CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The market of wireless communications is continuously experiencing rapid growth. Companies have already spent an enormous amount of money on third generation mobile licences. The leap of faith by such companies indicate a belief that there is considerable growth potential in the mobile communications sector.

The proposed third generation systems must deliver high speed data and voice services, while remaining compatible with second generation systems. Furthermore, new techniques of modulation, coding, equalization, multipath combining, multiuser detection, antenna and spatial diversity, and other mobile radio techniques are required to broaden the variety of existing services. There were several proposals for the new third generation cellular standard, of which the Wide band Code Division Multiple Access (W-CDMA) systems were taken the most seriously. The reason for this, is that W-CDMA offers increased flexibility when compared with the Time Division Multiple Access (TDMA) schemes that are predominant in current second generation cellular systems.

These recent developments in the cellular telecommunications market stimulated much research on how to increase system capacity in CDMA systems. One way in which the system capacity can be increased within a CDMA system is by minimizing the interference caused by other users. This type of interference, called Multiple Access Interference (MAI), can be limited by utilizing different multiuser detection techniques. In addition, frequency selectivity in the channel introduces another type of interference called, Inter Symbol Interference (ISI).

The field of MAI cancellation, which is collectively called multiuser Detection (MUD) [1], is rather broad. The optimum multiuser detector derived by Verdu [2] attains single-user performance when the following is known:

1. The signature waveform of the desired user.
2. The signature waveform of the interfering user.
3. The timing of the desired user.
4. The timing of each of the interfering users.
5. The channel impulse responses of the desired user.
6. The channel impulse responses of the interfering users.

The optimum multiuser detector uses the maximum likelihood Viterbi Algorithm (VA) to do Maximum Likelihood Sequence Estimation (MLSE). There are distinct disadvantages when it comes to practical implementation of the optimum multiuser detector. Even for a small number of users, the computational complexity is enormous. A suboptimum approach is consequently needed.

Among the several different MUD methods there exists a class of suboptimum multiuser detectors which have an adaptive equalizer type structure (either linear or non-linear). The equalizer type detectors need to adapt to time varying radio channels, and use different criteria to do so. The most common of these are the decorrelating or zero forcing (ZF) and mean square error (MSE) criteria. The decorrelating or ZF criterion can be considered an asymptotic form of the MSE criterion. To initially adapt to the impulse response of the channel, training sequences are used. This means that only the desired user signature (1.), timing (3.) and impulse response (5.) in the above list needs to be known. When using training sequences, the channel impulse response can be estimated. Known training symbols are transmitted until accurate decisions can be made. After the training phase, the symbol decisions can be used to adjust the equalizer coefficients.

In [3], Honig proposed the use of a blind algorithm, based on the Minimum Output Energy (MOE) criterion, which eliminated the need for training sequences. There also exists a variety of other blind adaptation algorithms which is readily used for channel equalization, of which the Constant Modulus Algorithm (CMA) is the most widely used blind algorithm [4]. This dissertation will investigate the application of the Constant Modulus (CM) criterion to implement a blind equalizer multiuser detector. In this way, effective MAI cancellation can be achieved without the use of training sequences. This method will be implementable in CDMA systems that use constant modulus complex spreading sequences. An example of such sequences are the root of unity (RU) filtered generalized chirp like (GCL) sequences. [5,6] Surprisingly, it has been shown that the constant modulus algorithm can also be applied to non-constant envelope signals [4]. Applying the CMA to CDMA multiuser detection poses some new problems. To keep the CMA detector from capturing one of the interfering signals, a linear constraint must be imposed on the CMA cost criterion. The modified constant modulus criterion is termed the linearly constrained constant modulus algorithm (LCCMA).

In this dissertation the suitability of the LCCMA is investigated for the purpose of blind CDMA multiuser detection. The shortcomings of the LCCMA are identified, and improvements will be proposed.

1.1.1 GENERAL PROBLEM DEFINITION

The problem addressed in this dissertation can be defined as the investigation of the constant modulus criterion within the framework of multiuser detection in a linear decision directed (DD) equalizer structure, to achieve effective MAI cancellation in the uplink (asynchronous) and downlink (synchronous) of Direct Sequence (DS) CDMA systems.

Concerning system evaluation, the CDMA multiuser system must be evaluated within semi-static and mobile channel conditions by means of computer simulation. This is to be done by means of Bit Error Rate (BER) comparative testing as a function of bit energy to noise spectral density ratio E_b/N_0. In this way, the performance of the constant modulus technique can be compared with the matched filter detection bound (which will be explained later), as well as the multiuser channel single detection case. Furthermore, comparison with the standard Minimum Mean Square Error (MMSE) multiuser detection scheme will give a comparative measure of performance.

In summarizing, the dissertation objectives are

- The investigation of the constant modulus technique for effective MUD.
- The comparative C++ software simulation of the applicable constant modulus techniques in a single path static and a multipath mobile channel.
- Convergence performance by plotting signal to interference ratios versus time for different types of channels.
- BER performance evaluation of chosen techniques compared with the single user and MMSE multiuser detection cases in theory and software simulation.
- Investigation of other performance criteria such as asymptotic multiuser efficiency, signal to interference ratio, etc.

1.2 AN OVERVIEW OF CODE DIVISION MULTIPLE ACCESS (CDMA)

There are three CDMA categories that can be distinguished. These are direct sequencing (DS), time hopping (TH) and frequency hopping (FH). The FH and TH categories are generalizations of the FDMA (Frequency Division Multiple Access) and TDMA techniques respectively, in which the assignment of frequency bands and time slots are changed according to certain hop patterns. We will be mainly concerned with the DS category, which is based on spread spectrum principles.

The DS-CDMA system is a multiple access system in which many users are simultaneously multiplexed on the same frequency band by means of quasi-orthogonal codes. The data from each user is modulated by a technique called direct sequence spread spectrum (DSSS) modulation. In this method the modulated signal is generated by mixing a high frequency (chip rate) code sequence with the data at a much lower data rate. Some of the advantages of DS-CDMA, is the manner in which it can effectively reuse the available frequency resources and the efficient multiple access system capacity. Furthermore, the spread spectrum modulation scheme has an inherent immunity against multi-path mobile channels. This makes it ideal for cellular wireless mobile and semi-static channels.

By a proper choice of spreading codes, the cross correlation between the different users in a CDMA system can be minimized, thus decreasing the interference between different users. The residual interference can then be removed by means of multiple access interference cancellation techniques.

The basic DS-CDMA principle is based on conditions such as an additive white Gaussian noise (AWGN) channel with perfect power control. Acceptable power control is difficult to achieve in a time variant mobile fading channel. Imperfect power control causes the situation where the signal of a strong mobile completely overpowers weaker mobile signals. This situation is called the near-far effect, and is very detrimental to system capacity. It is thus important that multiuser detection techniques should be near-far resistant for mobile channels.

1.3 THE CDMA DATA DETECTION HIERARCHY

In order to form a proper heuristic view of all existing data detection principles, the references of Klein [1] along with Woodward and Vucetic [7] are of great value. The references [8] and [9] are successful in presenting a less detailed overall view of the CDMA multiuser detection problem. Because of the unified manner in which the set of multiuser detection algorithms are presented in [1], the hierarchical structure adopted in this reference will, with minor modifications, be presented in this section. Using this section, it is possible to see where the CM MUD method fits within the global CDMA data detection hierarchy.

1.3.1 SINGLE USER DETECTION

The traditional signal separation by means of matched filters (MFs) is termed single detection in [1]. We will use the term single user detection (SUD) as to avoid confusion with the term sequence detection (SD). The SUD method assumes perfect power control of all users. The SUD method is suboptimal in that it treats all interference (both known and unknown) as noise. We know that this is not the case with CDMA in a mobile channel, as both MAI and inter-symbol interference (ISI) are not noise like. MAI is caused by cross correlation terms between the different users' spreading codes, while ISI is caused by the interference of several unequally delayed incident waves due to scatterers surrounding the receiver. There is a strong connection between MAI and ISI, and is explained in the reference [2].

The SUD method is in a practical sense not near-far resistant, as it assumes perfect power control. As mentioned earlier, this is very difficult to achieve in a time variant mobile fading channel.

1.3.2 MULTIUSER DETECTION

The poor system capacity in traditional matched filter signal separation (SUD), is the result of cross-correlation between user codes in synchronous systems, and the loss of orthogonality due to phase offsets in asynchronous systems. Recent advances in multiuser theory shows that the high MAI inherent in CDMA systems is not necessarily a shortcoming of the CDMA multiple access scheme. It is possible to use some or all of the code and channel information to cancel out MAI. This method of detection, of which many variants have already been proposed, is collectively called multiuser detection (MUD). We can subdivide MUD into two categories which are called interference cancellation (IC) and joint detection (JD). The hierarchical structure for data detection principles in CDMA is depicted in Figure 1.1.

INTERFERENCE CANCELLATION (IC)

The idea of IC is closely related to decision feedback (DF) and is

- to detect part of the transmitted data symbols,
- to reconstruct the contribution of these transmitted data to the compound received signal and
- to subtract the contribution from the compound received signal.

This means that there remains a component of MAI that is still treated as noise, thus making the joint detection principle suboptimum. There are currently two methods of interference cancellation. The methods of

- successive or serial IC and
- parallel IC

can be distinguished.

Successive IC sorts users from the strongest to the weakest signal and then detects the data symbol of the strongest user to cancel its influence. With the contribution of the strongest user cancelled out, the method then cancels the influence of the second strongest user. This is repeated until all of the users' influence is cancelled out. This method is ideally suited for the case of users with varying signal strengths [1, 9], i.e. the near-far effect. It is related to the decision feedback algorithm and is non-linear. Standard Parallel IC on the other hand, detects the contributions of all the users' data simultaneously at the output of each single user detector. The influence of all of the users, except the user in question, is cancelled from the received signal. In general, the parallel IC method has a higher potential of performance enhancement than successive IC, since the contributions of all the users are cancelled, and not only those which have stronger signal power. The parallel IC method can be repeatedly performed, leading to a *multistage canceller* default.

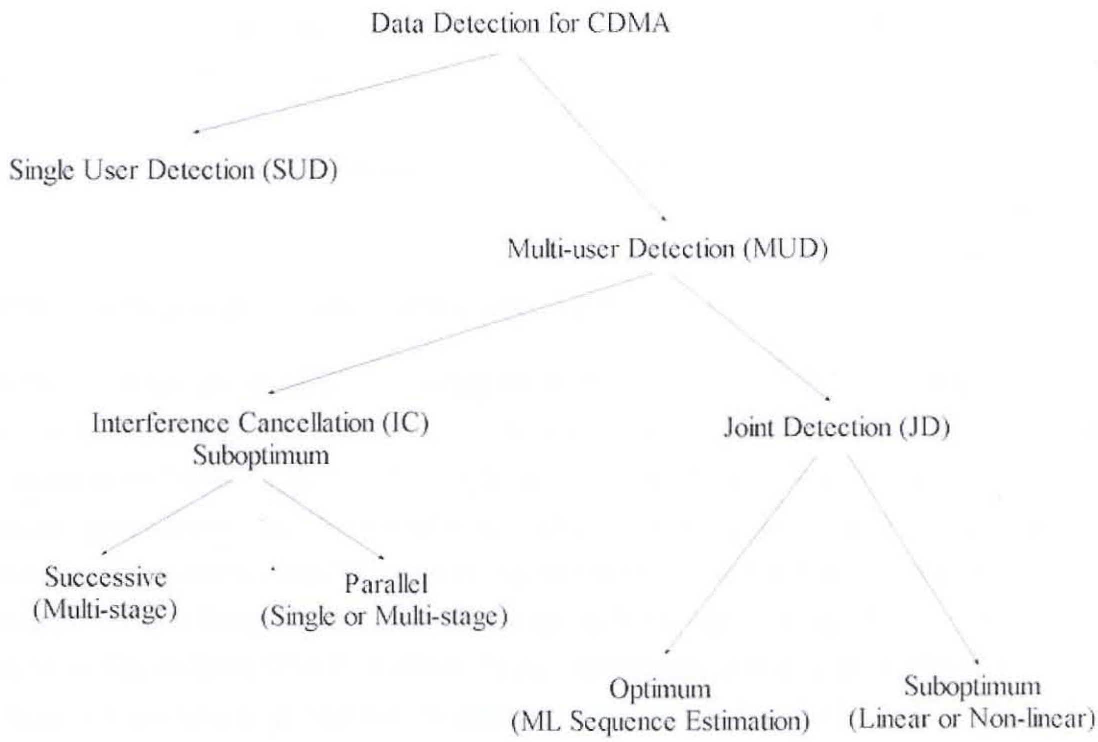

Figure 1.1: Data detection hierarchy structure for CDMA

1.3.2.1 JOINT DETECTION (JD)

The joint detection idea is based on the idea that the data symbols of all the users are detected jointly, using all the a priori knowledge about the MAI. We can divide joint detection into two groups. These are optimum and suboptimum detection. Both the optimum and suboptimum joint detection algorithms have a greater potential to enhance system capacity than IC methods.

1.3.2.1.1 Optimum Maximum Likelihood (ML) JD

The optimum detector for the multiuser CDMA system was first demonstrated by Verdu [2]. It was shown that the output of a bank of matched filters (MF), i.e. SUD, contains sufficient statistics to achieve optimum detection. This can be done by a Viterbi algorithm for maximum likelihood sequence estimation (MLSE). The practical application of this approach is limited by two main factors. The first is that the number of states required by the Viterbi algorithm is exponentially complex in the number of active users. For many users, the problem becomes intractable. Secondly, the MF filter bank is formulated in an AWGN channel. In a practical time varying mobile channel with ISI, the MF bank will have to be synthesized with knowledge of the activity, time and phase synchronization, spreading sequence, power, and channel conditions for each user. Much of this information is also required by the Viterbi algorithm.

There are numerous simplified algorithms that can replace the Viterbi algorithm, as proposed in [10–12]

1.3.2.1.2 Suboptimum (Linear and Non-linear) JD

This family of JD can be classified as being adaptive linear (Decision Directed - DF) or non-linear (decision feedback - DF) [1,7,9]. The linear type JD receivers perform a linear transformation on the output of the MF bank. The non-linear type receiver, has a forward filter operating directly on the received signal samples, and a backward (feedback) filter operating successively on a non-linear decision to cancel out interference. There are two minimization operations that can be implemented with both linear and non-linear JD techniques. These are the decorrelating or Zero-Forcing (ZF) and Minimum Mean Square Error(MMSE) methods. These combinations give us a group of four suboptimum JD receiver types which are near-far resistant. As mentioned earlier, the ZF and MMSE multiuser detectors have the disadvantage of needing to be trained either at the beginning of reception, or at regular intervals between blocks of data. Honig [3] was the first person to suggest blind suboptimum JD.

Blind Methods

Li [13], gives a summary of recent work on blind MUD. Honig [3] first proposed blind MUD using the minimum output energy criterion. Recently, some other methods for joint MUD and blind equalization were presented [13–23].

The first kind is subspace-based methods [14–16]. These methods usually require Singular Value Decomposition (SVD) or Eigenvalue Decomposition (EVD) of some data correlation matrix. These computations are complex and not very practical to implement. Another drawback of the subspace type methods, is that accurate rank determination is difficult in a noisy environment.

The second kind of blind MUD methods is constrained optimization [3,17,18], which result in computationally efficient adaptive algorithms. The methods in [3] and [18], are based on the MOE criterion, where as the CMA MUD is based on the constant modulus criterion. The major drawback of the MOE methods, is that there exists a saturation effect in the steady state, which causes a significant performance gap between the blind MOE detector and the true MMSE detector [3, 16]. Furthermore, the performance of the MOE method critically depends on the nonzero magnitude of the selected tap of the channel response. Some improvements are proposed in [18] to find better constraints. Lee [13] mentions the possible use of the CM or Godard cost function as a constraint. A general equalization method for Multiple Input Multiple Output (MIMO) channels using the Godard or CM cost function is proposed in [19]. The CMA MUD methods in this dissertation will be based on the recent work done in [19–23].

The third kind of blind MUD detection methods is based on linear prediction methods [24], or linear prediction like methods [25]. The main idea of the linear prediction approach is to use the null subspace of the desired user's spreading code matrix to estimate the channel and then to estimate the detector. One possible drawback of the linear prediction method, is that the channel estimation may suffer from system noise and computation errors [13], which will deteriorate the symbol detection. In [26], it is shown that a direct blind equalizer can be obtained by using linear prediction to estimate the column vector subspace of the channel without estimating the channel itself. Instead of two stages of linear prediction in [26], only one stage is required for CDMA [13].

1.4 APPLYING THE CONSTANT MODULUS CRITERION TO MUD

The most studied and implemented adaptation algorithm of the 1990s is the CMA [4]. The CMA is a special case of the Goddard algorithm [27,28]. The CMA seeks to minimize a cost defined by the CM criterion. This criterion penalizes deviations in the modulus (magnitude) of the equalized signal away from a fixed value. A major advantage of the CMA is that it is a blind algorithm, and does not need a known training sequence to be transmitted. It is obvious that the inclusion of such a training signal sacrifices valuable channel resources. The CMA is a stochastic gradient algorithm [27], which applies a memoryless non-linearity at the output of the linear FIR equalizer in order to generate the desired response with each iteration. The nature of the non-linearity in the CMA will be discussed later in the dissertation. The CM and MSE criteria have several similarities with regard to their cost surfaces. The cost surface is a multi-dimensional surface of the MSE or CM cost versus the equalizer coefficients. Under AWGN conditions, MSE and CM cost functions also have exactly the same minima [4].

The CMA was widely implemented in a Single Input Single Output (SISO) channel for adaptive equalization. The CDMA channel is a MIMO channel, as several users share the same bandwidth. Tugnait [19] proposed the use of the Goddard cost function in a MIMO channel. In this way the CMA can be generalized to the MIMO case, and can specifically be applied to MUD in CDMA systems. The use of a linear constraint, utilizing information about the desired user signature vector, can prevent the detector from locking on to interfering user signals. After this, several authors proposed the use, and evaluated the use of the linearly constrained constant modulus detector. These issues are discussed in detail in Chapter 5. A notable advantage of the linearly constrained constant modulus (LCCM) detector is the fact that it requires no more information than the SUD. It only requires knowledge of the timing and the signature waveform of the desired user. In this dissertation, variants of the LCCM detector i.e. the LCCM and the linearly constrained differential constant modulus (LCDCM) detectors will be thoroughly studied and evaluated.

1.5 CONTRIBUTIONS OF THIS DISSERTATION

This dissertation focuses on the application of the constant modulus algorithm to the multiuser detection problem within the context of adaptive linear detector structures. Two different forms of the constant modulus multiuser detector are analyzed, evaluated and compared with each other and the MMSE detector. The main unique contributions of this dissertation can be itemized as follows:

- Existing signal, channel and detector models are expanded to encompass the complex valued *multipath* DS-CDMA channels.
- For the first time, a global convexity condition is extensively derived for the LCCM detector cost function.
- Simulation results for different channel types are generated and discussed. These channel types range from the additive white Gaussian noise (AWGN) channel to multipath fading channels.
- The application of the variants of the LCCM detector to non-linear multipath fading channels are thoroughly investigated. The issues and limitations with respect to non-linear channels are

discussed, analyzed and evaluated.

The following *research outputs* were generated during the completion of this dissertation:

1. Submission of a paper to IEEE Transactions on Communications, June 2002 [29].

2. International Conference presentation at IEEE Africon October 2002, George, South Africa [30].

3. Submission of an abstract for a paper in a special issue of the Transactions of the SAIEE.

The following conclusions are presented as determined by analysis and simulation:

- The blind adaptive LCCM detector suffers from ill-convergence under the condition that the desired user amplitude falls below a certain level. This is due to the LCCM cost function exhibiting undesired minima under this condition.

- The blind adaptive LCDCM detector converges independent of desired user amplitude. The LCDCM cost function exhibits a global minimum in an AWGN channel.

- Tap weight vector convergence of both LCCM and LCDCM detectors approach the mean tap weight vector of the MMSE detector in an AWGN channel, but not in a multipath fading channel.

- Under normal operation, the MMSE detector can combine static multipaths, while the LCCM and LCDCM detectors attempt to cancel it out.

- If inverse channel plus noise estimation can be used within the linear constraint, the LCCM and LCDCM detectors can effectively combine the multiple paths, providing that the multipath channel plus noise inverse can be accurately modelled within the length of the detector.

- BER and SIR simulation measurements show that the blind LCCM and LCDCM detectors exhibit similar performance to that of the non-blind MMSE detector in an AWGN channel. Ill convergence of the LCCM detector is demonstrated if the desired user amplitude falls below a certain level as calculated analytically.

- BER simulation measurements show effective operation of the LCCM and LCDCM detectors in a minimum phase *non-fading* multipath channel.

- In a multipath fading channel, the resulting channel may at times be ill-behaved. This means that the inverse channel plus noise may not accurately modelled by a linear filter. Consequently, the linear MMSE, LCCM and LCDCM detectors are at times unable to equalize the channel, and the eye closes.

1.6 OUTLINE OF DISSERTATION CHAPTERS

This chapter gives a qualitative introduction to the CDMA environment and a heuristic view of the multiuser detection problem. Application of the CMA to multiuser detection is briefly visited, and a general problem definition is stated. Chapter 2 introduces the reader to the CDMA signal and channel models that will be extensively used within the dissertation. Chapter 3 makes the reader intuitively aware of the issues regarding the multiuser detection problem. Two user graphical examples are used to assist in this process. Several criteria are given whereby multiuser detectors may be evaluated. Chapter 4 starts with a generalized discussion on all linear multiuser detection techniques. The MMSE detector model is presented in detail, supported by a rigorous theoretical performance evaluation. Chapter 5 treats the linearly constrained constant modulus detector and an improved variant, the linearly constrained differential constant modulus detector. The cost criteria of these detectors are analytically analyzed and scrutinized. The advantages and disadvantages of both detectors are discussed. In Chapter 6, simulation results are presented. These results, along with the theoretical results obtained in Chapters 4 and 5 are comparatively discussed. Conclusions are drawn, and areas for further possible study and investigation are also proposed. The dissertation outline is depicted in Figure 1.2.

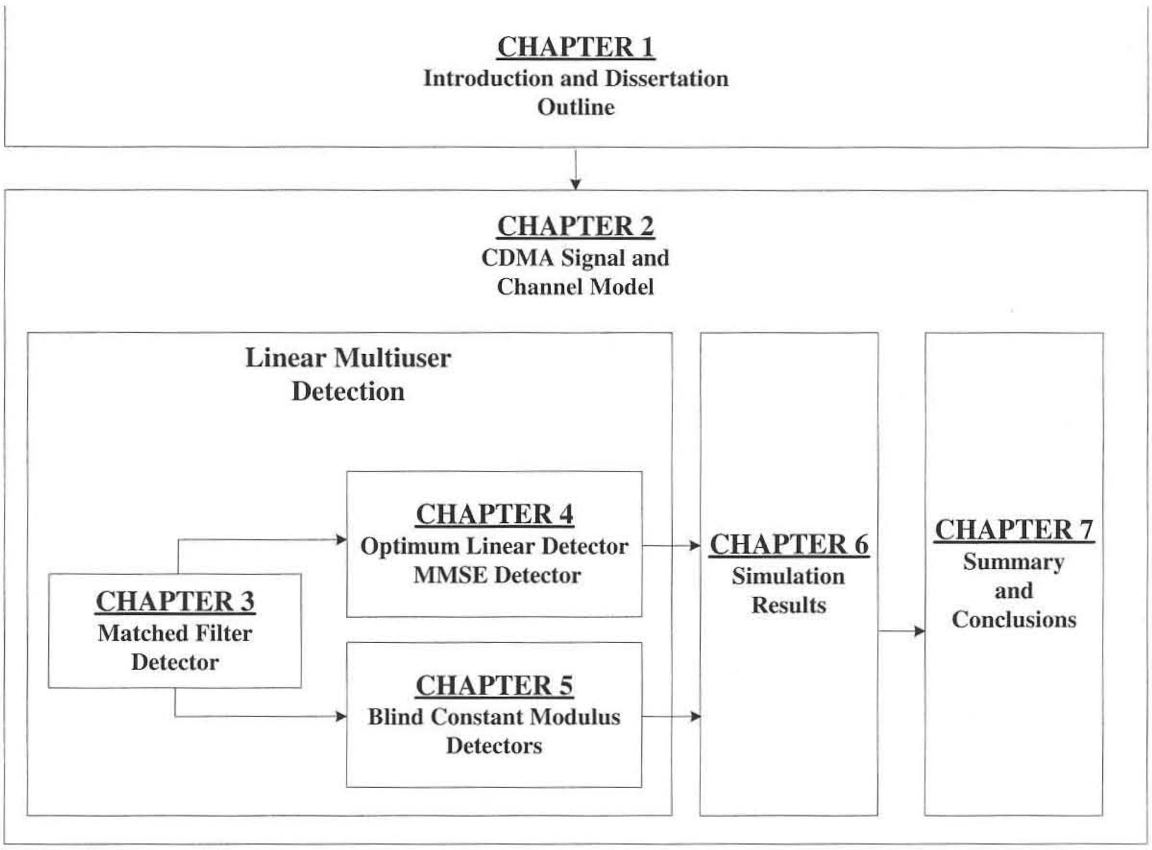

Figure 1.2: Graphical representation of the structure and outline of the dissertation.