LATTICE SPHERE DETECTION TECHNIQUES IN BLOCK DATA TRANSMISSION AND MULTIUSER WIRELESS SYSTEMS

MAHMOUD A. M. ALBREEM

UNIVERSITI SAINS MALAYSIA

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by

MAHMOUD A. M. ALBREEM

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Last but not least, I was told that feeling at home and indigenous in a foreign country is rare. To me, and after I have socialized with the people in Malaysia, I really felt at home in Malaysia. Thanks to the people of Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AWGN Additive White Gaussian Noise

BER Bit Error Rate

BPSK Binary Phase-Shift Keying

BDTS Block Data Transmission Systems

BOLS Block-wise Orthogonal Least Squares

CDMA Code-Division-Multiple-Access

CIR Channel Impulse Response

CS Compressive Sensing

CP Cyclic Prefix

DMT Discrete Multi-Tone

DFE Decision Feedback Equalizer

dB Decibel

DVB Digital Video Broadcasting

DSL Digital Subscribers Line

DAB Digital Audio Broadcasting

ES Exhaustive Search

FP Fincke-Pohst

FIR Finite Impulse Response

Gbps Giga bits per second

GA Genetic Algorithms

GLRT Generalized Likelihood Ration Test

HF High Frequency

HMGA Hybrid Micro Genetic Algorithm

ISI Inter-Symbol-Interference

JD Joint Detection

LTE Long Term Evolution

LMMSE Linear Minimum Mean Square Estimation

LSD Lattice Sphere Detection

MIMO Multiple-Input Multiple-Output

ML Maximum Likelihood

MS-LSD Minimum-Mean-Square-Lattice Sphere Detection

OFDM Orthogonal Frequency Division Multiplexing

PDF Probability Density Function

QPSK Quadrature Phase Shift Keying

QAM Quadrature Amplitude Modulation

QoS Quality-of-Service

SDR Semi-Definite Relaxation

SNR Signal-to-Noise Ratio

SC-FDMA Single Carrier-Frequency Division Multiple Access

SE Schnorr-Euchner

U-LSD Under-determined Lattice Sphere Detection

VC Virtual Channels

VA Viterbi Algorithms

ZF Zero Forcing

4G Fourth Generation

LIST OF SYMBOLS

τ	Condition number
d	Sphere radius
s	Transmitted signal
$\hat{s}$	Estimated signal
h	Channel Impulse Response
q	Channel length
σ	Noise variance
H	Channel matrix
μ	Noise
ε	Predefined threshold
y	Received signal
Λ	Lattice field
Z	Restricted area
Q	Orthogonal matrix
R	Upper triangular matrix
y'	Reduced form of the received signal
μ'	Reduced form of the noise
Z^{n+1}	$n+1$ coordinates to defined n-dimensional lattice sphere

n	lattice dimension
δ_{max}	Maximum singular value
δ_{min}	Minimum singular value
p	Norm order
λ	Regularization/user parameter
L	Guard symbol
P_{avg}	Average power
γ	Signal-to-Noise Ratio
P_{BLER}	Probability of block error
P_{BER}	Probability of bit error
M	Points encapsulated inside the sphere
ζ	Number of objective function evaluations
r	difference between the transmitted and received signals
$\|\cdot\|$	2-Norm
G_{no}	Normalized Gram matrix
G	Gram matrix
I_N	Identity matrix
O	Big O notation
χ	Modulation alphabet
χ_a	Augmented alphabet

P_a	Probability of active user
$\sum$	Summation
$\geq$	Greater than or equal to
$\leq$	Less than or equal to
©	Registered trademark
$\Im$	Hypothesis
N	Number of user terminals
Γ	Standard gamma function
N/A	Not Applicable

TEKNIK PENGESAN KEKISI SFERA DALAM PENGHANTARAN BLOK DATA DAN SISTEM TANPA WAYAR PELBAGAI PENGGUNA

ABSTRAK

Tahun kebelakangan ini telah menyaksikan peningkatan dalam permintaan yang lebih tinggi kadar penghantaran data tanpa wayar untuk aplikasi komunikasi multimedia. Sistem Penghantaran Blok Data (SPBD) dan Pelbagai Bahagian Kod Akses (PBKA) di anggap sebagai teknik-teknik berkesan untuk penghantaran kadar data yang tinggi dan terdapat dalam generasi akan datang teknologi mudah alih dan tanpa wayar seperti sistem Evolusi Jangka Panjang (EJP). Pengesan Pencarian Menyeluruh (PM) adalah optimum. Disebabkan beban tinggi pengiraan, teknik Penyahkodan Kekisi Sfera (PKS) dan variannya telah dicadangkan. Bagi pereka sistem, objektif utama ialah untuk mencapai keseimbangan antara prestasi dan kerumitan yang menarik. Dalam kajian ini, pengesan berasaskan PKS direka untuk PBKA dan sistem Pengesanan Pelbagai-Pengguna (PPP). PKS Mencari titik kekisi dalam sfera didalam lingkungan yang telah ditetapkan jejari (d). Dalam PKS, apabila jejari awal (d) meningkat, prestasi dan kerumitan meningkat. Kajian ini menghasilkan nilai yang tepat bagi jejari sfera (d) yang digunakan dalam teknik PKS yang bergantung kepada dimensi kekisi (n) dan purata kuasa diterima (P_{avg}). Ia adalah fakta yang diketahui bahawa beberapa keadaan kecil (τ) menyebabkan prestasi pengesanan yang lebih baik. Kajian ini bertujuan untuk mengurangkan nilai beberapa syarat untuk sekecil mungkin dengan menggunakan kaedah rombakan (rombakan-L_1 dan rombakan-L_2), dan menggunakan matriks khas (iaitu, Hankel dan Toeplitz). Kemudiannya, kajian ini mencadangkan satu teknik pengesanan baru yang dipanggil sebagai teknik hampir-A_n-PKS. Hubungan yang tepat antara prestasi PKS dan bilangan keadaan (τ), dan hubungan antara

jejari (d) dan beberapa keadaan (τ) telah diperolehi. Hubungan yang diperolehi menunjukkan penumpuan mereka kepada fakta bahawa prestasi bertambah apabila jejari (d) meningkat. Daripada keputusan prestasi dan analisis kompleks, ia adalah jelas bahawa teknik yang dicadangkan mencapai keseimbangan yang baik antara kerumitan dan prestasi.

Dalam kajian ini, sistem Pengesanan Pelbagai-Pengguna (PPP) kekisi sfera juga telah dipertimbangkan apabila sparsiti isyarat berubah dari masa ke masa. Dalam PPP, menarik sekali apabila saiz minimum urutan merebak adalah lebih kecil daripada bilangan pengguna yang juga bermotivasi untuk jalur lebar dan penjimatan kuasa tetapi hakikat ini menarik membawa kepada bawah sistem ditetapkan. Teknik-teknik PPP mencadangkan mengurangkan masalah dalam uplink sistem PBKA apabila urutan merebak lebih kecil daripada bilangan pengguna. Ini dicapai dengan memperkenalkan pengesan gabungan hibrid yang terdiri daripada Penganggaran Minimum-Linear-Min Persegi (PMLMP) dan teknik Penyahkodan Kekisi Sfera (PKS). Kemudian kita memanggil cadangan skim pengesan hibrid sebagai Minimum-Min-Persegi-PPP (MP-LSD). Satu lagi teknik dicadangkan yang juga diperkenalkan untuk menyelesaikan masalah di bawah ketentuan yang dipanggil Di Bawah Ketentuan-PPP (DBK-PPP). Selain itu, teknik-teknik yang dicadangkan adalah di analisis dalam keadaan di mana sparsiti isyarat berubah dari masa ke masa. Teknik-teknik yang dicadangkan adalah dikira berkesan dan boleh digunakan walaupun tahap aktiviti pengguna yang tidak diketahui, adalah satu senario yang menarik yang berpotensi dalam rangkaian tanpa wayer radio kognitif.

LATTICE SPHERE DETECTION TECHNIQUES IN BLOCK DATA TRANSMISSION AND MULTIUSER WIRELESS SYSTEMS

ABSTRACT

Recent years have witnessed an increase in demand for higher transmission data rates for wireless multimedia communications applications. Block Data Transmission Systems (BDTS) and Code Division Multiple Access (CDMA) are considered as efficient techniques for high data rate transmission and found in the coming generation of mobile and wireless technologies such as Long Term Evolution (LTE) systems. The Exhaustive Search (ES) detector is the optimum. Owing to its high computational load, lattice sphere detection (LSD) technique and its variants had been proposed. For the system designer, the main objective is to achieve an attractive performance-complexity tradeoff. In this research, LSD based detectors are designed for BDTS and Multi-User Detection (MUD) system. LSD searches lattice points in a sphere within a predetermined radius. In LSD, when the initial radius increases, the performance and complexity increased. This research produces exact expression for the sphere radius used in LSD technique which depends on the lattice dimension and average received power. It is well known fact that a small condition number results in a better detection performance. This research aims to reduce the condition number value to its smallest possible using the regularization methods (L_1-regularization and L_2-regularization), and utilizing special matrices (i.e., Hankel and Toeplitz). Sequentially, this research proposed a new detection technique which called as a near-A_n-LSD technique. Exact relationships between the LSD performance and condition number, and the relationship between the radius and condition number had been derived. The derived relationships show their convergence to the fact that the performance increases

as radius increased. From the performance results and complexity analysis, it is apparent that the proposed techniques achieve a good balance between complexity and performance. In this research, a lattice sphere multiuser detection (MUD) has also considered when the signal sparsity is changing over time. In MUD, its attractive once the minimal-size spreading sequences is smaller than the number of users which is well motivated for bandwidth and power saving but this attractive fact leads to under-determined system. The proposed MUD techniques mitigate the problems in uplink of a CDMA system when the spreading sequences are smaller than the number of users. This is achieved by introducing a hybrid combination detector that consists of the linear minimum mean square estimation (LMMSE) and lattice sphere detection (LSD) techniques. Later the proposed hybrid detector scheme is called as Minimum-Mean-Square-LSD (MS-LSD). Another proposed technique is also introduced to solve the under-determined problem which is called Underdetermined-LSD (U-LSD). Moreover, the proposed techniques are analyzed in the condition whereby the signal sparsity is changing over time. The proposed techniques are computationally efficient and applicable even when the user activity levels are unknown, a scenario of potential interest in wireless cognitive radio networks.

CHAPTER 1

INTRODUCTION

1.1 Preface

The demand for high data rate mobile services with spectral, power efficient, and stringent Quality-of-Services (QoS) has been increased tremendously in recent years. The challenges posed in the coming generation mobile communication systems such as long term evolution (LTE) will be enormous in terms of performance and complexity (Ketonen et al., 2010). For example, the data rate of such systems is expected to be more than 1 Gbps. One of the hurdles to achieve high data rate is Inter Symbol Interference (ISI), which results from the underlying channel characteristics of mobile environment. With the help of advances in semiconductor technologies and advanced signal processing algorithms, complex communication systems can be constructed and meets this demand.

A Block-by-Block transmission scheme, found in many communication technologies, is one of the effective systems that reduce the effects of the channel (Kaleh, 1995)(Ain et al., 2008)(Ghani and Khatib, 2010)(Babu, 2010). Orthogonal Frequency Division Multiplexing (OFDM), Discrete Multi-Tone Modulation (DMT) schemes, Single Carrier Frequency Division Multiple Access (SC-FDMA), to name a few, operates on a Block-by-Block basis (Hayashi and Sakai, 2006). In the block data transmission systems (BDTS), blocks of data symbols are separated by zero symbols/known symbols, which confine the ISI to a block (Ghani and Khatib, 2010)(Hayashi and Sakai, 2006). Certain multiple antenna systems operate in this fashion, and Block-by-Block detection is also found in some Code Division Multiple Access (CDMA) systems (Mozos and Garcia, 2006).

Multipath fading caused by dispersion, reflection, and objects (building, trees, etc.) resulted in severe ISI (Hayashi and Sakai, 2006). In BDTS when there is a null in the channel frequency response or there is clipping noise, the effects of ISI are 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) (Kaleh, 1995). The use of optimum detectors like Maximum Likelihood Detector (MLD) become mandatory in this case (Hassibi and Vikalo, 2005). Even though Viterbi Algorithms (VA) can be used to implement optimal detectors, their computational complexity increases with increased in signal sets and channel memory (Babu, 2010). Short data blocks based BDTS can have VA type optimum detectors with reduced efficiency. A large data blocks based BDTS is preferred, but optimum detection in such a system leads to high complexity (Kaleh, 1995)(Khatib, 2009)(Babu, 2010). In such cases, Lattice Sphere Detection (LSD) technique with its variants is the alternate solution to implement such optimal detectors based BDTS where there have seen works done in (Li and Cui, 2004).

LSD technique was inspired from the mathematical problem of computing for the shortest non zero vector in a lattice. In LSD technique, the search can be restricted within a sphere around the received signal with a restricted radius d (Hassibi and Vikalo, 2005). The most important issues are the radius selection, and condition number. If the radius is too large, many points are encapsulated inside the sphere and therefore, requires high complexity. On the other hand, if the radius is taken smaller, there could be no point obtained inside the sphere. Therefore, the system will fail. Condition number measures the worst-case sensitively of an input data to small perturbation.

LSD has also seen as alternate detection technique in multiuser detection (MUD) systems where there have seen works done in (Zhu and Giannakis, 2011). A Multiuser Detection (MUD) techniques are mitigating the multi-access interference present in Code Division Multiple Access (CDMA) (Verdu, 1998). These MUD algorithms simultaneously detect the transmitted data of all active users. In this research, a multiuser detection technique is considered when the signal sparsity changes over the time. In the design of practical CDMA system, one is interested in saving the bandwidth and power resources. As shown in (Zhu and Giannakis, 2011), this is possible by reducing the size of the spreading sequences. Thus, it also reduces the amount of computation which in turn reduces the energy consumption. Therefore, the minimal-size spreading sequences, even smaller than the number of users, is well motivated for bandwidth and power saving which leads to under-determined scenario In channel matrix (H), if the number of rows is smaller than the number of columns; the channel matrix is called as fat matrix and the system is called under-determined system) (Parkvall, 1998)(Angelosante et al., 2010)(Zhu and Giannakis, 2011)(Shim and Song, 2012)(Schepker and Dekorsy, 2012). The present research exploits fruitfully this a priori information to improve the performance and complexity of multiuser detectors. The proposed techniques (Under-determined lattice sphere detection (U-LSD) and minimum-mean-square-lattice sphere detection (MS-LSD)) are well modeled for the under-determined system. Moreover, the proposed techniques are analyzed in the condition whereby the signal sparsity is changing over time. The proposed techniques are computationally efficient and applicable even when the user activity levels are unknown, a scenario of potential interest in wireless cognitive radio networks.

1.2 Problem Statement

It is found that when ISI is severe, the Exhaustive Search (ES) is superior to other equalizer methods (Ghani and Khatib, 2010). In ES, if a BPSK symbol is used to represent one bit; the corresponding transmitted message of size n, the received signal should be compared with all 2^n possible bit sequences (points) in the receiver. For small data sizes, all possible transmitted signals can be searched. This becomes impossible when the data size is huge (Babu, 2010). Lattice Sphere Detection (LSD) technique is found in literature as an alternative detection technique.

LSD technique searches lattice points in a sphere within a certain radius (d) (Hassibi and Vikalo, 2005). The selection of d is very crucial which affects the system performance and complexity. It is well known fact that the performance increases as radius (d) increases. If d is too large, many points are encapsulated inside the sphere and therefore, requires huge amount of mathematical operations (better performance but high complexity). On the other hand, if d is taken smaller, there could be no point obtained inside the sphere. Therefore, the system will fail. Thus, an efficient way of selecting radius must be determined to achieve a good balance between performance and complexity. For the system designer, the main objective is to achieve an attractive performance-complexity tradeoff.

The small number of lattice points inside the sphere produces worse performance (Hassibi and Vikalo, 2005). In order to increase the number of encapsulated lattice points inside the sphere, a more denser space should be created. Therefore, near-A_n-LSD technique is proposed.

A high condition number (τ) of a system produces an ill-conditioned system which results a low performance (Kreyszig, 2011). Experiments in (Artés et al., 2003) show that the channel matrix condition number is strongly related to the performance of optimal and suboptimal detection schemes, since it is a measure of how the original constellation is distorted by the channel. In order to improve the quality of communication systems, one of the best solutions is to reduce the system condition number (τ) (Roger et al., 2009).

In order to reduce the condition number (τ), this thesis proposed LSD with regularization (i.e., L_1-regularization and L_2-regularization) methods, LSD with special matrices (i.e., Toeplitz and Hankel matrices), and also proposed near-A_n-LSD technique.

In MUD systems, it has shown in (Parkvall, 1998)(Angelosante et al., 2010)(Zhu and Giannakis, 2011) that long-size spreading sequences require more power and higher complexity detection. In the design of a practical CDMA system, one is always interested in saving the bandwidth and power resources. As shown in (Zhu and Giannakis, 2011), this is possible by reducing the size of the spreading sequences, even smaller than the number of users which leads to under-determined scenario. The conventional LSD cannot solve the under-determined scenario since the channel matrix (H) becomes "fat" (Zhu and Giannakis, 2011). This thesis proposes two detection techniques to overcome the under-determined MUD system.

1.3 Research Objectives

The present research centers on the LSD based BDTS and MUD, which have many advantages and applications, as discussed in the previous sections. The key objectives of this research include:

1. To develop a lattice sphere detection (LSD) techniques assisted optimal BDTS receiver for wireless communication systems with a deterministic approach of radius selection.
2. To develop a lattice sphere detection (LSD) technique assisted optimal BDTS receiver for wireless communication systems with small condition number.
3. To propose an efficient sparse lattice sphere multiuser detection techniques for the under-determined scenario.

1.4 Summary of Original Contributions

The original contributions of this research can be generally categorized into different areas namely: LSD based BDTS for communication systems and sparse lattice sphere multiuser detection. The original contributions are summarized below:

1. **Deterministic approach for initial radius selection applicable to LSD technique.**
   In LSD, if the initial radius (d) increases, the performance and complexity increase. However, the good balance between performance and complexity is necessary. In this thesis, the exact expression of initial radius (d) is obtained. The deterministic initial radius (d) value results in a good balance between performance and complexity.
2. **Proposed near-A_n-LSD technique.**

Proposed near-A_n-LSD technique assisted optimum detector for BDTS. Instead of using the traditional Lattice Sphere Detection (LSD) technique, a new near-A_n-LSD technique is proposed for optimum detection in BDTS. The proposed generator matrix mimics the generator matrix of A_n lattice. The proposed technique encapsulates more lattice points inside the sphere and therefore, improve the system performance. Sequentially the condition number (τ) of the proposed generator matrix is less than the previous traditional LSD matrices.

3. **LSD with small condition number.**

   This part aims to reduce the condition number (τ) as much as possible by using:

   - Two regularization methods are utilized. First, L_1-regularization method is introduced, which sums the mixed norms. Second, L_2-regularization method, which is the most commonly used methods of regularization for ill-conditioned problems in mathematics, is utilized.
   - Two special matrices structures are utilized. Channel matrices are created in the form of Toeplitz and Hankel matrices. LSD with Toeplitz matrix and LSD with Hankel matrix provide a significant detection improvement in terms of performance and complexity.

4. **Sparse lattice sphere multiuser detection for under-determined system.**

   In this part, a multiuser detection technique is considered when the signal sparsity changes over time. The proposed techniques are also effective for the under-determined system. Two detection techniques are proposed; the first technique is called U-LSD which aims to solve the under-determined system using LSD. The second technique is called MS-LSD. The key feature of MS-LSD technique is its hybrid composite of two detection techniques to detect the active and idle users, as well as to detect the modulation alphabet. The proposed hybrid technique is a composition of linear minimum mean square estimation (LMMSE) and LSD.

1.5 General Methodology

This research focuses on new detection techniques for block data transmission (BDTS) and multiuser wireless systems (MUD). The proposed detection techniques are presented and analyzed mathematically. In this thesis, the proposed detection techniques are also being verified using *MATLAB*©.

This thesis verifies the validity of the simulated proposed detection techniques with the mathematical expressions. These mathematical models are represented by equations that describe the variables that affect the systems, which can be analyzed using computer software such as *MATLAB*©. The performance of the proposed techniques are analyzed based on the profile of the signal to noise ratio (SNR) against the bit error rate (BER). The complexity is firstly analyzed in term of the number of floating-point operations per second (FLOPS). Second, complexity is analyzed using the number of points encapsulated inside the sphere. Table 1.1 shows the target design specifications for c-ary modulation alphabets and n block size.

Depending on the results of the mathematical representations, simulation models will be done on *MATLAB*© (*m*-file as shown in Appendix A), and the results will be compared with those from the mathematical representations.

Table 1.1: Design specifications

Metric	**Target**
Number of bits	10^8
Number of users	20
Modulation scheme	BPSK, QPSK, 16-QAM
SNR	0 dB to 14 dB
BER	$\leq 10^{-5}$
Condition number	≤ 10
FLOPS	$< 10^4$
Number of points inside the sphere	$< c^n$

In the proposed techniques, the effective parameters are studied to determine the limitations and the boundaries of the design. The performance and complexity of the proposed techniques are compared with renowned works. Figure 1.1 shows the general methodology of the research.

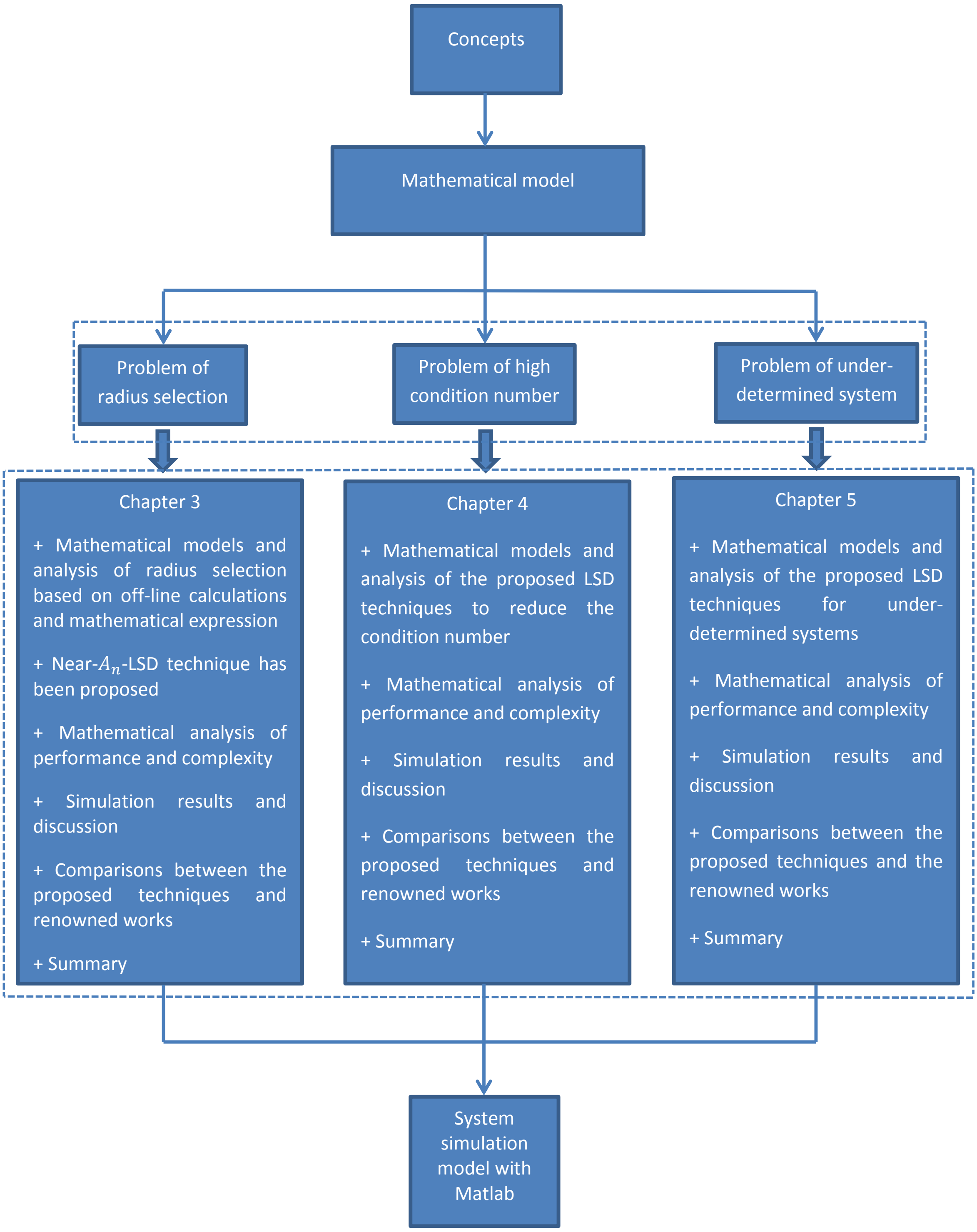

Figure 1.1: General methodology

In this research, no channel estimation is performed. Instead, the Channel Impulse Response (CIR) is assumed as the known quantity in advance and time invariant (Proakis, 2001a). This arrangement allows the performance analysis of various detectors under different levels of deep fades and channel lengths.

In multiuser detection (MUD), the work focuses only on the uplink CDMA system where many users can transmit simultaneously to the base-station. The key assumption made is that the number of active users simultaneously communicating with the base-station is smaller than the total number of users. Thus this leads to a sparse system. The proposed techniques are well modeled for the under-determined system. The system is analyzed when the sparsity is varied over time. Analytical analysis are introduced as proof of the proposed works. Fig. 1.2 shows the general block diagram of the communication system where the proposed LSD techniques are settled in the receiver. Appendix A shows the *MATLAB*© code of the proposed techniques.

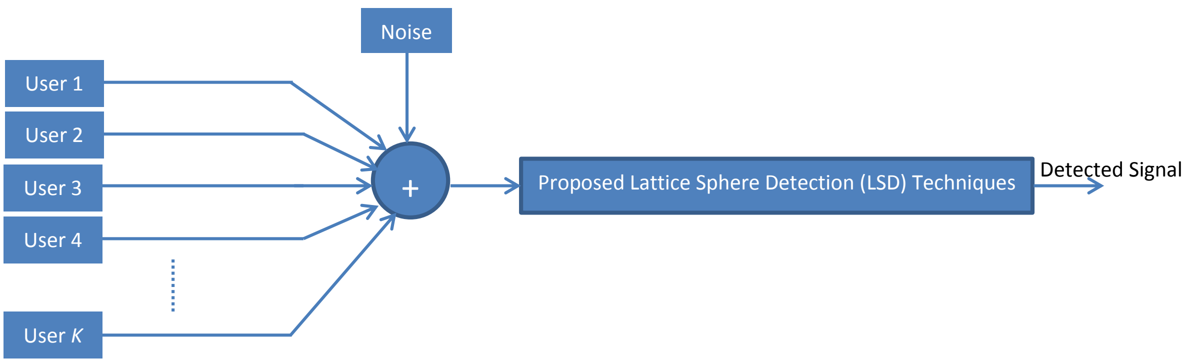

Figure 1.2: General block diagram of the proposed LSD technique

1.6 Outline of the Thesis

The remainder of this thesis is organized into six chapters. Chapter 2 consists of three main parts; the first part provides background basic concepts of the study and the second part reviews the previous works in LSD, BDTS, and MUD. The first part contains a general view of continuous transmission digital communication system, the effect of noise, ISI, and their combination. Various methods to mitigate those effects are also illustrated in details. The chapter also includes the topic of channel modeling and noise consideration for the deriving probability of error. A background of LSD technique is also given in this part. The second part contains the literature review and tabulated comparisons between the proposed techniques and renowned works.

Chapter 3 presents the implementation of the LSD on BDTS. Radius selection is proposed using the off-line calculations and mathematical expression. Relationship between the performance and radius has been shown as well as the relationship between the complexity and radius. In this chapter, a denser lattice sphere detection technique is proposed. Later the proposed detection scheme is called as near-A_n-LSD technique.

Chapter 4 proposes different regularization techniques to improve the LSD performance in BDTS by reducing the condition number (τ). This chapter proposes LSD with L_1 and L_2 regularization methods. This chapter also proposes another way to reduce the condition number (τ) which is the usage of special generator matrices. The Toeplitz and Hankel matrices are used as generator matrices with LSD. In this chapter, the proposed near-A_n-LSD technique is tested in term of condition number (τ).

Chapter 5 proposes a sparse lattice sphere multiuser detection techniques for under-determined system. It is shown that the proposed techniques provide substantial performance gain and complexity reduction.

Chapter 6 concludes the thesis by summarizing the major findings of the research. It also provides several suggestions to further extend the research in detection techniques.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Background

The demand for better applications in communications has been increased in recent years especially after the revolution of Long Term Evolution (LTE) systems (Shah et al., 2010). Many applications for wireless multimedia communication such as Video Telephony, Wireless Internet, Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), to name a few, require a large volume of data transmission over a limited amount of resources. The high data rate transmissions especially through time dispersive channels, introduce Inter-Symbol-Interference (ISI). In order to study the effect of ISI towards transmission data, it is very important to analyze the properties of the channels. Many works have been done to study the channel properties which led to channel models as explained in (Khatib, 2009)(Proakis, 2001b). Although channel modeling is not part of the objectives of this research, it is important to review how the properties of the channels affect the detection system performance.

In this chapter, the fundamental concepts required for this thesis are presented. Channel models, along with their properties are reviewed. Basic discussion about ISI in digital communication is also covered. The concept of lattice sphere detection (LSD) technique is introduced followed by the concept of regularization methods and special matrices such as Toeplitz and Hankel matrices. This chapter also introduces the concept of condition number. Equalizers and Maximum Likelihood Detectors (MLD) are also presented. The fundamental concepts of Block Data Transmission Systems (BDTS) are also presented. This chapter also covers the concepts of Multiuser Detection (MUD) and sparse signals as well. The second part of this chapter contains the review of related works in lattices, LSD, BDTS, MUD, LTE, special matrices, and regularization methods. Finally, the last section of this chapter tabulates the comparisons between the proposed work and renowned works.

2.1.1 General Block Diagram of Digital Communication Systems

Figure 2.1 shows the general block diagram of digital communication systems.

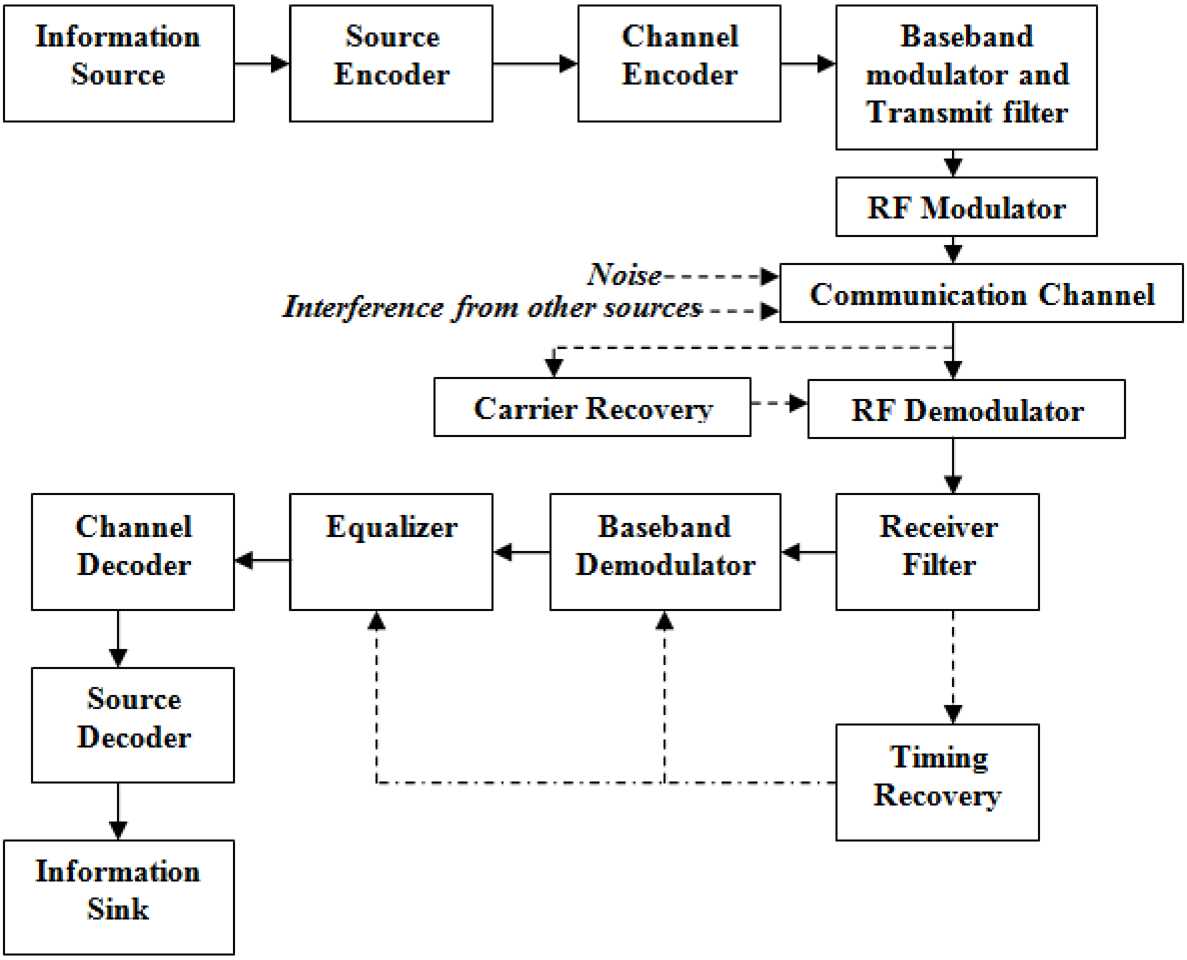

Figure 2.1: Block diagram of a digital communication systems (Haykin, 2001)

The general block diagram of a digital communication system contains three main parts; 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 using modulation schemes such as BPSK, QPSK, and QAM. The transmit filter restricts the bandwidth of the source. The communication channel in this research is assumed to be a wireless channel with spectral null where noise is added to the modulated signals. To observe the benefit of the proposed techniques in a more realistic scenario, rayleigh fading channel has also been used in this thesis.

In the receiver, the reverse process of the transmitter is performed so that the messages are retrieved from the changes it went through the 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 have replaced the analog communication system.

The general description of the digital communication system is given in Figure 2.1, and it clearly indicates that designing and testing the whole system is very complex and time consuming. Thus, the simplification of this communication system has been introduced in Figure 2.2. This simplified model is more suitable, as it has fewer parameters and reduces the computational burden (Tranter et al., 2003)(Babu, 2010).

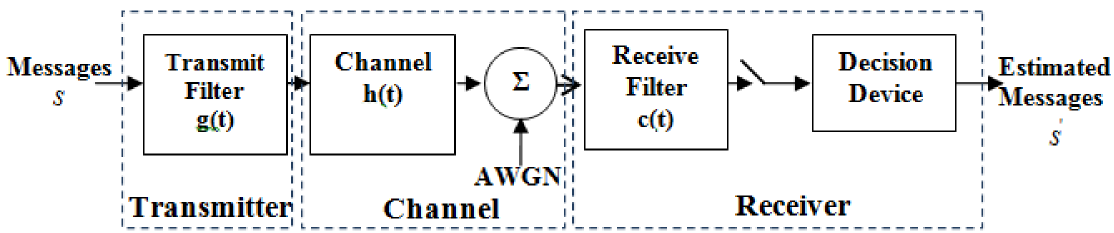

Figure 2.2: Simulation model of a baseband digital communication system (Babu, 2010)

Figure 2.2 illustrates the simulation model of baseband digital communication system. Most of the processing, such as coding/decoding, modulation/demodulation, and synchronization are done at the baseband (Tse and Viswanath, 2005). Figure 2.2 consists of a transmit filter to restrict the bandwidth of the message signal and band-limited linear time invariant channel corrupted by AWGN. The linearity and time invariance is an approximation when the analysis is done for a short time.

Digital modulation technique such as BPSK, QPSK, etc., should be used in the communication system. The basic unit in digital modulation techniques is called a symbol, which is composed of a segment of the sinusoidal waveform (Chiueh and Tsai, 2008). On 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 block can be added or multiplied, thereby greatly reducing the complexity and simulation time (Babu, 2010).

In Figure 2.2, once the symbol S is transmitted over a channel, its corrupted by the noise and channel properties such as spectral nulls and ISI effects. The received symbol $\hat{S}$ may be the same as transmitted or different due to the effect of noise and channel properties. When they are different, then an error occurred. The capability of wireless channels is affected by many factors such as scattering, delay, and reflections (Khatib, 2009). Inter Symbol Interference (ISI) is the most unwanted phenomena that may happen through the wireless channel (Khatib, 2009). ISI is a form of a signal distortion where a symbol interferes with subsequent symbols. This is an unwanted phenomenon that makes the communication system less reliable. ISI is usually caused by multipath propagation where a signal from a transmitter reaches the receiver via many different paths. Since all of these paths are of different lengths, this results in the different versions of the signal arriving at the receiver at different times. These delays mean that part or a given symbol will be spread into the subsequent symbols, thereby interfering with the correct detection of those symbols. Furthermore, the various paths often distort the amplitude and/or phase of the signal and therefore, results interference with the received signal (Haykin, 2001). Noise is also one of the most fundamental impairment in any communication system. Noise is a random fluctuation in the signal. Usually, the noise depends on device type or manufacturing quality and semiconductor defects. In communication systems, the noise is undesired disturbance of a useful information signal.

2.1.2 Wireless Channel Models

A communication channel is a medium through which a signal passes from a transmitter to a receiver. It can be a copper wire, twisted pair wire, optical cable, underwater, or free space. The performance of wireless communication systems is mainly managed by the wireless channel environment. The essential aspect of wireless communication that makes the problem challenging and attractive is called fading. Fading is the time variation of the channel strengths due to the small-scale effect of multipath and large-scale effects such as path loss via distance attenuation and shadowing by obstacles. Second is the significant interference between wireless users communicate over the air (Tse and Viswanath, 2005)(Sklar, 1997).

Due to time dispersion, a transmit signal may suffer fading over a frequency domain either in a selective or a non-selective manner, which is referred to as frequency-selective fading or frequency-non-selective fading, respectively (Cho et al., 2010). 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 (Babu, 2010). The signal distortions, which occur in the channels, are mainly at the amplitude and phase. A channel with impulse response (h) 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 responses are obtained from received sequence (Benvenuto and Cherubini, 2002).

The amplitude and phase distortions of a sequence transmitted can be visualized using the constellation point in Figure 2.3. This figure shows the amplitude and phase distortion effect on a Quadratic Phase Shift Keying (QPSK) constellation diagram of the modulated signal. The wireless channel of a communication can be modeled, so that it can be used in simulation for finding the system's performance (Tranter et al., 2003).

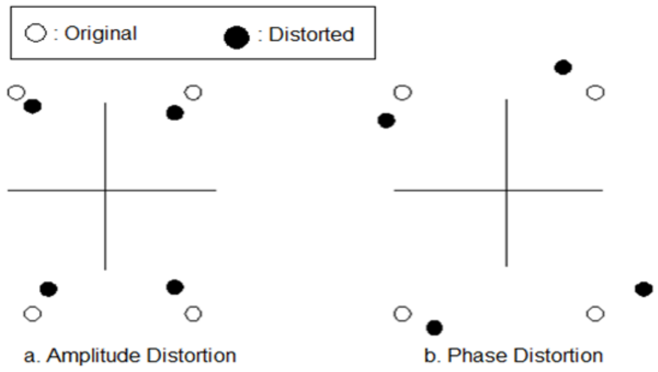

Figure 2.3: QPSK constellation size and effect of amplitude and phase distortions

A well-known channel model technique is to use the impulse response measurement. Transmitter and receiver filters are used for pulse shaping and linear modulation and demodulation as shown in Figure 2.2 (Ghani and Khatib, 2010). Therefore, the resultant signal at the output of the receiver filter is (Babu, 2010)

$$s(t) = \sum_{k} s_k \delta(t - kt) \tag{2.1}$$

where s_k are the transmitted symbols, k is any integer, and δ is the standard unit impulse function. The continuous channel model can be discretized when one sample per symbol period is considered. Therefore, this channel can be efficiently modeled as a Finite Impulse Response (FIR) filter (Proakis et al., 2002).

According to (Proakis et al., 2002)(Choi, 2006), two scenarios should be taken into consideration in the channel models:

1. The gain of a channel remains constant throughout the simulation. The worst case scenario happens when the frequency response of the channel shows spectral nulls which

produce the worst BER.

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

In this thesis, the two scenarios are considered for data transmission. The Channel Impulse Response (CIR) h is defined as follows:

$$h = \begin{bmatrix} h_0 \\ \vdots \\ \vdots \\ \vdots \\ h_{q-1} \end{bmatrix} \tag{2.2}$$

Parameter q refers to the channel length. Here, it should be noted that there are memory and memoryless channels. One of the most famous estimation methods of channels without memory is the Block-Least Squares Estimation method (Aronsson et al., 2009). On the other hand, one of the most famous estimation method of memory channels is the Kalman filtering (Aronsson et al., 2009). In memoryless channels, each output bit from the channel depends only on the corresponding input bit (Proakis, 2001a).

Channels can be expressed using the impulse response. Channel Impulse Response (CIR) estimation is one of the most important tasks for the realization of communication channels (Ali et al., 2006). Different methods for estimating the channel impulse response (CIR) length are available in the literatures. A method has been introduced in (Nguyen et al., 2005), in which the CIR length is estimated based on the difference between the statistical characteristics of the radio channel and that of the additive noise. However, it needs a long averaging duration. A joint estimation of the symbol timing and the channel length has been introduced in (Larsson et al., 2001) where the method is based on the maximum likelihood principle and generalized Akaike information criteria of eigenvalues. In (Athaudage and Jayalath, 2004), a cyclic-prefix based delay-spread estimation technique for wireless OFDM systems has been proposed. A channel estimation method based on parametric channel modeling has been proposed in (Yang et al., 2001), which is based on the Maximum Descriptive Length (MDL) of eigenvalues of the averaged autocorrelation matrix.

In the mathematical and simulation levels, it is assumed that the channel impulse response is already known by choosing any channel vector, and uses this vector in the procedure. The advantage for that is the possibility of testing the worst channels with nulls and bad amplitude spectrums (Khatib, 2009). If the systems would be implemented in hardware level, an estimation technique must be used, which is not a part of this thesis. Although literature is rich with many estimation techniques, the main goal was to focus on the detection techniques itself without facing the possibilities of having some errors due to the estimation error. That was the main obstacle that prevented us from implementing the system at this stage.

In this thesis, five different channels are chosen which are used widely in various literatures (Porat and Friedlander, 1991)(Proakis, 2001a)(Proakis et al., 2002)(Li and Cui, 2004)(Choi, 2006)(Babu, 2010) for simulation of BDTS. Each CIR has it is own characteristics. These channels are shown in Table 2.1 which are the discrete time channel characteristics.

Table 2.1: Channel Impulse response of various channels

Channel number	**Channel Impulse Response (*h*)**
1 (Babu, 2010)	[1 0 0]
2 (Proakis et al., 2002)(Babu, 2010)	[0.4082 0.8165 0.4082]
3 (Choi, 2006)(Babu, 2010)	[0.2294 0.4588 0.6882 0.4588 0.2294]
4 (Proakis, 2001a)(Li and Cui, 2004)	[0.227 0.460 0.688 0.460 0.227]
5 (Porat and Friedlander, 1991)(Choi, 2006)(Babu, 2010)	[0.1197 0.4782 0.7169 0.4782 0.1197]

Most of those channels (except channel 1) have spectral nulls of various widths to reflect the deep fades. Table 2.1 has also 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 channel characteristics whether it has a mild amplitude distortion or stronger amplitude distortion and its spectral characteristic exhibits a spectral null (Proakis, 2001a). If the channel has a strong amplitude distortion or spectral null, the performance of the linear equalizer for this channel will be very poor (Proakis, 2001a).

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 (Babu, 2010).

Characteristics of channels 1, 2, 3 and 5 are given in (Babu, 2010) whereas characteristics of channel 4 are given in (Li and Cui, 2004)(Proakis, 2001a). Because of the random nature of channels, channel models are statistical. The channels perform as filters to incoming waveforms. More specifically, the models or channel impulse responses are the resultant waveforms if a single ideal impulse were sent through the system (Miniuk, 2003).

Channel 1 represents a non-ISI channel. It does not introduce ISI and has a flat magnitude response. It represents a linear phase response. The data that passed this channel do not get affected and remain unaltered. The main limitation of this channel is the Additive White Gaussian Noise (AWGN) alone. Channel 1 is used for comparison purposes.

Channel 2 is one of the worst channel vectors because it has a spectral null and the severity of the amplitude distortion at the spectral null is also very high as shown in Figure 2.4. The implementation of a linear equalizer in the communication system is not suitable for this type of channel since the performance will be very poor (Proakis, 2001a).

Channel 3 is preferred to be used in this thesis because it is length is useful to compare long channels with shorter ones (Babu, 2010)(Choi, 2006). As shown in Figure 2.4, the magnitude response of this channel shows a severe spectral null. The amplitude distortion is also very high. The impulse response shows that the span of the ISI is wide. The coefficient of the impulse response shows the magnitude of the distortion in frequency domain. Using this channel, comparisons between the proposed LSD and its variants (in BDTS) and the works in (Babu, 2010)(Babu et al., 2009) are done.

Other important comparisons are done with the works in (Li and Cui, 2004) using channel 4 which suffers a strong amplitude distortion and spectral characteristic and exhibits a spectral null as shown in Figure 2.4.

The last important channel used in this research is channel 5 (Babu, 2010). The magnitude response of this channel shows a spectral null as shown in Figure 2.4. The amplitude distortion is severe for this channel. The phase response is linear and the channel does not introduce phase distortion.

The above mentioned channels are are real practical channels that are available in the literature such as (Proakis, 2001a)(Kaleh, 1995)(Babu, 2010). Figure 2.4 shows the channels properties in terms of magnitude and impulse responses.

In MUD systems, the channel is assumed as a non-dispersive Rayleigh fading channel for a fair comparison with the works in (Zhu and Giannakis, 2011). Communications system toolbox in MATLAB provides algorithms and tools for modeling noise, fading, interference, and other distortions that are typically found in communications channels.

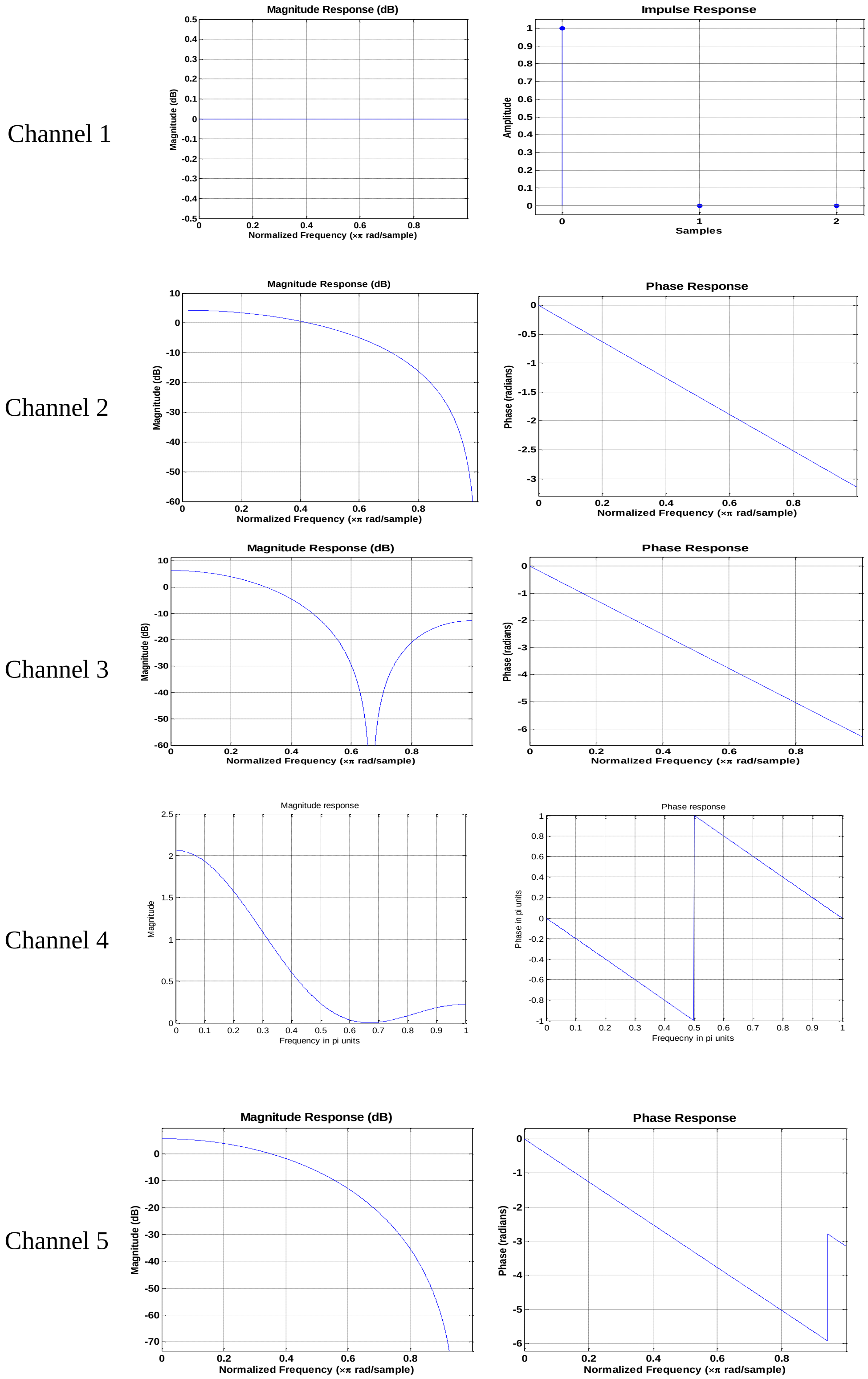

Figure 2.4: Channels properties

The system toolbox supports AWGN, fading, Rayleigh, Rician fading, and binary symmetric channels. A MATLAB Channel object provides a concise, configurable implementation of channel models, and enabling the user to specify parameters such as (MathWorks, 2013):

- Path delays.
- Average path gains.
- Maximum Doppler shifts.
- K-factor for Rician fading channels.
- Doppler spectrum parameters.

2.1.3 Equalizers for ISI

An equalizer is a digital filter that is used to mitigate the effects of ISI. The effect of ISI can be reduced by using a proper shape of pulse used to represent message bits. When the SNR is relatively high, the effects of Inter Symbol Interference (ISI) alone play an important role in the performance of the communication system (Proakis et al., 2002). The detection problem is becoming very complex once the transmitted signal has the combined effect of noise and ISI. Thus, many research works have been done to overcome this issue and a device called "equalizer" is one of the popular solutions. Equalizer is placed after the receive filter and before a detector as shown in Figure 2.5 (Babu, 2010).

Digital equalizers can be categorized as either linear or nonlinear. Linear equalizers remove ISI through filtering that compensates for channel's non-flat frequency response. Nonlinear equalizers use some other form of signal processing to remove ISI that cannot be described with a transfer function (Fay, 2008).

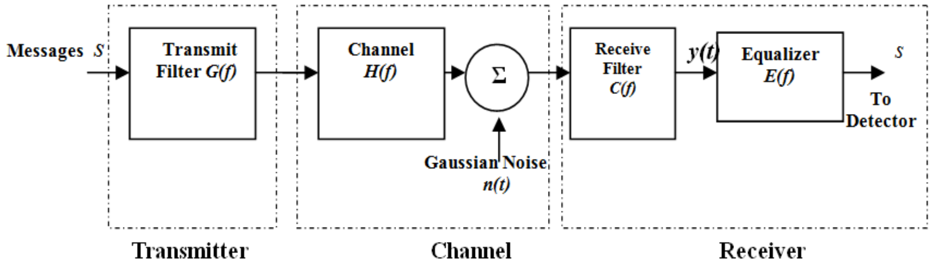

Figure 2.5: Baseband digital communication systems with Equalizer (Proakis et al., 2002)

In this section, Linear Minimum Mean Square Error Estimator (LMMSE) is presented since it is part of the proposed techniques in Chapter 5.

2.1.3(a) Linear Minimum Mean Square Estimator

Linear Minimum Mean Square Estimator (LMMSE) approach alleviates the noise enhancement problem by considering the noise power when constructing the filtering matrix using the LMMSE performance-based criterion. The vector estimates produced by an LMMSE filtering matrix becomes

$$\hat{s} = \left(H^T H + \sigma^2 I\right)^{-1} H^T y \tag{2.3}$$

where σ^2 is noise variance, y is the received signal, $\hat{s}$ is the estimated signal, T is the transpose, and H is the channel matrix.

Note that the LMMSE estimates s_k of $k-th$ signal can be modeled as $\hat{s}_k = s_k + \mu_k$ when the signal present and $\hat{s}_k = \mu_k$ when the signal is absent where μ is the noise, $k = 1, \cdots\cdots, n$ and n is the signal length. Therefore,

$$\begin{cases} \Im_0 : \hat{s}_k = \mu \quad (Absent \quad user) \\ \Im_1 : \hat{s}_k = s_k + \mu \quad (Present \quad user) \end{cases} \tag{2.4}$$

Since s_k is an element of modulation set, it is not fixed. The Generalized Likelihood Ration Test (GLRT) (Kay, 1998) replaces the unknown parameters by their maximum likelihood estimates (MLEs). Although no optimality is associated with the GLRT, in practice, it appears to work quite well (Kay, 1998). In general, the GLRT decides $\Im_1$ if

$$\Delta = \frac{p(\hat{s}_k|\Im_1)}{p(\hat{s}_k|\Im_0)} > \varepsilon \tag{2.5}$$

where ε is a predefined threshold and $p(\hat{s}_k|\Im_1)$ assign the prior probability to the possible occurrence of hypothesis $\Im_1$. The approach provides information about the unknown parameters because the first step in determining Δ is to find the MLEs.

2.1.4 Maximum Likelihood Detector

Analytical models typically take the form of equations that define the input-output relationship of the system being modeled (Tranter et al., 2003). In communication systems, the input-output relationship can be expressed as

$$y = Hs + \mu \tag{2.6}$$

where y is the received signal (output), H is the channel matrix, s is the modulated signal (input), and μ is the noise. It's a well-known fact that the Maximum Likelihood Detector (MLD) offers the optimum solution for the system in Eq. 2.6 that could effectively recover the transmitted signal at receiver based on the following minimum distance criteria (Vikalo et al., 2004)(Damen et al., 2003),

$$arg_{s_k \in Z} min \|y - Hs\|^2 \tag{2.7}$$

Using the above criterion, MLD compares the received signal with all possible transmitted