instruction Multiple Data
TDL	Tapped delay line
3G	Third generation
TSP	Traveling Salesman Problem
VA	Viterbi Algorithms
VC	Virtual Channels
WLAN	Wireless Local Area network

WMAN	Wireless Metropolitan Area Network
ZF	Zero Forcing
ZP	Zero Padding

LIST OF SYMBOLS

μ	Micro
η	Gaussian noise variable
δ	Delta function
$\forall$	For all
Σ	Summation
Λ	Probability
σ	Variance of AWGN
π	Pi
®	Registered trademark
$\int$	Integration
∞	Infinity
$\leq$	Less than or equal to
$\geq$	Greater than or equal to
$\neq$	Not equal to
*	Convolution
T_b	Pulse duration
m	Block size
h	Channel Impulse Response
g	Known symbols size
$\theta_c(f)$	Channel phase response
N_o	Amplitude of Noise Spectral Density
z	Dimension of the signal space
P_{rc}	Raised Cosine pulse
R_{xx}	Autocorrelation
R_{xy}	Cross correlation
κ	Efficiency of the Block Data Transmission System
S	Transmitted message blocks
b_i	Uninterrupted bit stream
H	Channel matrix
N	Sample values of the statistically independent Gaussian

random variables representation with zero mean and with a common variance σ^2

n	Received block
$\subset$	Belongs to (Used in description of sets)
d_{min}	Minimum distance
P_{BER}	Probability of bit error
P_{blER}	Probability of block error
N_{min}	Number of blocks having d_{min}
m_g	Cyclic Prefix length in OFDM
e	Euclidean distance

PENGESAN OPTIMUM DENGAN BANTUAN GENETIK ALGORITMA UNTUK SISTEM PENGHANTARAN BLOK DATA

ABSTRAK

Dunia sedang memperlihatkan peningkatan dalam keperluan untuk transmisi data berkeupayaan tinggi di bidang applikasi multimedia tanpa wayar. Masalah penyuraian saluran berasaskan masa bukannya sesuatu yang baru di dalam sistem transimisi data berkeupayan tinggi tanpa wayar. Teknologi-teknologi baru yang mempergunakan kaedah transmisi data berbentuk "block" di mana data ditukarkan ke bentuk "block" yang diasingkan oleh simbol yang telah diketahui terlebih dahulu, telah diperkenalkan untuk megatasi masalah ketidaksepasangan disebabkan oleh penyuraian saluran. Pengaturan kaedah sebegini menyekat "Inter Symbol Interference" di dalam "block" tertentu dan membenarkan pemprosesan data secara "block" demi "block". System transmisi data berbentuk blok (BDTS) merupakan salah suatu teknik yang berpromisi dan didapati di dalam generasi keempat teknologi tanpa wayar seperti "Orthogonal Frequency Division Multiplexing (OFDM)", "Single Carrier Frequency Division Multiple Access (SC-FDMA)" dan "Discrete Multi Tone (DMT) Modulation Scheme". Di dalam BDTS, besar kemungkinan pemprosesan pengesanan adalah optimum tetapi pelaksanaannya memerlukan penghitungan yang intensif. Semasa saluran tanpa wayar mengalami kehilangan yang mendalam atau memorinya berlebihan berbanding simbol yang dikenali terlebih dahulu, kadar ralat bit (BER) memberi kesan kepada "Quality of Service (QOS)". Di dalam kes-kes sebegini, pengesanan ML menjadi mandatori. Kaedah untuk pelaksanaan pengesan ML adalah diperlukan untuk bersearah dengan kemajuan dalam teknologi "microchip". Di dalam penyelidikan ini, "Genetic Algorithm" (GA) digunakan sebagai kaedah untuk melaksanakan pengesan ML. Pengesan berasaskan GA direka untuk system komunikasi "Single Carrier" (SC) dan juga "Multi Carrier" (MC). Di dalam sistem komunikasi SC, saluran dengan kehilangan yang mendalam akan digunakan. Manakala di dalam sistem komunikasi MC, saluran yang bermemori lebih daripada "Cyclic Prefix" (CP) yang menghasilkan BER rendah akan dipertimbangkan. Kerumitan penghitungan dikurangkan melalui pengurangan kecil di dalam prestasi BER daripada pengesan optimum dengan menggunakan GA di dalam pengesan ML, contohnya sistem pencarian "Exhausitive". Analisis masalah di dalam pengesan ML yang lebih lanjut, memperkenalkan GA yang berlainan jenis, contohnya "Micro-GA" (μGA) untuk membantu proces pengesanan. μGA menggunakan populasi yang kecil dan bantuan penghitungan minima berbanding dengan GA. Seni bina perkakasan untuk pelaksanaan "Hybrid - μGA" dicadangkan dengan menggunakan seni bina selari berjenis "Single Instruction Multiple Data". Prestasi BER di dalam μGA adalah sebanding dengan sistem pengesan optimum dan menawarkan pengurangan sebanyak 50% di dalam penghitungan berbanding dengan GA. Process pengacukan di antara GA dan μGA dengan meghasilkan populasi awal daripada output pengesan linear "suboptimal" telah memperbaiki pemusatan GA berasaskan pengesan ML. Ini telah megurangkan lagi 50% kerumitan penghitungan.

GENETIC ALGORITHM ASSISTED OPTIMUM DETECTION FOR BLOCK DATA TRANSMISSION SYSTEMS

ABSTRACT

Recent years have witnessed an increase in demand for higher transmission data rates for wireless multimedia communications applications. Wireless data transmission systems with high data rates always face problems over time dispersive channels. New technologies that employ block data transmission where the data is converted into blocks separated by known symbols have been introduced to combat the impairments due to dispersive channels. This arrangement confines the Inter Symbol Interference (ISI) to a particular block and allows Block-by-Block data processing. Block Data Transmission Systems (BDTS) is one of the promising techniques for high data rate data transmission and found in the fourth generation wireless technologies such as Orthogonal Frequency Division Multiplexing (OFDM), Single Carrier Frequency Division Multiple Access (SC-FDMA) and Discrete Multi Tone (DMT) Modulation schemes etc. In BDTS, Maximum Likelihood Block-by-Block detection processing is optimum but computationally intensive to implement. When wireless channels experience deep fades or when the channel memory is longer than the known symbols, Bit Error Rate (BER) affects the Quality of Service (QOS). In these cases ML detection becomes mandatory. The methods for implementation of ML detectors are necessary with today's advances in microchip technologies. In this research Genetic Algorithm (GA) is used as a method to implement ML detectors. The GA based detectors are designed for Single Carrier (SC) as well as Multi Carrier (MC) communication systems. In SC communication systems, channels with deep fades are used. In MC communication

systems, channels whose memories are longer than Cyclic Prefix (CP) that produce low BER are considered. By using GA for ML detection, computational complexity is reduced with small reduction in terms of BER performance from the optimum detector, i.e., the Exhaustive search system. Further analysis of the problems in ML detectors has introduced a variant of GA, i.e., Micro-GA (μGA) to assist the detection process. The μGA uses a smaller population and less computational recourses as compared to GA. The hardware architecture for implementation of the Hybrid- μGA is proposed, using a Single Instruction Multiple Data type of parallel architecture. The BER performance of μGA is comparable with the optimum detector system and offers 50% reduction in computation as compared to GA. The hybridization of GA and μGA by generating the *Initial population* from the output from a suboptimal linear detector has improved the convergence of GA based ML detectors, which led to another 50% percent reduction in computational complexity.

CHAPTER 1
INTRODUCTION

1.1 Preface

The demand for high data rate mobile services with spectral, power efficiency and stringent Quality-of-Services (QoS) is expected. The challenges posed in the fourth generation (4G) mobile communication systems will be enormous. The users will demand a particular service with particular QoS. For example, the data rate of such systems is expected to have more than 1Giga bits per second (Gbps). One of a few hurdles to achieve high data rate is Inter Symbol Interference (ISI), which is due to the underlying channel characteristics in a mobile environment. With the help of advances in semiconductor technologies and advanced signal processing algorithms, we can construct complex communication systems that will meet the demands of the future.

A Block-by-Block transmission scheme found in the present and proposed future communication technologies are designed to reduce ISI. In this system blocks of data symbols are separated by zero symbols/known symbols, which confine the ISI to a block. Orthogonal Frequency Division Multiplexing (OFDM), Single Carrier Frequency Division Multiple Access (SC-FDMA), Discrete Multi Tone Modulation (DMT) schemes, to name a few, operate on a Block-by-Block basis. Certain multiple antenna systems operate in this fashion, and Block-by-Block detection is also found in some multiuser Code Division Multiple Access (CDMA) systems (Xu, et al., 2006).

Multipath fading channels cause severe ISI (Sklar, 1997). Shortwave ionospheric radio, tropospheric scatter radio and land mobile radio are a few examples of such channels. In Single Carrier Block Data Transmission Systems (SC-BDTS) when there is a null in the channel frequency response or in a Multi Carrier (MC) system like OFDM having channel length in excess of the Cyclic Prefix (CP) length or when there is clipping noise, the effects of ISI is high. This effect leads to a high Bit Error Rate (BER) that cannot be efficiently dealt by a Zero Forcing (ZF) equalizer or a Decision Feedback Equalizer (DFE). The use of optimum detectors like Maximum Likelihood Sequence Detection (MLSD) becomes mandatory in this case (Proakis & Sallehi, 2002). Even though Viterbi Algorithms (VA) can be used to implement optimal detectors, their computational complexity increases with an increase in signal sets and channel memory. In BDTS the number of zero symbols/known symbols per data block is dependent on the channel memory. Short data blocks based BDTS can have VA type optimum detectors with reduced efficiency (Kaleh, 1995). A large data blocks based BDTS is preferred, but optimum detection in such a system leads to high complexity. In such cases global optimization techniques like Genetic Algorithms (GA) are the alternate choice to implement such optimal detectors.

1.2 Problem Statement

It is found that when ISI is severe, the MLSD is superior to other equalizer methods. The performance can be further improved by converting symbols as blocks, separated by known or zero symbols. This blocking of symbols restricts the effect of ISI to be confined to a single block and allows block based processing. In BDTS, Block-by-Block processing is optimum and symbol based processing is suboptimum. Equalizers for this block based data transmission system are the Block Linear Equalizer (BLE) and the Block Decision Feedback Equalizer (BDFE), which are symbol based, and the Maximum Likelihood Block Detection (MLBD), which is block based. In the MLBD, if a symbol is represented by one bit then, a block (message) of size *m*, when received should be compared with all possible 2^m blocks in the receiver. When this comparison is based on Euclidean distance, then it is equivalent to the implementation of an optimum detection procedure (Proakis & Salehi, 2002). For small block sizes, all possible transmitted blocks can be searched. This is called an Exhaustive Search, and it becomes quite impossible when the block size is increased for efficiency as the number of known symbols is fixed irrespective of block size. A global optimization process like GA can replace the Exhaustive Search. In this research, the optimum detection problem is implemented using GA, a global search technique.

This implementation has to be analyzed in terms of performance and complexity. The performance in terms of BER is done using MATLAB® based simulation. The GA has various parameters and they are problem dependent. For this problem these parameters are analyzed and the best are to be taken. New variants of GA like Micro-GA (μGA) are also to be considered. Hybrid systems consisting of a simple conventional system assisted by a complex intelligent system are proven to be more efficient than using an intelligent system alone. An intelligent system like using GA based optimum detectors which is an intelligent system can be integrated with suboptimal linear equalizers, which are simpler in terms of implementation. All the above systems are to be analyzed in terms of their BER performance, complexity and hardware implementation issues.

1.3 Objectives of the Research

The present research centers on the BDTS, which has many advantages and applications, as discussed in the previous section. The key objectives of this research include:

1. To develop a GA assisted optimal BDTS receiver for Single Carrier and Multi Carrier communication systems.
2. To develop a reduced complexity GA using Hybrid techniques (Hybrid-GA) assisted optimum detector for Single Carrier and Multi Carrier communication systems.
3. To use Micro GA and hybridize the same to further reduce the complexity of the optimum detector for Single Carrier and Multi Carrier communication systems.

1.4 Summary of Original Contributions

The original contributions of the research can be generally categorized into two different areas namely: GA based BDTS for Single Carrier communication systems and GA based BDTS for Multi Carrier communication. The contributions are summarized below:

1. GA assisted MLBD for SC-BDTS

Extensive studies in BDTS equalizers did not concentrate on the MLBD due to the complexity of the Exhaustive Search procedure involved. In this research the suitability of GA for SC-BDTS is proposed and the performance is compared with the Exhaustive Search process.

2. Hybridization of the GA process.

GA starts with a set of possible solutions. The solution in this case is a set of possible messages that would have been transmitted. In this research to speed up convergence, the starting space, which has probable solutions, will have the output of BLE and its neighbors. The neighbors are the blocks which differ by one, two or three bits from the output of the BLE. By doing this, computational complexity is reduced by a substantial amount.

3. Micro-GA (μGA) used instead of GA.

The μGA uses a smaller population size than GA and its fast convergence, when compared to GA is reported for many applications. This technique is tried with BDTS and its BER performance is comparable to GA based BDTS with a reduced complexity.

4. Development of the Hybrid-μGA based optimal detectors in IEEE 802.11a based WLAN

The algorithms and techniques developed for the SC-BDTS are applied for Wireless Local Area Networks (WLAN) as defined in the IEEE 802.11a system. In the literature, GA based optimum detection was used in OFDM systems under nonlinear distortion. The other possible scenario where MLBD is mandatory is when channel length is higher than Cyclic Prefix (CP) length. For this scenario, in this research, μGA and Hybrid-μGA are used along with Ordinary GA as an optimum detector. This detector has shown similar performance as Maximum Likelihood (ML) detectors in terms of BER but with a reduction in complexity of about fifty percent (50%) and above.

1.5 Scope of the Work

In this research, the SC-BDTS uses zero symbols as guard symbols. Therefore, no channel estimation is performed. Instead, the Channel Impulse Response (CIR) is assumed as the known quantity in advance and time invariant. This arrangement allows the performance analysis of various equalizers and detectors under different levels of deep fades and channel lengths. In Multi Carrier BDTS (MC-BDTS) consideration, IEEE 802.11a is used instead of the recent IEEE 802.11n, which is better in terms of performance and capacity. The reason for choosing IEEE 802.11a is due to the simplicity in simulation.

The existing Single Instruction Multiple Data (SIMD) architecture for GA is extended for μGA and the performance of μGA in SIMD architecture is compared. No Field Programmable Gate Array (FPGA) or Application Specific Integrated Circuits (ASIC) implementation is done.

1.6 Thesis Organization

The remainder of the thesis is organized into six chapters. Chapter 2 serves as a background for the reader. In this chapter, for a continuous transmission digital communication system, the effect of noise, ISI and their combination is detailed. Various methods to mitigate those effects are also shown in detail. The chapter also includes the topic of channel modeling and noise consideration for deriving probability of error. Chapter 3 presents the literature review of the BDTS, its signal format and its impairments. Part of this chapter is dedicated to the earlier remedy of using equalizers to mitigate the impairments encountered. A visit to the concept and applications of GA and its variants is presented. The earlier proposal of GA for detection in an OFDM system under clipping noise along with a few applications of GA for a CDMA system is shown in detail.

In Chapter 4, the methodology opted for implementing the GA and its variants assisted optimum detector for SC-BDTS and MC-BDTS is presented. The procedure for calculating the computational complexity of the GA, GA variants and Exhaustive Search based detectors are also shown. The chapter also deals with design procedure used to study the performance of GA and μGA on parallel architectures.

Chapter 5 provides the results, which mainly include the BER performance analysis of GA and its variants based optimum detectors for both SC and MC communication systems. For SC systems, channels with spectral nulls and for MC systems channel length higher than CP length are taken into consideration. The results were compared with the Exhaustive Search method, which is an optimum detector implementation and the BLE which is the simplest method. In Chapter 6 the conclusions and future research direction of the thesis is presented.

CHAPTER 2
IMPAIRMENTS IN DIGITAL WIRELESS COMMUNICATION

2.1 Introduction

Many applications in wireless multimedia communication such as video telephony, wireless Internet, Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), etc., require a large volume of data transmission over a limited amount of resources. The high data rate transmissions especially through the time dispersive communications channels, introduce Inter Symbol Interference (ISI). This interference is the major limiting factor in such communication systems. It is well known that equalizers are used to combat ISI (Proakis & Salehi, 2002). They come in different types of design complexity and offer different performances.

In order to study the effect of ISI towards transmission data, it is very important to analyze the properties of the channels. Much research has been done to study the channel properties which led to channel models. Although channel modeling is not part of the objectives of this research, it is important to study how the properties of the channels contribute to ISI which is impairment to the communication systems. The Additive White Gaussian Noise (AWGN) is impairment due to the electron movement in a certain device that affects the transmitted signal. Thus, in a way, it limits the performance of the communication system. In this chapter the channel models, along with their properties used in the research, are studied. Section 2.2 provides the basic discussion about ISI in digital communications; Section 2.3 introduces the multipath fading effects along with channel modeling. In Section 2.4, the effect of noise on digital wireless transmission is studied. Section 2.5 presents the equalizers, and in Section 2.6 the Maximum

Likelihood Sequence Detectors (MLSD) are studied. Section 2.7 compares various equalization methods, and Section 2.8 concludes the chapter.

2.2 Inter Symbol Interference and their Effects

2.2.1 Introduction to Digital Communication

Digital communication systems, which use a predefined set of electrical signals to represent digital messages, are the preferred choice due to immunity to noise, cheap hardware, error control and security. Noise is inherent in any communication system. The messages, that can be voice, music, image or video, can be represented in digital format as bits. These bits are either directly or grouped together and mapped to electrical signals, which are then transmitted over the analog communication channels. The bits, which can be as individuals or as groups, are called symbols. In real world communication scenarios, we come across different types of channels, source destination pairs, signals, QoS, number of users, traffic over communication links, etc. In the case of digital communication systems, the design of a communication system for a specific scenario is unique. However the impairments seen in almost any communication system are the same.

2.2.2 General Block Diagram of Digital Communication Systems

A complete digital communication system used in the real world can be shown as a block diagram. The block diagrammatic approach is a system level representation that gives the overall function of each block. Each block, in turn, can be decomposed into smaller blocks until the need for decomposition vanishes.

The general block diagram of a digital communication system is shown in Figure 2.1. It contains three parts, namely the transmitter, channel and receiver, along with related functional blocks. In the transmitter, the source encoder removes the redundancy, and the channel encoder adds controlled redundancy for error detection and correction. The baseband modulator maps the bits into suitable signals for Radio Frequency (RF) modulation. The transmit filter restricts the bandwidth of the source. The communication channel in the research is assumed to be a wireless channel where noise and other interferences are added to the modulated signal.

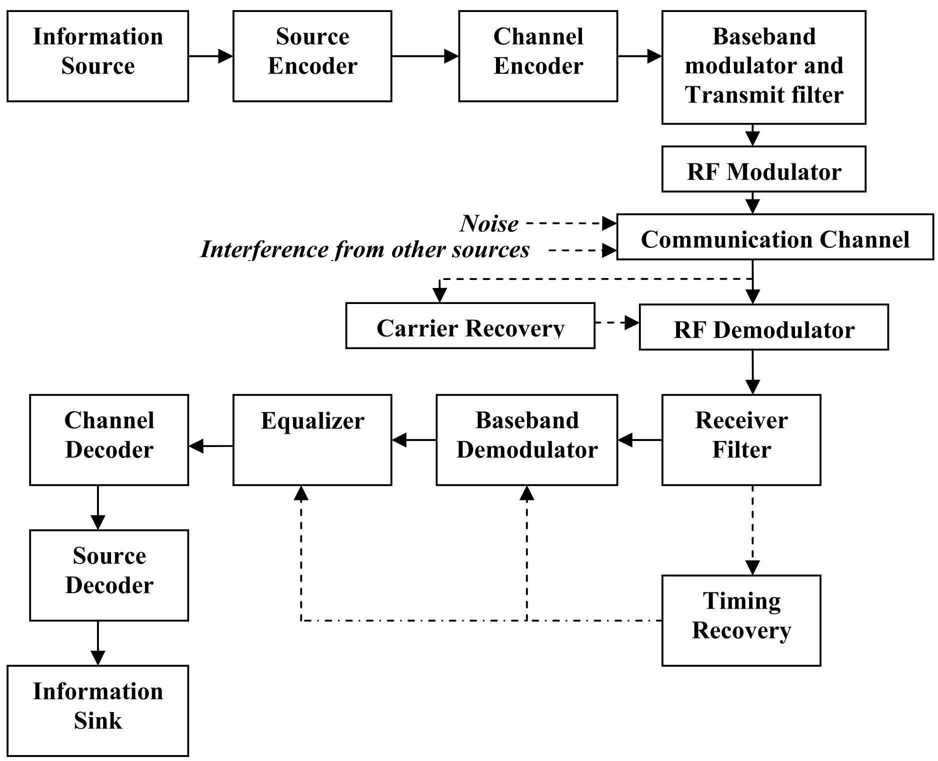


Figure 2.1 Block diagram of a digital communication system (Haykin, 1997)

In digital communication, good waveforms can be selected to match the channel impairments, thereby increasing the reliability when compared to an analog system, where such a possibility is not available (Anderson, 1997). In the receiver, the reverse process of the transmitter is performed so that the messages are retrieved from the changes it went through during transmission. The additional system blocks like carrier recovery and timing recovery are used to aid the receiver to process the received signals with more accuracy. Due to efficiency, cost reduction, and reliability, digital communication has replaced the analog communication system.

2.2.3 Simplification and Approximation for Simulation

In general research design of any new or better digital communication systems, the objective of research plays an important role in dealing with the complexity of design and analysis. In Section 2.2.2, the general description of the digital communication systems clearly indicates that designing and testing the whole system is very complex and time consuming. Therefore a high level model as shown in Figure 2.2 is more suitable, as it has few parameters and reduces the computational burden if simulation is to be performed (Tranter et al., 2006). Simulation is used to design and analyze a communication system without prototyping it in the laboratory. It has the advantage of reducing the development time and cost of the research. The results of such simulations are also accurate to a level of prototyping and testing. Approximations and assumptions are used to simplify simulation (Tranter et al., 2004). However if a part of the system is studied by itself, this can be done at a low level, while keeping other blocks at a high level. As seen in the abstract of this research, mainly the detection process is taken into consideration and the Bit Error Rate (BER) performance is one of the main goals. A much-simplified model which can be taken into consideration is shown in Figure 2.2. In this model the source and channel encoder/receiver is removed along with RF modulation. The BER of a digital communication system in RF or baseband transmission is the same. This leads to the removal of RF modulation/demodulation along with the carrier recovery, as it is also assumed that timing is unaltered in the simulation process.

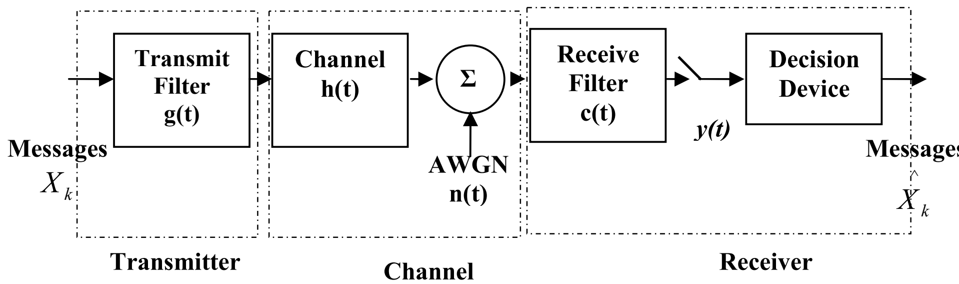


Figure 2.2 Simulation model of a baseband digital communication system

A general baseband digital communication system is shown in Figure 2.2. It consists of a transmit filter to restrict the bandwidth of the message signals and a bandlimited linear time invariant channel corrupted by AWGN. The linearity and time invariance is an approximation when the analysis is done for a short time. In the receiver there is another filter to restrict the out-of-band noise, and a decision device used as a detector to make a decision on the received signal as it is corrupted by noise. If the blocks are considered as linear, the overall response of the cascaded or parallel blocks can be added or multiplied, thereby greatly reducing the complexity and simulation time.

2.2.4 Communication Through Inter Symbol Interference Channels

In Figure 2.2 we found that the messages X_k, when communicated over a channel, are corrupted by the noise. The received messages $\hat{X}_k$ may be the same as transmitted or different due to the addition of noise. When they are different, then an error has occurred. The other source of error in a digital communication system is ISI. In this section, the problem of ISI is illustrated. Let the messages be binary and let these messages be called as symbols. A symbol may have one or more bits. When a symbol having a single bit is converted to an antipodal rectangular pulse m_k , the amplitude of each bit is defined as

$$m_k = \begin{cases} +1 \text{ if symbol } X_k \text{ is } 1 \\ -1 \text{ if symbol } X_k \text{ is } 0 \end{cases} \tag{2.1}$$

If *g(t)*, *h(t)* and *c(t)* are impulse responses of the transmit filter, channel and the receive filter, respectively, the transmitted signal *s(t)* is defined as

$$s(t) = \sum_k m_k g(t - kT_b) \tag{2.2}$$

The output of the receive filter is written as

$$y(t) = \alpha \sum_k m_k p(t - kT_b) + \eta(t) \tag{2.3}$$

The pulse *p(t)* is the rectangular pulse, which is used to represent "1" or "-1". The received pulse is due to the double convolution

$$\alpha p(t) = g(t) * h(t) * c(t) \tag{2.4}$$

where "*" represents convolution and for a normalized pulse *p(0)* = 1, α accounts for the scaling in the amplitude, and $\eta(t)$ is assumed to be AWGN.

The receiver samples the output in synchronization with the transmission and compares the sampled value to a threshold. If the value of the sample is higher than the threshold, it decides as "1" and otherwise as "0".

In deciding the reception of the i^{th} pulse the received signal *y(t)* is sampled at time $t_i = iT_b$ (with *i* taking on integer values and T_b the pulse rate).

$$y(t_i) = \alpha \sum_{k=-\infty}^{\infty} m_k p[(i-k)T_b] + \eta(t_i) \tag{2.5}$$

$$y(t_i) = \alpha m_i + \alpha \sum_{\substack{k=-\infty \\ k \neq i}}^{\infty} m_k p[(i-k)T_b] + \eta(t_i) \tag{2.6}$$

In Equation 2.6 the first term is due to the i^{th} pulse and the second term is due to the residual effect of all other pulses (Proakis & Salehi, 2002). These residues, from the before and after pulses of the i^{th} pulse, is called ISI. The channels that produce these residues are called dispersive channels. An example of a dispersive channel is land mobile channel whose characteristics are randomly changing and have multipath propagation (Stüber, 2002).

If the pulse shape is controlled such that

$$p(i-k)T_b = \begin{cases} 1, i = k \\ 0, i \neq k \end{cases} \tag{2.7}$$

then the receiver output given in Equation 2.6 gives the perfect reconstruction in the absence of noise, with only the scaling factor. The result is shown in Equation 2.8.

$$y(t_i) = \alpha m_i \tag{2.8}$$

Pulse *p(t),* which satisfies the condition given in Equation 2.7, are Sinc and Raised Cosine pulses (Haykin, 1997).

One of the solutions to deal with the ISI is the equalizer. It can be categorized generally as linear or nonlinear. Examples of linear equalizers are Zero Forcing (ZF) equalizer and Minimum Mean Square Error (MMSE) equalizer. Examples of nonlinear equalizers are the Decision Feedback Equalizer (DFE) and the Maximum Likelihood Sequence Detection (MLSD). Out of the above four, the MLSD is the optimum and outperforms the others with the disadvantage of high complexity (Forney, 1972, Proakis & Salehi, 2002).

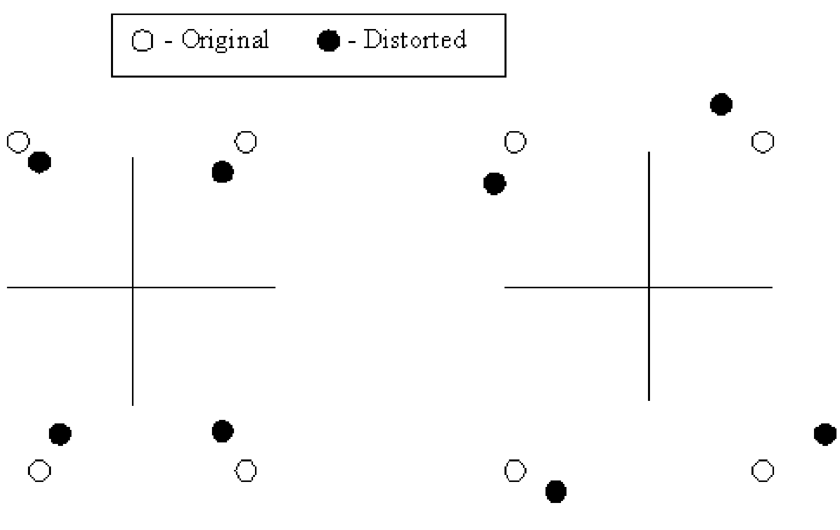
2.3 Modeling of a Wireless Channel

A communication channel is the medium in which a signal passes from a transmitter to a receiver. The channel can be a copper wire, twisted pair wire, optical cable, free space or underwater. In a wireless communication system, the received signal at the antenna of a receiver is the superimposed signal that comprises the signals arriving from different directions and time. Each path behaves like an individual fading path. This fading is due to reflection, delay and scattering, etc. (Proakis & Salehi, 2002; Sklar, 1997). This fading process is characterized as a Rayleigh distribution for a Non Line-of-Sight (N-LOS) path and a Rician distribution for a Line-of-Sight (LOS) path. If the number of paths is just one, then it is called frequency flat fading, and if more, as frequency selective fading (Marvin & Alouini, 2000; Tranter et al., 2004).

The frequency selective fading in time domain is called as delay spread and measured as the overall time span of the path delays from the first path to the last path. This is also called as the length of the channel. Due to delay spread there is a time dispersion of the signal. This time dispersion causes ISI. The channels, which have the above characteristics, are found in different communication systems such as Mobile Radio, Ionosphere High frequency (HF) channel, underwater channel and telephone channels (Fonta & Espineira, 2008).

The signal distortions, which occur in the channels, are mainly at the amplitude and phase. A channel with impulse response *h(t)* can be considered as a bandlimited linear filter. This impulse response can be used to design, plan or develop any communication system. This can be done by a measurement system that uses the unique properties of the pseudo random numbers transmission and extraction via a channel, where the magnitude and phase response are obtained from the received sequence (Benvenuto & Cherubini, 2002). The Fourier transform of the impulse response is given as $H(f) = |Y(f)|e^{j\theta_c(f)}$, where $h(t)$ and $H(f)$ are Fourier transform pairs, $|H(f)|$ is the channel's amplitude response, and $\theta_c(f)$ is the channel's phase response. The term $|H(f)|$ must be constant and $\theta_c(f)$ must be a linear function of frequency. If both do not follow the above condition then distortion occurs. If the term $|H(f)|$ is not constant and varies with frequency, then amplitude distortion occurs. Amplitude response will give the details of amplitude versus frequency. Some channels exhibit severe amplitude variation and for some channels the variation are minimal. The channels that have very low amplitude (80dB) for some frequencies are called channels with spectral null. The frequency range of such null can be wide or narrow with respect to the signal bandwidth and are unpredicted. If $\theta_c(f)$ is not a linear function of frequency within the channel bandwidth, then the effect is phase distortion.

The amplitude and phase distortions of a sequence transmitted can be visualized using the constellation points in Figure 2.3 due to the effect of amplitude and phase distortions. This figure shows the amplitude and phase distortion effect on a Quadrature Phase Shift Keying (QPSK) constellation diagram.



a. Amplitude Distortion   b. Phase distortion

Figure 2.3 QPSK constellation and effect of amplitude and phase distortions

The amplitude distortion is noted when the constellation points move towards the center and the phase distortion leads towards the rotational spread of the constellation points (Marvin & Aloiuni, 2000; Tranter et al., 2004; Maurice, 2006). The channel characteristics are analyzed in the following aspects:

1. Impulse response
2. Pole/Zero locations
3. Phase response
4. Magnitude response

The wireless channel of a communication system can be modeled so that it can be used in simulation for finding the system's performance. A well known technique is to use the impulse response measurement. A linear baseband channel utilized in this research is modeled as a continuous time channel. The overall impulse response *h(t)* includes all components of the transmitter and receiver filters. These filters are used for pulse shaping, linear modulation and demodulation as shown in Figure 2.2 (Ghani, 2004). The transmitted signal is modeled as:

$$s(t) = \sum_{i} s_i \delta(t - kT) \tag{2.9}$$

where s_i*'s* are the transmitted symbols, i is any integer and $\delta(t)$ is the standard unit impulse function. The continuous channel model can be discretized when one sample per symbol period T is considered. Thus, this channel can be efficiently modeled as a Finite Impulse Response (FIR) filter (Proakis & Salehi, 2002).

In this analysis two scenarios are taken into consideration given as the following (Choi, 2006):

1. The gain of a path remains constant throughout the simulation. The worst case scenario happens when the frequency response of the channel shows spectral nulls. This spectral null produces a high BER.

2. The gains of the delayed paths vary. This variation is made to exhibit a Rayleigh distributed pattern to simulate the real world scenario. Thus, this scenario produces a random frequency response.

In this research, the time invariant model of the channel is considered where the channel is typically varying slowly with time. In addition, in this work, it is assumed that the channel is known and fixed for the duration of a detecting a block (Crozier, 1989).

The Channel Impulse Response (CIR) *h* is defined in Equation 2.10.

$$h_i = (h_0, h_1, \ldots\ldots h_g) \tag{2.10}$$

In this research seven different channels are chosen which are used widely in various literatures (Porat & Friedlander, 1991; Kaleh, 1995; Declercq et al., 2001; Zhang, 2002; Frédérique & Sari, 2005; Choi, 2006) for simulation of Single Carrier systems. Each CIR has its own properties. The channels are shown in Table 2.1.

Table 2.1 Channel Impulse response of various channels

Channel No.	**Channel Impulse Response (h_i)**	**Normalized Channel Impulse Response (h_n)**
1	[1 0 0]	1 0 0
2(Proakis 1998)	$(1.5)^{-1/2}$ [0.5 1 0.5]	0.4082 0.8165 0.4082
3(Choi , 2007)	(19)-$^{1/2}$[1 2 3 2 1]	0.2294 0.4588 0.6882 0.4588 0.2294
4(Porat , 1991; Choi, 2007)	$(2)^{-1/2}$ [0.167 0.667 1 0.667 0.167]	0.1197 0.4782 0.7169 0.4782 0.1197
5(Porat , 1991; Choi, 2007)	$(2)^{-1/2}$ [-0.167 0.667 1 0.667 -0.167]	-0.1197 0.4782 0.7169 0.4782 -0.1197
6(Kumaran, 2005)	$(2)^{-1/2}$[1 1]	0.7071 0.7071
7(Kumaran, 2005)	$(2)^{-1/2}$[1 0 1]	0.7071 0 0.7071

Table 2.1 is a collection of channels which may have spectral nulls of various widths to reflect the deep fades. These channels are considered to show the effect of

ISI. The above table also has channels with various lengths, which helps in demonstrating the fact that ISI and its effects do not depend on the channel length but on the characteristics. Channel 1 is an ISI free channel and it is used for comparison purposes. One can model any fading channel in a similar way.

The characteristics of each channel can be analyzed in terms of magnitude, phase, impulse response or by plotting Pole/Zero locations. Each of the above analysis techniques is used in the design considerations. For example, in Pole/Zero plot of a channel characterization analysis, the location of zeros acts as the constraint in the MLSD scheme which utilizes Viterbi Algorithm (Lee & Messerschimitt, 1994) and it can also check for the physical realizability of the channel model. The impulse response technique of channel characterization shows the extent of propagation delay, path loss and Doppler effects. In the magnitude response technique of channel characterization, the number of signal replicas and their arrival times can be determined from the shape of the magnitude and phase response (Asrar, 2003).

Each channel is to be normalized as explained below. Normalization of the channel is done before simulation and it is done by dividing each element in the CIR by the sum of squares of all the elements. The normalization procedure is given as Equation 2.11 (Anderson, 1997):

$$h_{in} = \frac{h_i}{\sum_{i=1}^{n} h_i^2} \tag{2.11}$$

By normalizing, the energy of the channel is placed on the average symbol energy and the ISI property of the channel separately in *h(t)* (Anderson, 1997). By this arrangement the energy received is the same as transmitted when the filter (channel) energy is normalized. The ISI loss is contained in the distance to the decision boundary between the symbols which are having separate boundaries.

2.3.1 Channel 1: [1 0 0]

This Channel 1 is typically a non-ISI channel. It does not introduce ISI and has a flat magnitude response. The magnitude and impulse responses are plotted in Figure 2.4. These findings are well explained in Proakis & Salehi (2002) and Ghani (2004).

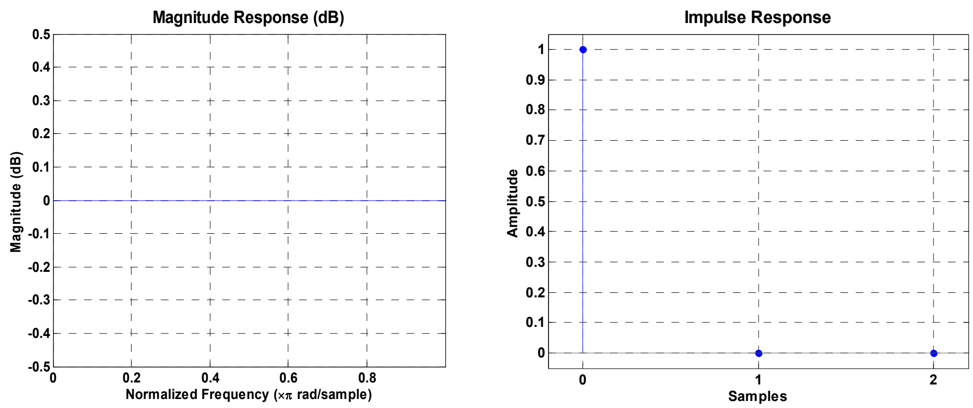


Figure 2.4 Magnitude and impulse response of Channel 1

The phase response is also linear. The symbols, which pass through this channel do not get affected and remain unaltered. The main limitation of this channel is the AWGN alone. The performance of a communication system for this channel gives the upper limit (Haykin, 1997).

2.3.2 Channel 2: $(1.5)^{-1/2}$ [0.5 1 0.5]

The magnitude response seen from Figure 2.5 of Channel 2 shows the severe amplitude distortion.

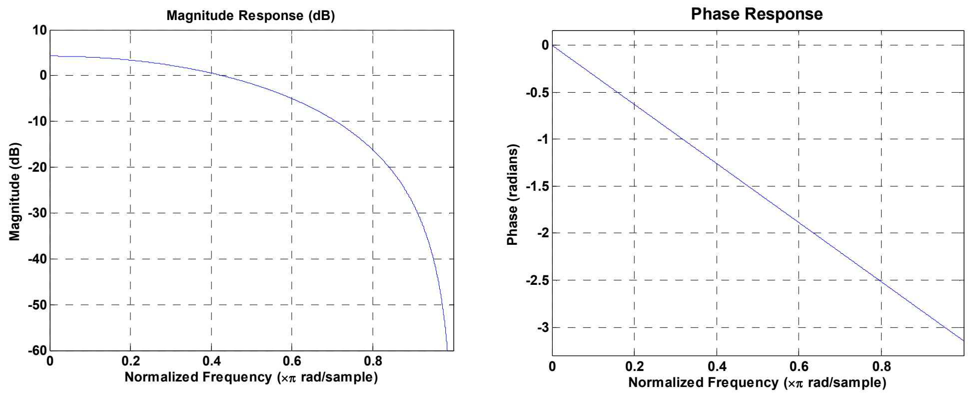


Figure 2.5 Magnitude and phase response of Channel 2

There is a spectral null and the severity of the amplitude distortion at the spectral null is also very high (see Figure 2.5). The implementation of a linear equalizer in the communication system is not suitable for this type of channel. The phase response as shown in Figure 2.5 is linear and this shows that there is no phase distortion introduced by this channel. This channel is used often in many literatures, for example see Ghani (2004) and Proakis & Salehi (2002).

The impulse response plotted as Figure 2.6 shows that the span of ISI is small. However, this does not relate to the severity of the distortion (Proakis & Salehi, 2002). The coefficients of the impulse response also give an idea about the amplitude distortion. The locations of poles and zeros are shown in Figure 2.6. There are two zeros which lie on the unit circle.

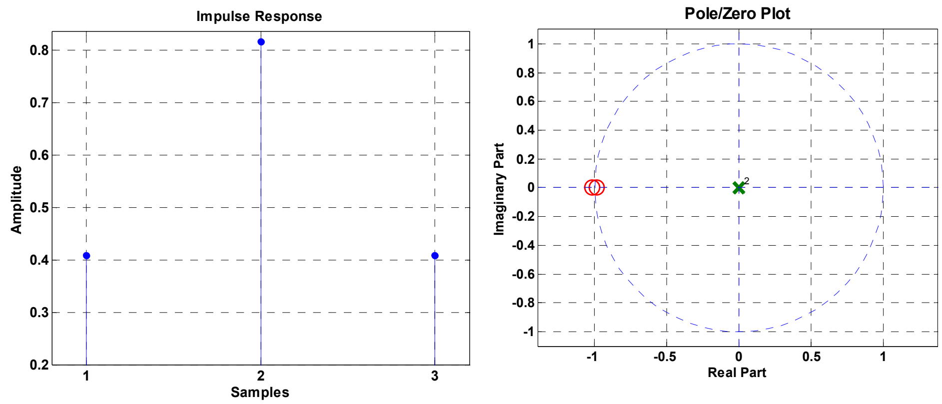


Figure 2.6 Impulse response and Pole/Zero Plot of Channel 2

2.3.3 Channel 3: $(19)^{-1/2}$[1 2 3 2 1]

The magnitude and phase response of Channel 3 are shown in Figure 2.7. The magnitude response shows a severe spectral null. The amplitude distortion is also very high. These findings are well explained in Proakis & Salehi (2002) and Ghani (2004). However, the phase response is linear and the channel does not introduce phase distortion.

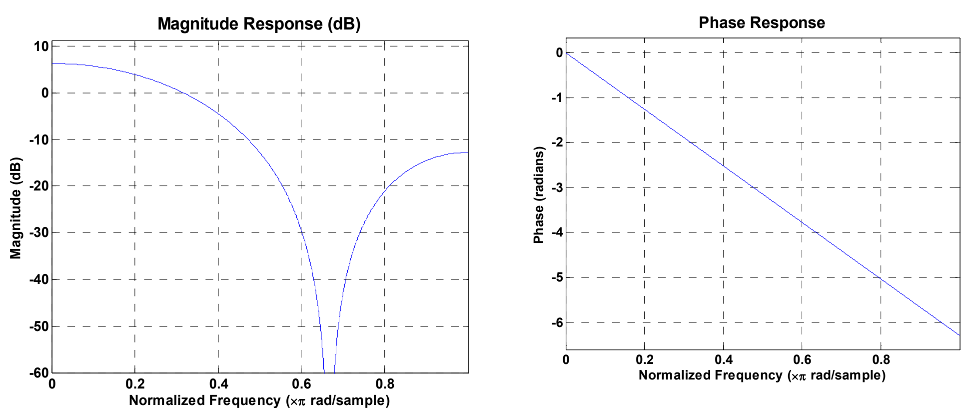


Figure 2.7 Magnitude and phase response of Channel 3

The impulse response and Pole/Zero plots are shown in Figure 2.8. The impulse response shows that the span of the ISI is wide. The coefficient of the impulse response shows the magnitude of the distortions. The Pole/Zero plot shows that there are two zeros located on the unit circle.

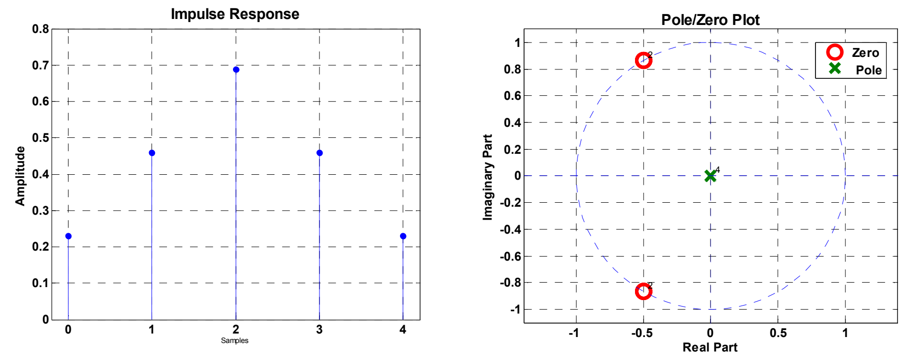


Figure 2.8 Impulse response and Pole/Zero plot of Channel 3

2.3.4 Channel 4: $(2)^{-1/2}$ [0.167 0.667 1 0.667 0.167]

The magnitude and phase response of Channel 4 is shown in Figure 2.9. These findings are well explained in Proakis & Salehi (2002) and Ghani (2004). The magnitude response shows a spectral null. The amplitude distortion is severe for this channel. The phase response is linear and the channel does not introduce phase distortion.

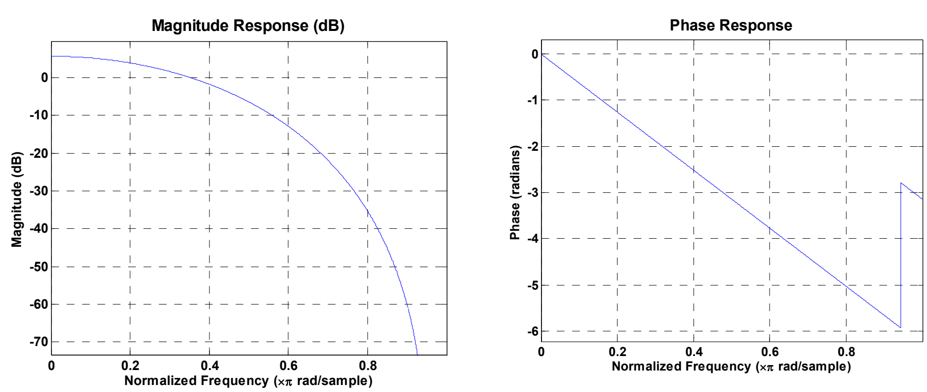


Figure 2.9 Magnitude and phase response of Channel 4

The impulse response and Pole/Zero plot of Channel 4 are shown in Figure 2.10. The impulse response shows that the ISI span is wide and the coefficients magnitude gives the amplitude distortion produced by the channel. The Pole/Zero plot shows that there are four zeros. Two of them lie on the unit circle and two lie outside the unit circle.

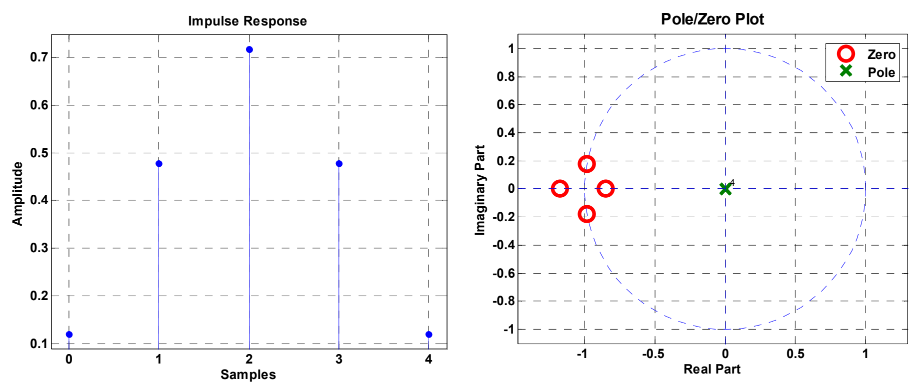


Figure 2.10 Impulse response and Pole/Zero plot of Channel 4

2.3.5 Channel 5: $(2)^{-1/2}$ [-0.167 0.667 1 0.667 -0.167]

The magnitude and phase response of the Channel 5 is shown in Figure 2.11. The amplitude response shows that there is a spectral null. But under careful inspection we find that the amplitude distortion is not as severe as channels 2, 3 and 4 (See Table 2.1 for details). The phase response shows that there is a phase non-linearity. Therefore this channel introduces the phase distortion.