DESIGN AND PERFORMANCE EVALUATION OF AN ADAPTIVE RESOURCE ALLOCATION SCHEME FOR MIMO-OFDMA SYSTEMS WITH FAIRNESS CONSTRAINT.

BY

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Verily all praise is for Allah, we praise Him, seek His help and ask for His forgiveness....

To

My beloved Parents for their prayers, love, guidance and support.

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Thesis Abstract

Name: Mohammed Akber Ali.

Title: Design and Performance Evaluation of Resource Allocation Schemes for MIMO-OFDMA Systems with Fairness Constraint.

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Multiple input multiple output (MIMO)-Orthogonal Frequency Division Multiple Access (OFDMA) systems have great potential for providing enormous capacity due to its integrated space-frequency and multi-user diversity. It is generally hard to find an optimal solution for sub-channel and power allocation in a multiuser MIMO-OFDMA system that maximizes the overall systems capacity, given proportional rate constraints. In this thesis, an adaptive subcarrier and power allocation scheme is proposed for a MIMO-OFDMA system. This algorithm optimizes power distribution, guarantees quality of service requirements, and ensures fairness to all active users. In addition, the performance of the designed algorithm is also investigated by applying it to practical MIMO schemes, taking into account adaptive modulation and bit loading techniques. Simulation results show that the proposed scheme satisfies the proportional rate constraints in strict sense and therefore can provide absolute rate guarantees in contrast to other schemes found in literature.

MASTER OF SCIENCE DEGREE
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ملخص الرسالة

الاســـــــــم: محمد اكبر علي

عنوان الرسالة : تصميم وتقيم أداء مخطط تخصيص الموارد لنظم الإدخال والإخراج المتعدد ذو الوصول المتعدد ذو التضمين الترددي المعامد (MIMO – OFDMA) بقيود منصفة.

التخصـــــــص: هندسة الاتصالات

تاريخ التخـرج: ذو الحجّة ١٤٣٢هـ

أنظمة الإدخال والإخراج المتعدد (MIMO) ذات الوصول المتعدد ذو التضمين الترددي المعامد (OFDMA) لديها إمكانات كبيرة في زيادة السعات؛ بسبب الفضاء التردد المتكامل والمستخدمين المتعددين . إنه من الصعب عموما العثور على الحل المثالثي لقناة فرعية وتحديد القدرة في نظام MIMO - OFDMA والتي من شأنها تعظيم قدرات النظم الكلية، مع اعتبار قيود المعدل النسبي. في هذه الأطروحة، نقترح حامل فرعي متكيف و وخوارزمية لتحديد القدرة لنظام الإدخال والإخراج المتعدد ذو الوصول المتعدد ذو التضمين الترددي المعامد بقيود منصفة.هذه الخوارزمية تحسن توزيع الطاقة وتضمن نوعية متطلبات الخدمة، وتتأكد من المساواة لجميع المستخدمين النشطاء. بالإضافة إلى ذلك ، يتم التحقيق من أداء الخوارزمية المصممة بواسطة تطبيقه على مخططات MIMO العملية، مع مراعاة التكيف في التشكيل وتقنيات تحميل البت. نتائج المحاكاة تبين أن المخطط المقترح يفي قيود المعدل النسبي بالمعنى الدقيق، وبالتالي يمكن تزويد معدل مطلق لضمان القيود لمخططات أخرى موجودة في دراسات سابقة.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

Chapter 1

Introduction

1.1 Overview of Wireless Communications

With the advent of wireless communication the lifestyles of people have changed, allowing us to have freedom of mobility. We are no longer required to be at a fixed position to make voice call, or use a personal computer with wired connections to send or receive an e-mail, download data or chat with colleagues. These days, cellular phones and wireless devises are widely used to access internet or make a voice call while toddling down the streets or travelling in a vehicle. Therefore, with a drastic increase in number of users accessing wireless services, there is an increasing demand for larger bandwidths to accommodate more users with higher data rates, faster response and more reliable communication. However, it is hard to meet these diverse set of consumer requirements due complexity, bandwidth and power limitations of wireless systems. Moreover, factors like channel shadowing, path loss and multipath fading phenomena affect the wireless channel characteristics limiting the effective use of channel.

1.2 Resource Allocation in Wireless Communications

In order to maximize the overall performance of wireless communication systems, the system has to make use of progressive physical layer technologies and effectively manage the available wireless resources over these technologies. Radio resource allocation refers to optimal utilization of radio resources based on channels state information and quality of service (QoS) requirements of users in the system [1]. The most primary wireless resources that can be managed are transmission power, channel bandwidth and number of antennas at transmitting as well as receiving ends. The problem of resource management is more complex in a multi-user scenario due to increasing interference from multiple users. Therefore, optimal resource allocation considerably increases the data rates despite of low bandwidth, acclimatizing to channel conditions and system’s QoS requirements.

Bandwidth refers to a frequency range that is occupied by a signal during transmission [2]. The maximum transmission rate and rate of accessing a channel is determined and limited by the systems bandwidth. When there are multiple users in the system then the channels’ access to transmit data is shared among all users based on scheduling strategy of the system. The reliability of a transmitting signal mainly depends on availability of transmission power. It is very important to effectively manage the transmission power because transmission of one user is most likely to interfere with transmissions of other users. Therefore, it is essential to have power control to support simultaneous existence of interfering users. Also, there is a need for optimal power allocation over multiple sub-channels to maximize system’s efficiency over transmission power.

In recent years there has been a considerable amount of research to show that use of multiple antennas increases channels capacity drastically without additional bandwidth or power [2-5]. However, increase in antennas increases the complexity of the operating circuitry used, thereby increasing the cost of the device. Consequently, for efficient use of available antennas there is a need to have an adequate antenna management scheme, based on the instantaneous channel state information (CSI). From the above discussion, it is clear that the wireless resource management can be seen as bandwidth, power and antenna management. Also, it is very important to manage these resources due to their scarcity.

Therefore, for a resource management scheme to be effective, it must take into account all the available resources, the CSI available, service requirements of each user and all the constraints used to optimize the function of the system.

1.3 Multiple-Input Multiple-Output (MIMO) Systems

MIMO is a technology for wireless communication systems in which multiple antennas are used at both the source (transmitter) and the destination (receiver) as shown in Figure 1.1. The antennas at each end of the communication channel are combined to minimize errors and optimize data rate. A network design incorporating MIMO technology provides the scalability needed to quickly deliver multimedia content to the mass market. MIMO works by creating multiple parallel data streams between the multiple transmit and receive antennas. By exploiting the multi-path phenomenon, MIMO can differentiate the separate signal paths from each antenna [3].

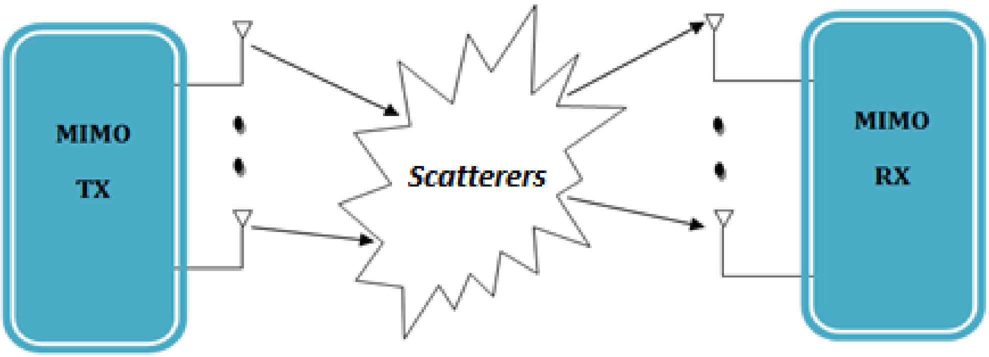

Figure 1.1: MIMO system showing transmitter & receiver equipped with multiple antennas.

MIMO systems can be implemented in various ways. If we need to take the transmit diversity advantage to combat multipath fading then the same signal is sent through various transmit antennas and the receive antennas will receive the same signal traversed through various paths. In this case, the entire received signal must pass through un-correlated channels. If we are concerned to use MIMO for capacity increase then different set of data are sent over the transmit antennas and receive antennas will receive the signals at the receiving end [2].

Therefore, future wireless technology includes communication based on multiple antennas both at the transmitters and the receivers. The spectral efficiency of MIMO transmission significantly increases if CSI is available at the transmitter, allowing the system to effectively adapt to the wireless channel and take full advantage of the available spectrum.

1.4 Orthogonal Frequency Division Multiplexing (OFDM)

For transmission, OFDM makes use of multiple sub-carriers which are closely spaced to each other without any interference, thereby eliminating guard bands between adjacent sub-carriers as in frequency division multiplexing (FDM) [6]. This is possible because the frequencies (sub-carriers) are orthogonal, i.e., the peak of one sub-carrier coincides with the nulls of all adjacent sub-carriers, as shown in Figure 1.2. OFDM is not a multiple access strategy, but it is a modulation technique that creates many independent streams of data that can be used by different users [7].

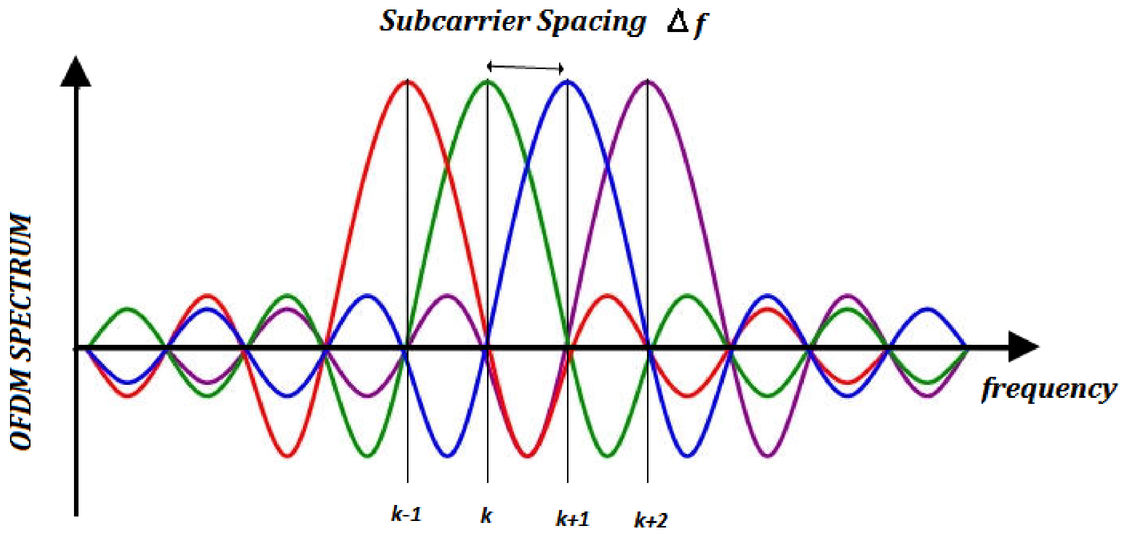

Figure 1.2: OFDM spectrum showing overlapping peaks.

In an OFDM system, a very high rate data stream is divided into multiple parallel low-rate data streams. Each data stream is then mapped to an individual sub-carrier and modulated. Normally, these signals would be expected to interfere with each other, but by making the signals orthogonal, mutual interference is eliminated. Additionally, having data carried at a low rate across all the carriers means that the effects of reflections and inter-symbol interference can be overcome [1]. Also, problems with multi-path signal cancellation and spectral interference are greatly reduced by selectively modulating the "clear" carriers or ignoring carriers with high bit-rate errors [7].

Like OFDM, OFDMA employs multiple closely spaced sub-carriers, but the sub-carriers are divided into groups of sub-carriers called sub-channel. The sub-carriers that form a sub-channel need not be adjacent. To utilize OFDM as a multiple access scheme for cellular technology, two different methods are used, one for the uplink and one for the downlink. In the downlink, a sub-channel may be intended for different receivers where a mobile user receives the whole signal transmitted by the base station and extracts the data destined for the particular user. In the uplink, a transmitter may be assigned to one or more sub-channels depending on the data to be transmitted.

In OFDMA systems, the sub-carrier and power allocation should be based upon the channel conditions in order to maximize the throughput. There are a number of different ways to take advantage of multi-user diversity and adaptive modulation in OFDMA systems. The idea is to develop algorithms for determining which users to schedule, how to allocate sub-carriers to them, and how to determine the appropriate power levels for each user on each sub-carrier. The problem of sub-channel and power allocation for a multi-user OFDM system, while maximizing the total system throughput and satisfying the typical constraints of total power and fairness can be modelled as a mixed-binary integer programming problem [8]. The optimal solution for this problem is generally hard to find. The typical approach is to utilize a sub-optimal sub-channel allocation algorithm and then obtain the optimal power distribution for that specific sub-channel allocation [9].

Therefore, OFDMA allows sophisticated time and frequency domain scheduling algorithms to be integrated in order to best serve the user population. Also, additional flexibility from OFDMA provides an increase in multi-user diversity, more freedom in scheduling of users, and many more implementation advantages. A disadvantage in OFDMA system is that the transmitter requires channel information for all users, and the receiver should be provided with the information of the sub-carriers assigned to it [1].

1.5 Scope and Motivation

From the literature and recent research, it is illustrious that MIMO based Orthogonal OFDMA scheme has the potential to achieve high data rates and transmit-receive diversity for reliable communication over wireless communication links, and so is considered as the future of wireless communication systems. MIMO-OFDMA systems support a large number of users with flexibility in QoS and provide high quality transmission in comparison with the existing systems. However in order to fulfill these requirements, some constraints have to be very well-addressed such as limited availability of frequency spectrum, availability of total transmit power and nature of wireless channels [1]. Power and sub-carrier allocation schemes for single-input single-output (SISO)-OFDMA systems in multi-user downlink scenario are very well-acknowledged and documented in the literature. However, the resource scheduling strategy for downlink multi-user MIMO-OFDMA scenario is rarely found in the literature. Most of the recent works in literature [3, 10, 11] have been extending these concepts of SISO-OFDMA to MIMO-OFDMA systems.

The main idea of this thesis is to devise a radio resource allocation algorithm for MIMO -OFDMA scheme. Although there are some algorithms proposed in the literature that are successful in achieving high data rates, none of them accomplishes proportional data rate fairness among users in strict sense. Here, strict sense fairness refers to a scenario where all the active users in a system strictly satisfy their proportional data rate requirements [8]. Therefore, we aim at allocating available wireless resources in a way that we can have the best possible overall system throughput while satisfying the systems proportionality fairness constraints in the strict sense.

1.6 Resource Allocation for MIMO-OFDMA Systems

Multi-user MIMO-OFDMA is observed as a vital technology for improving the flexibility and efficiency of wireless systems in future. A well-organized resource allocation technique that takes into account all system constraints is crucial for the performance of multi-user MIMO-OFDMA systems. There are two types of resource allocation optimization strategies that were considered in the literature for adaptive multi-user systems, (a) minimum transmission power optimization strategy and (b) maximum system throughput strategy with constraints on overall transmission power and sub-channel assignments. However, a multi-user MIMO-OFDMA system with an optimal scheduling scheme has an exponentially increasing wireless systems complexity with increasing number of sub-channels, users and transmit antennas. Consequently, a low complexity suboptimal scheduling algorithm has been a major research objective in recent years [6, 9, 12, 13].

Resource allocation for multi-user MIMO-OFDMA systems can be seen as scheduling of all the available resources among users efficiently. In general, sub-carrier allocation to users and power allocation on these assigned sub-carriers in a given wireless system is termed as resource allocation [1].

The resource allocation problem can be served both in data link layer (DLL) by scheduling based on the type of application with QoS parameters, and in physical (PHY) layer by choosing among various multiple access schemes and multiple antenna systems based on the type of CSI available at the base station through the feedback channel [14]. Figure 1.3, shows various resource allocation strategies available at DLL and PHY layer. The combination of channel-aware and application-aware scheduling with different transmission and multiple access schemes can help achieve high data rates with acceptable level of fairness among users, if the resource allocation is done in an efficient way taking into account all the QoS and resource constraints.

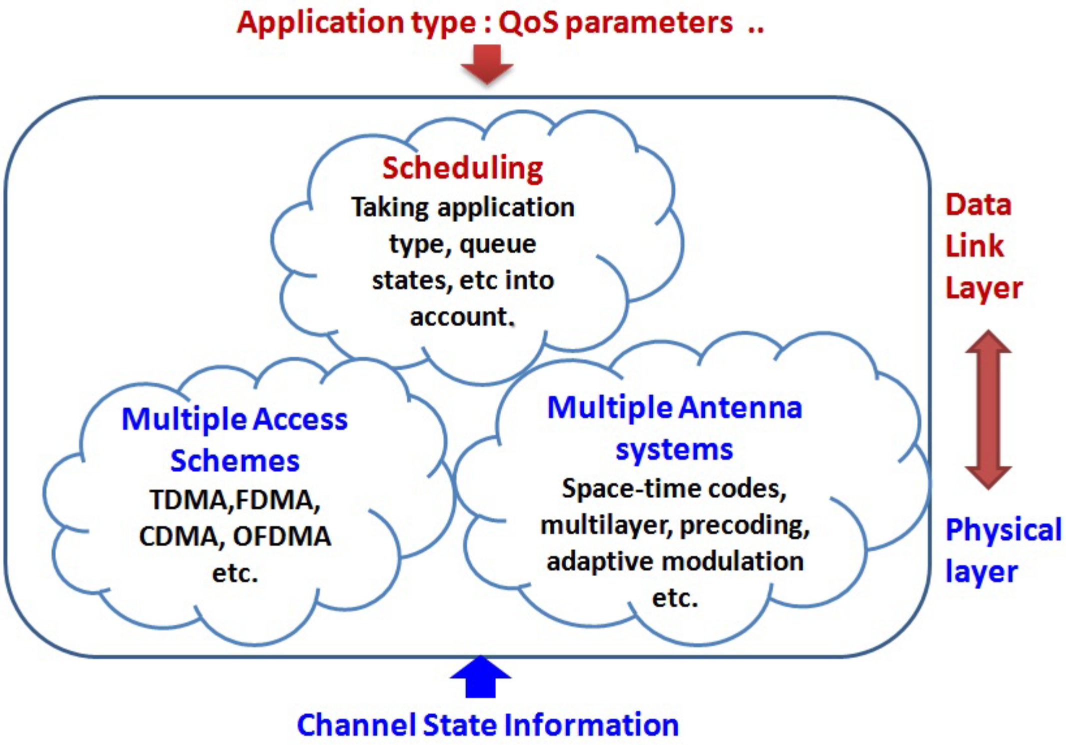

Figure 1.3: Resource Allocation in data link & physical layers.

A major emphasis in recent research has been given to a deeper analysis of extending the multi-user OFDM systems to MIMO-OFDMA systems [2, 3]. In multi-user resource allocation algorithms, all users are considered to be transmitting in all time slots. Therefore, when a set of user data rates are defined, the algorithm aims to minimize transmit power under a fixed performance requirement. These algorithms optimize the allocation process by minimizing the overall transmit power by allocating the sub-carriers to the users and by determining the number of bits and the power level transmitted on each sub-carrier based on the instantaneous fading characteristics of all users [13]. Most of the algorithms in literature, propose scheduling schemes that prefer dynamic sub-carrier allocation using Lagrange multiplier technique [8, 12-15], in order to make efficient use of the available wireless resources. By using various techniques algorithms in [6, 8-15] aim at minimizing the overall transmit power for a given bit error rate (BER), data rate and QoS requirement target values, or increase the system capacity with low computational complexity.

1.7 Thesis Contributions

In this thesis, a resource allocation scheme has been successfully proposed for MIMO-OFDMA systems. The proposed scheme performs sub-carrier assignment and power distribution, achieving high spectral efficiency and strict level of proportional fairness among users. Thereafter, in contrast to the proposed scheme another scheme is devised to study the effect of fairness constraints on overall systems capacity, when users have diverse data rate requirements. Simulation results and performance comparison of these schemes demonstrate a typical tradeoff between spectral efficiency and the level of proportional fairness among users in MIMO-OFDMA systems.

Other contributions include a unique performance study of proposed scheme over practical MIMO systems like Vertical Bell Laboratories Layered Space-Time (V-BLAST), Space Time Block Coding (STBC), and Multi-Layered Space Time Coding (MLSTBC) systems. It was observed that MLSTBC scheme performs better than STBC at low outage probabilities, and is more power proficient compared to V-BLAST scheme.

In addition to the above contributions, two adaptive modulation schemes based on zero forcing (ZF) precoding and V-BLAST techniques were devised as an extension to the proposed scheme. Both the schemes were successful in maintaining BER performance of the users less than the target BER under all conditions by adaptively adjusting to appropriate modulation modes.

1.8 Challenges

This work implicated considerable challenges because of the restricted power, bandwidth and complexity of the wireless systems. The first challenge was to evaluate the vast literature for various schemes that were proposed for resource allocation in OFDMA and MIMO-OFDMA systems that were significant in providing an acceptable tradeoff between overall system throughput and proportional fairness among users. MIMO and OFDMA are the techniques that are usually combined to handle the problems induced by multipath fading channels more efficiently. Specifically, MIMO-OFDMA has been incorporated into the IEEE 802.16 standard and MIMO-OFDM has been recommended in the IEEE 802.11n standard.

Thus, we sought to develop an adaptive resource allocation algorithm for MIMO-OFDMA systems in order to achieve higher data rates than OFDMA systems by extending familiar MIMO radio channel model to OFDMA transmission that efficiently utilizes channel variations and exploits multi-user diversity. However, in an adaptive resource allocation, capacity enhancement, fairness improvement and complexity reduction are usually conflicting parameters. Since current algorithms have relatively high computational complexity and may not be suitable for practical applications, efficient implementation of an adaptive resource allocation algorithm with good performance was our main concern.

1.9 Organization of the Thesis

In this thesis, we formulate a new optimization problem that balances the tradeoff between systems' overall capacity and fairness among users. The objective function is still the sum capacity, but proportional fairness is assured by imposing a set of nonlinear constraints into the optimization problem. The rest of the thesis is organized as follows.

Chapter 2 gives an extensive literature survey of the related work. In Chapter 3 a resource (sub-carrier and power) allocation algorithm is proposed, and its performance is compared with other resource allocation algorithms existing in literature. Performance evaluation of the proposed algorithm has been conducted in Chapter 4 practical MIMO schemes such as V-BLAST, STBC and MLSTBC. Subsequently, In Chapter 5, adaptive modulation schemes are proposed as an extension to the proposed algorithm. Finally Chapter 6 concludes the study, and proposes future direction of work.

Chapter 2

Literature Survey

2.1 Background

In past, the field of radio resource management in multicarrier systems has been moderately well-investigated. Abundant research and development works have dealt with solutions for OFDMA power and sub-carrier allocation adapting to various channel conditions. The optimization concerns vary widely from minimum requirements for users data transfer rate to limited transmit power and fairness, i.e., proportionality requirements. Compared to OFDMA, there are fewer researches related to radio resource management in MIMO-OFDMA systems.

A multi-user communication system aims at sharing the resources efficiently among a number of users [2]. Usually, these users require different levels of protection according to their applications type and their quality of service (QoS). Strictly speaking, these users can be ranked based to their QoS requirements. The future wireless systems aim at using MIMO-OFDMA scheme for transmission due to various benefits as discussed in Chapter 1. On one hand, MIMO extends the adaptation freedom to the spatial domain, which enhances the spatial efficiency or transmission diversity. On other hand, OFDMA has a fine frequency granularity which exploits the multi-user diversity, thereby, enhancing the spectral efficiency. Therefore MIMO-OFDMA has the ability to realize different QoS requirements by adapting the transmission parameters to the instantaneously varying channel state information (CSI) of each user according to his performance constraints [13].

2.2 Single User to Multi User Systems Altering the MIMO archetype

In comparison to single-user MIMO, multi-user MIMO (MU-MIMO) achieves higher transmission capacity in the system as a whole with the help of additional users. However, the technological hurdles become progressively higher in a multi-user scenario owing to more complex scheduling schemes and transceiver techniques. In a multi-user scenario, the multiple antennas of various users can be efficiently utilized to enhance the overall systems throughput, by scheduling users to simultaneously access the spatial channel [3]. From the concepts of information theoretic studies, it can be said that resource allocation techniques help us in exploiting the gains of MU-MIMO systems [1]. It is well known that deploying multiple antennas at the transmitter and/or receiver will improve the performance and capacity effectively. Some of the works in the literature focus mainly on developing the strategies to allocate sub-carriers among users of a multi-user system trying to combined beam-forming, sub-carrier and bit-allocation methodologies [13]. Also, improved appreciation of the impact of MIMO scheme in multi-user is mainly due to advancement in the field of information theory for multi-user scenarios.

2.3 Resource Allocation Schemes for MIMO-OFDMA systems

In last few years a lot of resource allocation schemes have been proposed for multi-user systems. Most of the schemes concentrate on maximizing the capacity while having constraints on the total available power and proportional fairness. In this survey, we analyze the problems confronted in dynamic resource allocation for multi-user MIMO-OFDMA systems in a downlink scenario. Based on instantaneous channel knowledge, dynamic resource allocation schemes can efficiently utilize channel variations and exploit the multi-user diversity to achieve higher throughputs. A margin-adaptive solution mainly concentrates on minimizing transmitting power subject to strict data rate constraints of the users [1]. Margin-adaptive resource allocation especially in MIMO-OFDMA systems is a challenging task due to association with various levels of QoS constraints demanded by multiple users. Spectral efficiency and fairness among users are thereby considered to be conflicting goals in general. However, in a practical telecommunication system, it is impermissible to overlook a user’s QoS requirements [16].

Opportunistic resource allocation for MIMO-OFDMA systems is also among the key methods to enhance the spectral efficiency in future wireless communication networks [17].The MIMO-OFDM systems multiplex the users both in the frequency as well as spatial domains but the co-channel interference caused by the sub-carrier reuse may possibly lower the system's performance to some extent. Hence, while for MIMO-OFDM systems with co-channel interference, the combination of power control with adaptive modulation is desirable to reduce the effect of co-channel interference [18].

2.4 Margin-adaptive Resource Allocation

Broadly classifying, there are two major classes of dynamic resource allocation schemes that have been stated in literature; namely 1) margin-adaptive, 2) rate-adaptive. The optimization problem in margin-adaptive allocation schemes is formulated with the objective of minimizing the total transmit power while providing each user with its required QoS in terms of data rate and bit error rate (BER). The rate-adaptive schemes have an objective of maximizing the total data rate of the system with the constraint on the total transmit power [1].

While the sum capacity of a system provides a fine measurement of the spectral efficiency, it is not a legitimate indication of each user's satisfaction in a multipath fading channel. It is known that the total throughput of a multi-user system can be maximized if each sub-channel is assigned to the user with the best channel gain over it and the power is distributed using the water-filling technique [8]. However, when the path loss difference among users is huge, the users with higher channel gains will be allocated most of the resources while leaving fewer resources for the users with low channel gains.

In margin-adaptive schemes, the main objective is that the Base Station (BS) has to satisfy individual QoS constraints of all users subject to transmit power minimization. This solution is hard to achieve due to the fact that the multiple streams from different users on the same sub-carrier cause interstream interference(ISI) which forces the use of low complexity beam-forming strategies and crafts it as a joint beam-forming and resource allocation problem [19]. Beam-forming is a technique in which each user's signal is multiplied with complex weights in order to adjust the magnitude and phase of the signals transmitted or received from each antenna. This causes the output from the array of antennas to form a transmit/receive beam in the desired direction whilst minimizing the output in other directions [20].

With the perfect knowledge of the instantaneously varying channels of an N-antenna user at M-antenna BS, eigenmode decomposition of MIMO channel on each sub-carrier results in Q = Min(M, N) parallel SISO sub-channels and a separate data stream can be transmitted on each eigenmode [4]. In multi-user scenario, performance can be further improved by multiplexing Q streams from different users resulting in Multi-user Eigenmode Transmission (MET) [21]. In [21] and [22] MET based margin-adaptive resource allocation in MIMO-OFDMA systems which results in transmit power minimization subject to QoS requirements of the users. Margin-adaptive solution is more applicable to delay-sensitive traffic e.g. voice transmission or real-time video streaming, in which target data rates need to be satisfied all the times based on instantaneous channel conditions.

In [21], a two step approach was used to decouple beam-forming from resource allocation. In the first step, a user grouping algorithm was deployed based on the fact that power can be minimized when multi-user interference (MUI) is reduced or canceled. Consequently the user and eigenmode assignment produce the least amount of interference. [21] also aim at maximizing the sum capacity by figuring out the best user group based on largest channel gain criteria and then in each step they drop the users whose channels are not semi-orthogonal to the already selected users. A user with the largest projected norm to the orthogonal component of the span of already selected users is then included in the user set. In this way a user group is formed that has the least amount of MUI. In this type of schemes, the objective is to minimize transmit power with MUI reduction as it can also contribute in minimizing power. It generally aims at combining a low complexity user grouping algorithm with the resource allocation algorithm thereby converting the combinatorial, non-convex problem into a convex optimization problem.

By using this approach sub-carriers are allocated to user groups instead of individual users and the target data rates of all the users are successfully achieved [21].

2.5 Rate-Adaptive Allocation Algorithm

Rate-adaptive algorithms found in literature, can be categorized into two major groups based on the user data rate requirements. If all users demand fixed data rates, then the scheme designed for that system to allocate resources is referred to as fixed-rate-adaptive allocation algorithm. These algorithms try to maximize the overall systems capacity while supporting each user with its fixed data rate requirement. On the other hand, the second group of algorithms take into account the concept of fairness or constrained-fairness among the users while allocating resources and this kind of algorithms are referred to as variable-rate-adaptive allocation algorithms [8, 9, 12, 13, 23, 24]. Figure 2.1, gives a summary of different classes variable-rate-adaptive allocation algorithms [8, 9, 12, 13, 23, 24] developed in multiuser OFDM systems. In this group of schemes, although the purpose is to maximize the systems overall capacity within the available limited power, the main task is to sustain the data rate proportionality among all the users based on proportional data rate constraints requirement.

2.5.1 Rate-Adaptive Algorithms for OFDMA Systems

In [24] utility functions were used in order to formulate the problem of resource allocation in a multi-user OFDMA system. This utility function records the network resources used by a user as a real number, which is a function of user’s throughput. In a utility-based optimization problem, the main task is to decide on the utility function depending on the systems requirements. Generally, a utility function is taken as a non-decreasing function of data rate, due to the fact that the reliable data rate transfer is the most significant factor to decide on users demand’s satisfaction in a wireless scenario.

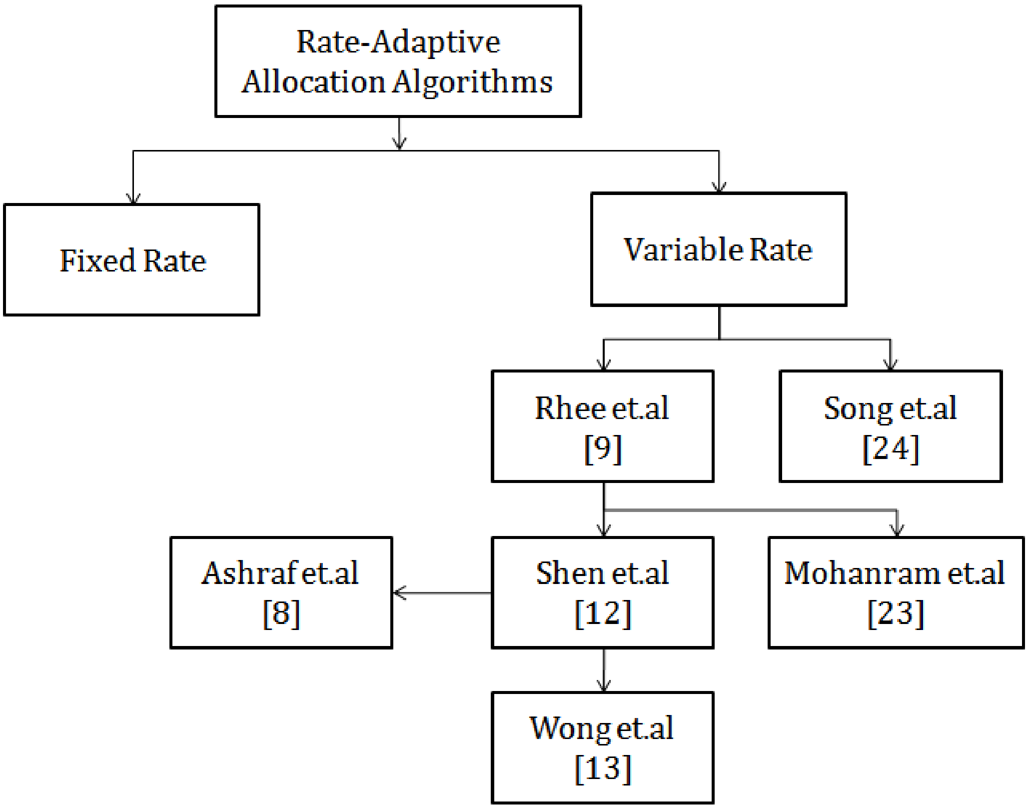

Figure 2.1: Various rate-adaptive algorithms proposed in [8, 9, 12, 13, 23, 24].

Optimal utility functions should be able to achieve both efficiency and fairness by increasing as well as decreasing marginally. Thereby, the slope of the utility functions curve decreases with an increase in throughput. A resource allocation algorithm that makes use of use of a logarithmic function (which is both increasing and marginally decreasing) can be seen as a proportionally fair scheduler [25]. In the literature, various utility functions are found that vary based on application type and requirement. Therefore, formulating a proper utility function that guarantees both efficiency and fairness for the given application must be given utmost priority while designing an allocation algorithm.

The problem of maximizing the overall systems capacity with fairness was formulated diversely by various authors for OFDMA scheduling scenario. In [9], the max-min problem was considered to propose a scheme, whereby an attempt was made to maximize the worst user's capacity, while assuring all other users the same data rate. The algorithm proposed by Rhee et al. [9] concentrates mainly on sub-carrier allocation, considering equal transmit power allocation over all sub-carriers. Although acceptable fairness was obtained for flat transmit power allocation, still the frequency selective nature of the channels was not utilized to its maximum.

In [12] an optimization problem was formulated by introducing the concept of proportional data constraints among all the users of the system. Shen et al. [12], proposed a two-step algorithm for resource allocation procedure. In the first step the sub-carriers were allocated based on a modified Rhee sub-carrier allocation scheme, where the priority of allocating sub-carrier was given to the user with least proportional data rate in the system, instead of user with least data rate (while assuming equal transmit power allocation). In the second step, the optimization problem is formulated as k^{th}-user optimization problem using Lagrange multipliers technique [12]. Thus, resulting in k nonlinear equations (where k is a particular user in the system), that cannot be solved easily without building some basic assumptions. Therefore an assumption was made that the proportion in which sub-carriers are allocated is the same as the proportional data rate constraints defined, which helps in making the optimization problem linear. With the help of this optimization criterion, the total power is re-allocated to users and is distributed over the sub-carriers assigned to a particular user with the help of water-filling technique. This step particularly helps in obtaining rate proportionality between users to a greater extent by utilizing adaptive-power allocation [1]. While, Wong et al. [13] made an attempt to solve the k-nonlinear equation obtained by [12] assuming that the BS can provide large amount of power and for high channel-to-noise ratios (CNR) the signal-to-noise ratios (SNR) obtained is very much greater than unity. Therefore, they reduced the optimization problem of k nonlinear equations into a single-nonlinear power optimization problem with the help of Newton's root finding method. This algorithm was successful in obtaining better capacities when compared to the algorithm of [12] but compromises to a greater extent on fairness among the users in the system.

In [8], Ashraf et al. proposed an efficient resource allocation algorithm that makes optimal power allocation for a given sub-channel allocation scheme. The algorithm is based on the power optimization problem formulated in [12], and the k nonlinear equations are solved to allocate power, without making any assumptions for the sub-channel gains and the proportionality ratios used in the fairness constraint, as in [12], and [13]. The algorithm proposed by Ashraf et al. drops the weak channels from the set of channels assigned to a user until a valid solution for the power optimization problem is obtained. This algorithm then re-distributes the power assigned to each user over the assigned sub-carriers utilizing the water-filling scheme. Therefore, the algorithm proposed ensures satisfying proportional data rate constraints in the strict sense without compromising much on the system's capacity.

Most of the suboptimal algorithms proposed in literature considered fixed-power allocation and focused on sub-carrier allocation [9] or performed sub-carrier allocation and power allocation one after the other reducing the complexity of the scheduling scheme as in [12], and [13]. However, in order to obtain an optimal scheduling algorithm, there is a dire need to perform sub-carrier and power allocation simultaneously. In [23], Mohanram et al. further modified the Rhee's sub-carrier allocation algorithm [9], in order to perform the sub-carrier and power allocation simultaneously. In this algorithm, the power assigned to each user is incremented by a proportionate amount with each sub-carrier allocation done for that user. This power allocated to the user along with each additional sub-carrier is directly proportional to the total power (P_{total}) available and inversely proportional to total sub-carriers (N) available, i.e., P_{total}/N. Then the total power assigned to each user is distributed over allocated sub-carriers by water-filling scheme, therefore very high user data rates are obtained when compared to other power allocation schemes. Then the algorithm determines the user who obtained minimum data rate to prioritize the next sub-carrier allocation. To obtain an apparent view about the various algorithms present in this Section we have obtained the systems overall capacity results for these algorithms along with their respective fairness indices and compared them to identify the trade-off between systems throughput, fairness and algorithms complexity. The channel model utilized for simulating these algorithms was a frequency selective multipath channel consisting of 6 independent Rayleigh multipaths, with an exponentially decaying profile, similar to the one used in [8, 12, 13]. The simulations were done using MATLAB software with following set of parameters,

Table 2.1: Parameters used for simulation of OFDMA based resource allocation algorithms discussed in [8, 9, 12, 13, 23].

Total Power	1Watt
Noise PSD	- 80 dBW/Hz
Number of Sub-carriers	64
System Bandwidth	1MHz
Number of Users in system	Varying from 2-16.

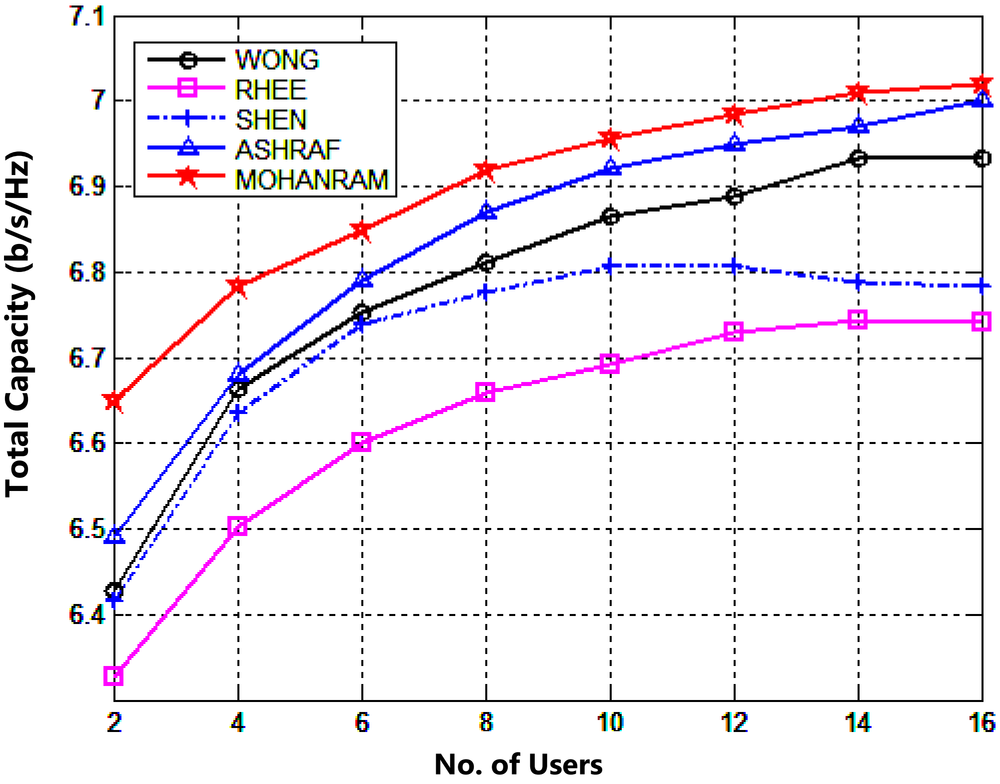

Figure 2.2: Total capacity (bits/s/Hz) versus number of Users comparison for various OFDMA resource allocation algorithms from [8, 9, 12, 13, 23].

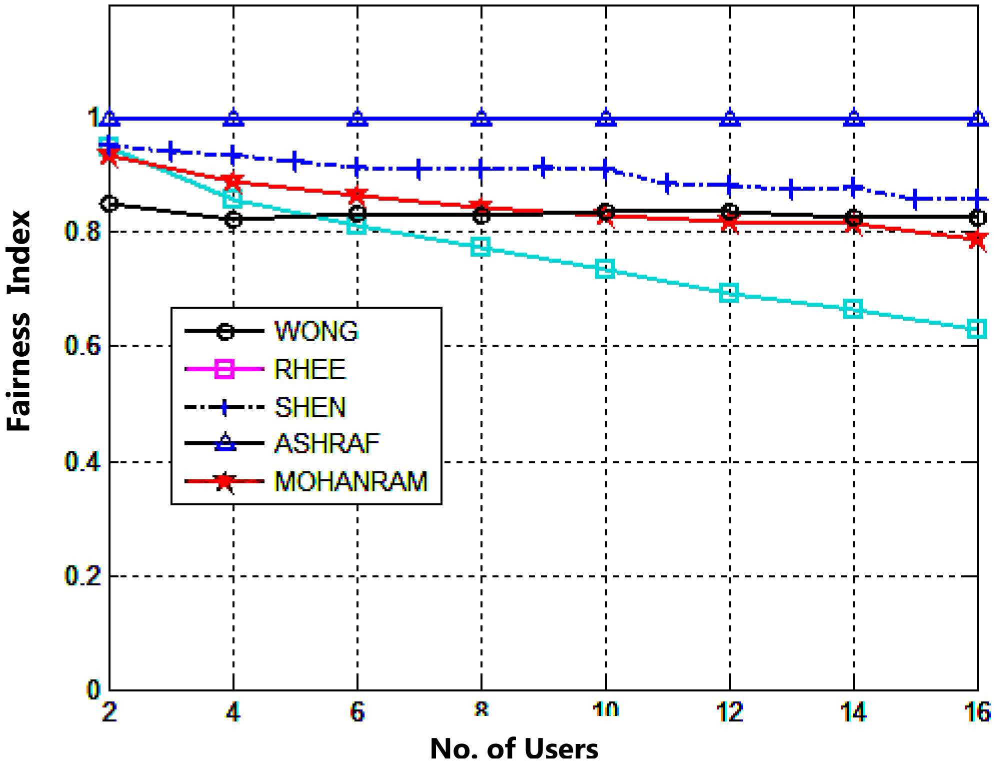

Figure 2.3: Fairness Index versus number of Users comparison for various OFDMA resource allocation algorithms from [8, 9, 12, 13, 23].

The Fairness indices are plotted based on the Jains fairness index, as used in [8], i.e., If the proportionality rate constraints are satisfied in strict sense then the Jains fairness index is equal to unity. The proportionality constraints are assumed to be varying randomly for the obtained set of plots. When the total capacity plot Figure 2.2, is analyzed the Mohanrams algorithm [23] seems to be leading all other algorithms with Ashraf’s algorithm [8] very much closer to it in terms of capacity, where as in fairness index plot only Ashraf’s algorithm is equal to unity always, implying the strictness with which the fairness constraint is satisfied amongst the users of the system.

From Figures 2.2 and 2.3 we can infer that there is always a trade-off between overall throughput and fairness in adaptive wireless resource allocation. When we compare the results for algorithms proposed by Mohanram and Ashraf, Mohanrams algorithm achieves higher throughput but negotiates reasonably with the level of fairness among users, i.e., algorithm achieves higher throughput, while being unfair to those users with bad channel conditions. Whereas the algorithm proposed by Ashraf achieves maximum level of fairness among users by satisfying proportional rate constraints in strict sense but the total capacity obtained is slightly lesser when compared to Mohanrams algorithm. A similar inference can be made from the results for the algorithms proposed Shen [12] and Wong [13]. Shen’s algorithm doesn’t satisfy the fairness constraint in strict sense, but makes an attempt to attain a fairness index that is much closer 1.

2.5.2 Rate-Adaptive Algorithms for MIMO-OFDMA Systems

In this section, we provide an overview of rate adaptive allocation algorithms found in literature. Most of these algorithms either classify users into different groups or assign priorities based on QoS requirements before allocating resources. In comparison to proportional fairness schemes found in literature for OFDMA systems, very few have been proposed for MIMO-OFDMA systems.

2.5.2.1 Grouping Based Rate Adaptive Schemes

Grouping users or sub-carriers can help in reducing the complexity of a resource allocation scheme, as the scheme works only on a selected group of users or sub-carriers at a time. In [26], the authors measured the spatial compatibility of users over sub-carriers by means of a meticulous distance metric. This metric tries to gather users whose distance between the row spaces is much closer to the other user's common null space. Thus the metric is known as Best-User-First Sub-carrier-User Scheduling (BUF-SUS) as it is based on distance between two signal subspaces. With reference to the metric, Zhong et al. [26] proposed two simple and rate-adaptive schemes. The first scheme solved the power optimization problem by distributing power equally among all sub-carriers and maximizing the capacity over each sub-carrier independently. Whereas, in the second scheme, the unused power obtained from the bit truncation respective sub-carrier null spaces was accumulated and assigned to other sub-carriers in order to further optimize the system. With this power reuse strategy the performance of the second scheme advances closer to that of an optimal scheduler depending on user selection criterion.

In [27], the whole spectrum was divided into a number of sub-carriers that were further grouped into sub-bands, each containing several sub-carriers based on the spreading factor (number of sub-carriers per transmitted symbol). In [28], the authors proposed an opportunistic scheme, in which adjacent sub-carriers are clustered into groups and then information on the best clusters is fed back to the base station. Thereby, [28] presents different feedback scenarios where each user feeds back only partial CSI for a group of neighboring sub-carriers. In [29], Jouko et al. proposed an optimal rate-adaptive technique based on information theoretical capacity results for MIMO-OFDMA systems well-known as best-M feedback method. In this allocation method, the M best resource blocks were selected out of the total of N resource blocks available and were allocated to users randomly. The indices indicating the selected combinations of the resource blocks fedback to the transmitter. The simulations results suggest that the best-M feedback resource allocation algorithm can provide significant improvement in capacity with limited feedback. Resources can also be classified as 3-dimensional (3-D) structure with sub-carriers, time slots, and spatial layers with regards to frequency, time, and space respectively. A novel scheme was proposed in [30], where the scheduler adaptively assigns the 3-D slots, i.e., space, frequency and time, among users depending on the instantaneous CSI. The 3-D scheme proposed, at first evaluates the users channel and decomposes it into number of non-interfering parallel channels with SVD. Then, the resource blocks are sorted based on Signal-to-Interference-plus-Noise-Ratio (SINR), and assigned to users with good channel conditions. Thus the scheduling of resource blocks and allocation of transmit power is done on a jointly basis in order to achieve higher system capacities. As equivalent SISO channels were decomposed from the original 3-D resource blocks, the power allocation done in this scheme was an extension to the space-frequency water filling algorithm, for single input single output SISO channels. One major achievement of this scheme was its approval at the World- wide interoperability for Microwave Access (WiMAX) systems following IEEE 802.16e media access control (MAC) protocols [31].

2.5.2.2 Priority Based Rate Adaptive Schemes

The basic allocation rule for priority based rate-adaptive schemes considering proportional fairness is that the user having the least proportional data rate has the priority, and is allocated an additional sub-carrier at an instance [22]. Tsai et al. proposed a dynamic priority resource allocation algorithm [32], which gives high priority to urgent users and dynamically adjusts the priority of users frame by frame. Yu et al. proposed a QoS guarantee scheduling scheme for MIMO-OFDMA system, [33] that serves users by considering fixed priority of service traffic.

In [34], a real-time scheduling algorithm was proposed that prioritizes the users taking into account urgency, proportional fairness requirement, packet delay and achievable instantaneous transmission rate in order to reduce the packet drop ratio. In [35], a resource scheduling algorithm, namely joint channel-aware and queue aware scheduling (JCQS) algorithm, was proposed. JCQS prioritizes the users based on unified urgent weight, which is evaluated taking into account various QoS requirements, such as delay deadline, minimum data rate, queue state information and user fairness. Thereafter, JCQS dynamically allocates resources to the user with the highest priority. Simulation results indicate that JCQS algorithm is efficient in terms of average system throughput, packet loss rate, and unsatisfied ratio of users with minimum data rate requirement.

[36] considers a number of resource scheduling policies concentrating on real-time Voice over IP (VoIP) traffic. In [36], a scheduling algorithm was proposed that achieved short term resource allocation fairness by giving enhanced scheduling priority to weak users. With the help of numerical results [36] shows that the conventional notion of fairness fails to guarantee service for low latency applications such as VoIP for an increasing traffic load.

2.5.2.3 Rate Adaptive Schemes with Fairness Constraints

Fairness constraints are defined in order to have fair distribution of available resources among the users, which restricts the systems objective function from being maximized without any consideration to marginalized users [37]. Fairness can be defined in terms of various system parameters. It can be defined in terms of bandwidth where same number of sub-carriers are assigned to all users [38], or it can be in terms of power the available transmit power is distributed equally among all the users [1]. It can also be in terms of data rate where the main objective of the scheduler is to allocate resources to the users such that all the users achieve equal data rates [9]. When the objective of a resource scheduler is to ensure rate proportionality among the users, it is called optimization with proportional fairness constraints [12].

In [16], a radio resource allocation algorithm was devised for multi-user MIMO–OFDMA scenario in order to satisfy proportional fairness among users. In this scheme the known MIMO radio channel model was extended to OFDMA transmission, by taking advantage of multi-user diversity. The algorithm realizes antenna selection to perform adaptive M-QAM modulation over sub-carriers, to maximize the overall system throughput based on MIMO channel estimation that is used to calculate the power gain values from singular value decomposition (SVD), and the MIMO channel capacity by transforming channel matrix into parallel SISO channels. Thus, the algorithm was successful in providing the required level of fairness among users, due to transmit power control over sub-carriers and antenna selection criteria. One main deduction that can be made from the scheme proposed by [16] is that to maximize MIMO-OFDMA systems overall throughput, it is better to keep up regulations pertaining to sub-carrier assignment for OFDMA systems.

Chan et al. [39], proposed a resource allocation schemes for high data rate, delay-sensitive users. It was supposed that, in high data-rate service group users had high datarate requirements, and were subject to some delay requirements. Thereby, some fairness constraints were considered in order to have fair distribution of resources among users. Lo et al. [27], formulated the resource allocation problem as a cross-layer optimization framework, and algorithms were proposed for MIMO-OFDMA systems in downlink scenario while taking effect of fairness into consideration. In [27], the system was investigated with and without the need for fairness among users, where fairness was modeled as maximum number of allowable channel assignments per user. Another unique aspect of the algorithm proposed in [27] is that the optimal water level for power distribution was obtained with the help of bisection method [40].

Bin Da et al. [41], proposed an adaptive algorithm for MIMO-OFDMA systems that does the resource allocation based on the instantaneous CSI feedback obtained at the BS. The algorithm also assumes that the allocation details are sent to the respective user through a separate channel in order to decode intended data over allocated sub-carriers. The proposed low complexity scheme allocates sub-carriers based on dominant Eigen-channels with gains, obtained from the instantaneous MIMO channel state information. For the first time in literature, Bin Da et al. [41] introduced a Tradeoff Factor (TF) parameter in order to re-allocate the sub-carriers between users and enhance the system’s fairness level while compromising the systems overall throughput to some extent with the help of an iterative exchange process. Thus, simulation results obtained imply that the proposed scheme is the most suitable one for satisfying diverse QoS requirements in MIMO-OFDMA systems.

2.6 Resource Allocation Schemes for Practical MIMO-OFDMA Systems

As we know that “spatial dimension” is another effective resource that can be exploited in devising an algorithm for resource scheduling in a wireless environment. To take advantage of this particular spatial resource various practical methods were proposed in the literature widely known as space-time coding methods. Some of these practical methods are Space Time Block Codes (STBC) [42], layered space time codes like Horizontal Bell Laboratories Layered Space Time Code (HBLAST) [2], Vertical Bell Laboratories Layered Space Time Code (V-BLAST) [42], and Diagonal Bell Laboratories Layered Space Time Code (DBLAST) [2].

Kim et al. [20] devised a novel resource allocation algorithm to allocate the sub-carriers based on the sub-channel gains to increase the performance of multi-user MIMO-OFDMA system. At transmitter station depending on the CSI the data symbols of a given user are allocated on assigned sub-carriers with an index set. To obtain transmitter diversity, an Alamouti STBC was employed at transmitter. While a multi-branch maximal ratio combining (MRC) diversity receiver system was implemented at the receivers end. After performing STBC decoding, the receiver extracts information from the allocated sub-channels and is demodulated to retrieve the intended data.

A less complex scheduling scheme was proposed in [43] to allocate sub-carriers and total transmit power among users in STBC-OFDMA systems, where users were able to share same sub-carrier simultaneously for data transmission The sub-carriers were assigned to users with the help of a greedy scheme, whereas the transmit power was distributed among users by means of various power allocation techniques like water-filling, equal power distribution etc. The power allocations were done differently for different user groups, where the users were classified based on the user channel conditions (either worst or best user group). The simulations suggest that the scheme was successful in achieving higher system capacities with reduced complexity.

2.7 Conclusions

In this Chapter, we presented an overview of algorithms in the literature that dynamically allocate the available resources in OFDMA and MIMO-OFDMA systems. Different classes of algorithms considered different objectives so as to obtain a solution that is close to optimum and simple enough to be implemented. The two important points that are consequent from the survey is that most of the algorithms use dominant Eigen-channels with gains to determine sub-carrier allocation in MIMO-OFDMA systems, and the power is distributed among the assigned sub-carriers by means of multi-dimensional water-filling technique. Thus, with these two techniques most of the algorithms in literature propose an optimal or near-optimal solution to improve the systems performance, while achieving high data rates and satisfying the defined fairness constraints.

Chapter 3

Resource Allocation for MIMO-OFDMA Systems

In this Chapter, we formulate the resource optimization problem for MIMO-OFDMA systems, describe the channel model, and discuss its characteristics. Later, a rate-adaptive resource allocation algorithm is proposed for MIMO-OFDMA systems. This algorithm performs sub-carrier allocation and optimal power allocation in order to maximize the overall systems capacity, whilst achieving strict fairness levels among active users of the system. The best possible efforts have been made to incorporate the deduced optimal resource allocation strategies from the literature survey in to the proposed scheme. Towards the end of the Chapter, the simulation results of the proposed schemes are compared to other existing ones, in terms of system sum capacity, minimum user's capacity and level of fairness achieved among users based on proportional rate constraints. The proportional data rate constraints are defined by the service providers based on user's quality of service (QoS) requirements, which vary depending on the service class to which the users belong.

3.1 Problem Formulation for Rate-Adaptive scheme in MIMO-OFDMA

In this Section, we formulate the resource allocation problem for MIMO-OFDMA systems subjected to various constraints, and optimization criterion. We consider a downlink MIMO-OFDMA scenario where a BS has to communicate simultaneously to several active mobile users in the system, as shown in Figure 3.1. In a downlink case, the major task of a radio resource scheduler is to assign sub-carriers for each BS – mobile user, and then distribute the power over these sub-carriers in order to maximize the systems performance.

The resource allocation problem for MIMO-OFDMA systems can be formulated in a manner similar to that of OFDMA systems. A major difference is that in a MIMO-OFDMA system the BS and mobile users are equipped with multiple antennas, which drastically improves the system’s overall capacity without any need for additional transmit power or bandwidth. However, multiple antennas at both transmitting and receiving ends make the resource allocation problem complex, and more challenging as the scheduling scheme has to deal in spatial domain as well as multi-user diversity simultaneously.

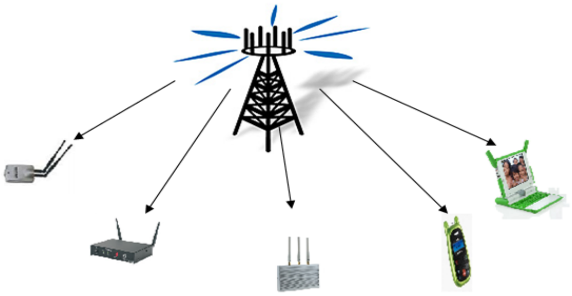

Figure 3.1: Downlink scenario for a multi-user MIMO-OFDMA system.

3.1.1 MIMO-OFDMA Channel Model

There is a need for complex equalization procedures to counteract the problem of inter symbol interference (ISI) when transmissions are made over a single carrier, in frequency selective fading channels. The other way of dealing with ISI problem in sub channels is to make multi-carrier transmissions over same frequency range. The multi-carrier modulation (OFDMA) technique is applied to MIMO frequency selective channels to obtain MIMO-OFDM channel model as shown in Figure 3.2 for MIMO-OFDM system.

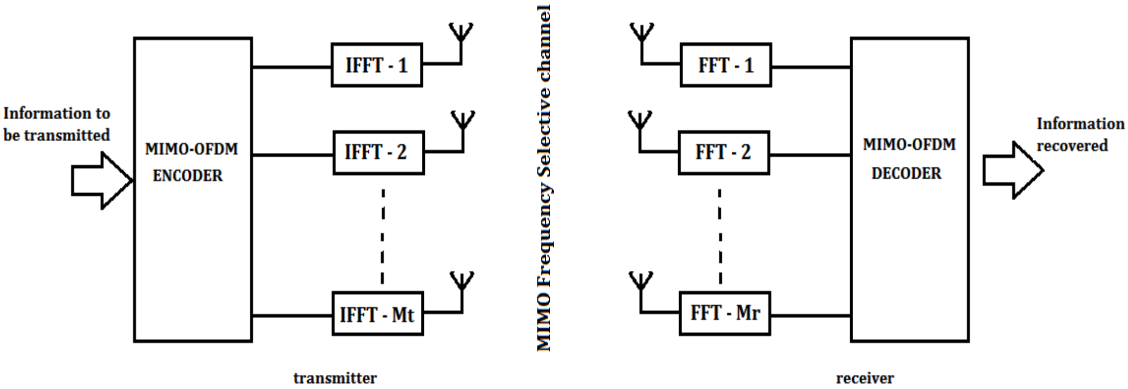

Figure 3.2: Block representation of MIMO-OFDM system.

In our system we consider tapped-delay line model [2], for MIMO frequency selective channels. We reflect on the spatial multiplexing aspect of MIMO channels, i.e., we can transmit different streams of data using multiple antennas over same frequency, time slot. In order to describe the MIMO-OFDMA channel matrix for the system, we assume that at a given time there are K active users in system, N sub-carriers that are to be assigned to these users. We assume that the BS has M_t transmit antennas and each mobile user has M_r receive antennas, where frequency selective fading is characterized by means of L significant delay paths, i.e., considering L ISI taps channel model as in [2]. Therefore for k^{th} user over n_s^{th} sub-carrier (where $k \epsilon K$, and $n_s \epsilon N$) the MIMO channel can be seen as following,

$$\overline{\boldsymbol{H}}_{k,n_s} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & & \cdots & h_{1M_r} \\ h_{21} & h_{22} & h_{23} & \ddots & \cdots & h_{2M_r} \\ h_{31} & h_{32} & h_{32} & & \cdots & h_{3M_r} \\ \vdots & \vdots & \vdots & & h_{m_t m_r} & \vdots \\ & & & & & \ddots \\ h_{M_t 1} & h_{M_t 2} & h_{M_t 3} & & \cdots & h_{M_t M_r} \end{bmatrix}, \qquad (3.1)$$

where, $h_{m_t m_r}$ represents the channel coefficient, (i.e., complex gain) from m_t^{th} transmit antenna to m_r^{th} receive antenna.

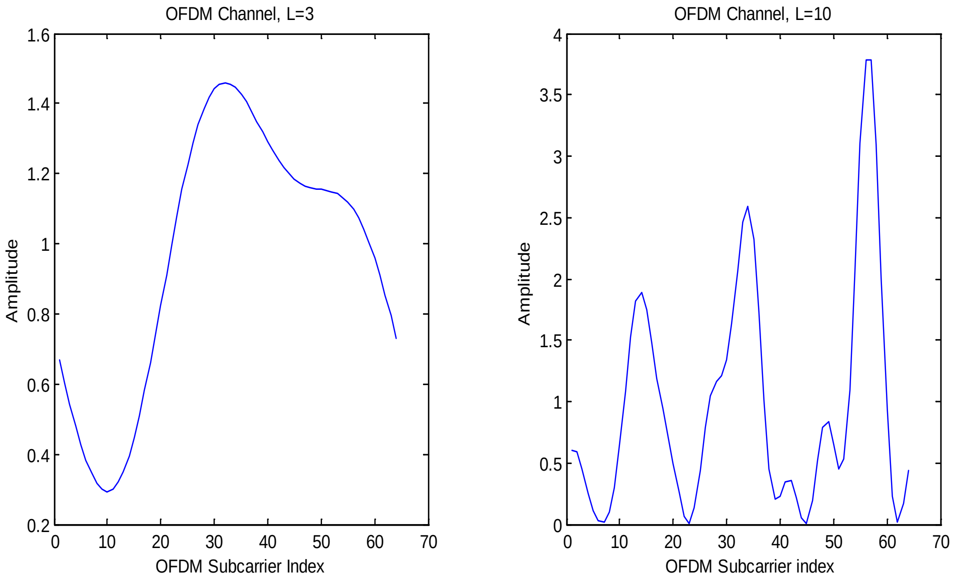

Figure 3.3: Snapshot of an OFDM Channel in the frequency domain for L=3 and L=10.

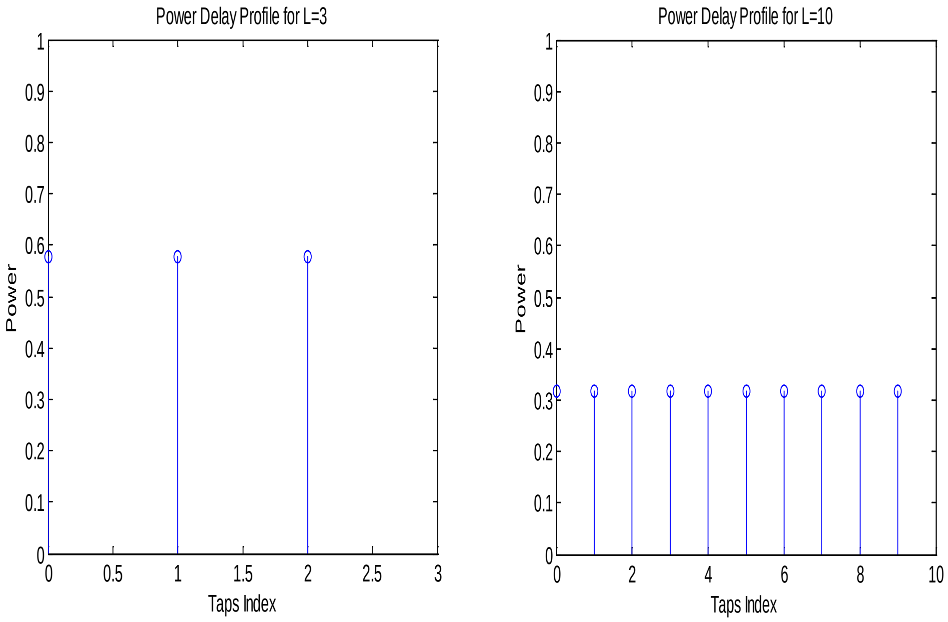

Figure 3.4: Power delay profile an OFDM Channel for L=3 and L=10.

The channel matrix is composed of samples drawn from quasi-stationary Rayleigh fading random processes that are assumed to remain constant during transmission of a complete data block. As signals in a scattering environment appear to be uncorrelated, it is assumed that $h_{m_t m_r}$ are independent and identically distributed (i.i.d) complex Gaussian random variable with zero-mean and unit variance. Snapshot of an OFDMA channel in frequency domain and uniform power delay profile of the channel for 3 and 10 ISI taps are shown in Figure 3.3 and Figure 3.4 respectively. In a MIMO-OFDMA channel, various users have varying channel conditions with respect to the BS, exhibits frequency-selective nature over sub-carriers. Therefore, the channel is distinguished for *K* active users over *N* sub-carriers as following,

$$\boldsymbol{H}_{MIMO-OFDMA} = \begin{bmatrix} \bar{\boldsymbol{H}}_{1,1} & \bar{\boldsymbol{H}}_{1,2} & \bar{\boldsymbol{H}}_{1,3} & & \cdots & \bar{\boldsymbol{H}}_{1,N_s} \\ \bar{\boldsymbol{H}}_{2,1} & \bar{\boldsymbol{H}}_{2,2} & \bar{\boldsymbol{H}}_{2,3} & \ddots & \cdots & \bar{\boldsymbol{H}}_{2,N_s} \\ \bar{\boldsymbol{H}}_{3,1} & \bar{\boldsymbol{H}}_{3,2} & \bar{\boldsymbol{H}}_{3,3} & & \cdots & \bar{\boldsymbol{H}}_{3,N_s} \\ \vdots & \vdots & \vdots & & \bar{\boldsymbol{H}}_{k,n_s} & \vdots \\ & & & & & \ddots \\ \bar{\boldsymbol{H}}_{K,1} & \bar{\boldsymbol{H}}_{K,2} & \bar{\boldsymbol{H}}_{K,3} & & \cdots & \bar{\boldsymbol{H}}_{K,N} \end{bmatrix}. \tag{3.2}$$

This result in a hyper matrix of size $K \times N \times M_t \times M_r$, that is 4-D in nature with each element representing the matrix defined in (3.1).

3.1.2 Formulation of Optimal Resource Allocation Problem

In wireless systems, the task of resource assignment can be classified majorly as sub-carrier allocation and total transmit power distribution. The sub-carrier allocation scheme decides on how the set of sub-carriers are allocated to each user, and then the resource management algorithm makes use of these sub-carrier assignments and instantaneous CSI to distribute the power over these sub-carriers in an optimal manner. These power allocations are to be done in a manner that they maximize the system's total capacity given by the following expression [44] , (derived from Shannon's capacity for MIMO systems):

$$\max_{p_{k,n_s}} \sum_{k=1}^{K} \sum\nolimits_{n_s \in \Omega_k} \frac{1}{N} log_2(\det(I_{M_R} + \frac{p_{k,n_s}}{M_t N_0} \boldsymbol{H}_{k,n_s} \boldsymbol{H}_{k,n_s}^H)) \tag{3.3}$$

where N_0 is the additive white Gaussian noise (AWGN) power, (i.e., product of noise power spectral density (PSD) and bandwidth) n_s varies from *1,2…N,* the sub-carrier allocation set for the kth user is denoted by Ω_k, $\boldsymbol{H}_{k,n_s}$ is the channel matrix for the respective MIMO channel existing between the transmitter and k^{th} receiver, and $\boldsymbol{H}_{k,n_s}^H$ is conjugate transpose (Hermitian) of $\boldsymbol{H}_{k,n_s}$. The maximization must also convene to the following set of constraints simultaneously:

1. The total power constraint should be assured of,

$$\sum_{k=1}^{K} \sum\nolimits_{n_s \in \Omega_k} p_{k,n_s} \leq P_{total} \;\; and \;\; p_{k,n_s} \geq 0, \tag{3.4}$$

where P_{total} is the total transmit power budget available for the system in each time slot and p_{k,n_s} is power allocation for $\boldsymbol{H}_{k,n_s}$ sub-channel.

2. Sub-channel allocations Ω_k's for different users are mutually exclusive, i.e.,

$$\Omega_1 \cup \Omega_2 \cup \Omega_3 \dots \dots . . \cup \Omega_k \;\subseteq \{1,2, \dots . N\}. \tag{3.5}$$

3. The proportional data rate constraints are to be satisfied for a promised level of QoS, as following

$$\frac{R_1}{\gamma_1} = \frac{R_2}{\gamma_2} = \; \dots \dots . = \frac{R_k}{\gamma_k}, \tag{3.6}$$

where R$_k$ is K^{th} user bit rate given by:

$$\mathrm{R}_{\mathrm{k}} = \frac{1}{N} log_2 \left\{ \det \left(I_{M_r} + \frac{p_{k,n}}{M_t N_0} \boldsymbol{H}_{k,n_s} \boldsymbol{H}_{k,n_s}^{H} \right) \right\}, \tag{3.7}$$

and $\gamma_{1,}\gamma_{2,}\gamma_{3,} \dots .. \gamma_k$ are the proportional rates constants, which are characterized by the specified QoS parameters promised for the users, based on their service class.

3.1.3 Breakdown of MIMO capacity

In [4], Telatar showed that a MIMO channel matrix can be transformed into non-interfering parallel SISO channels through SVD of the channel matrix. Thus, we obtain *min*(M_t, M_r) parallel SISO channels with gains equal to the singular values of MIMO channel matrix, where M_t is number of transmitting antennas and M_r is number of receiving antennas. Therefore, once the MIMO channels 4-D hyper-matrix is resolved in to convenient 2-D parallel SISO channels matrix, we can consider the optimization problem to be similar to that of independent SISO channels. Thus, the system’s total capacity function in 3.3 can be re-written in the following form,

$$\max_{p_{k,n}} \sum_{k=1}^{K} \sum\nolimits_{n \in \Omega_k} \frac{1}{N} \rho_{k,n} \log_2 \left(1 + \frac{\lambda_{k,n}\, p_{k,n}}{N_0} \right), \tag{3.8}$$

where, $\lambda_{k,n}$ represents the Eigen-channel value of $\boldsymbol{H}_{k,n}\boldsymbol{H}_{k,n}^{H}$, $p_{k,n}$ is power allocated to respective Eigen-channel, and $n=1, 2\dots..T$, where T is product of N and $M_{k,n}$, i.e., rank ($\boldsymbol{H}_{k,n}$) or *min* (M_t, M_r). As we consider that all the users have equal number of antennas, we will represent $M_{k,n}$ with M from here on. The variable $\rho_{k,n}$ represents the element of the sub-carrier allocation matrix, which is 1 (scalar value ‘1’) if the nth Eigen-channel is assigned to kth user or 0 if not assigned.

3.1.4 Analyzing the Resource Allocation Problem Mathematically

A typical method found in the literature for solving such optimization problem along with their corresponding constraints for OFDMA systems is to make use of Lagrange multipliers, which can also be utilized for MIMO-OFDMA systems as following. Lagrange multipliers technique is a multi-variable calculus technique useful in determining the maximum and minimum values of a function subject to various constraints. Using this technique, we can formulate a function as in [12] where OFDMA system was considered,

$$\begin{aligned} L = {} & \sum_{k=1}^{K}\sum_{n_s\in\Omega_k}^{.}\frac{1}{N}\log_2\left\{\det\left(I_{M_r} + \frac{p_{k,n_s}}{M_t}\boldsymbol{H}_{k,n_s}\boldsymbol{H}_{k,n_s}^{H}\right)\right\} + \alpha_1\left(\sum_{k=1}^{K}\sum_{n_s\in\Omega_k}^{.} p_{k,n_s} - P_{total}\right) \\ & + \sum_{k=2}^{K}\alpha_k\left(\sum_{n_s\in\Omega_1}^{.}\frac{1}{N}\log_2\det\left(I_{M_r} + \frac{p_{k,n_s}}{M_t}\boldsymbol{H}_{k,n_s}\boldsymbol{H}_{k,n_s}^{H}\right)\right. \\ & \left. - \frac{\gamma_1}{\gamma_k}\sum_{n_s\in\Omega_k}^{.}\frac{1}{N}\log_2\det\left(I_{M_r} + \frac{p_{k,n_s}}{M_t}\boldsymbol{H}_{k,n_s}\boldsymbol{H}_{k,n_s}^{H}\right)\right). \end{aligned} \tag{3.9}$$

In (3.9) the Lagrange multipliers $(\alpha_1, \alpha_2, \ldots\ldots \alpha_k)$ are to be determined. The presence of MIMO channel makes it more complex and difficult to obtain solution for the above equation. Therefore, we consider transforming MIMO-channels into non-interfering parallel channels as in Section 3.1.3, and reformulate the (3.9) based on (3.8) as following

$$\begin{aligned} L = {} & \sum_{k=1}^{K}\sum_{n=1}^{T}\frac{1}{N}\log_2\left(1 + \lambda_{k,n}p_{k,n}\right) + \alpha_1\left(\sum_{k=1}^{K}\sum_{n=1}^{T} p_{k,n} - P_{total}\right) \\ & + \sum_{k=2}^{K}\alpha_k\left(\sum_{n=1}^{T}\frac{1}{N}\log_2\left(1 + \lambda_{k,n}\, p_{k,n}\right) - \frac{\gamma_1}{\gamma_k}\sum_{n=1}^{T}\frac{1}{N}\log_2\left(1 + \lambda_{k,n}\, p_{k,n}\right)\right), \end{aligned} \tag{3.10}$$

where T represents the product of total sub-carriers and min(Mt, Mr) antennas, because we obtain a total of T non-interfering parallel Eigen-channels when MIMO channels on all sub-carriers are transformed. Thus, the constraint defined in (3.5) is now applicable to

Eigen-channel allocations Ωk's for different users , i.e., they are mutually exclusive, and $\Omega_1 \cup \Omega_2 \cup \Omega_3 \ldots\ldots..\cup \Omega_\mathrm{k} \subseteq \{1,2,\ldots.T\}$. In order to maximize the system's capacity, we deduce the following cost function by differentiating (3.10) with respect to $p_{k,n}$, (i.e., our variable of interest) and equate its derivatives to zero for k=1, 2…K, $n \in \Omega_\mathrm{k}$ as follows

$$\frac{\partial L}{\partial p_{1,n}} = \frac{1}{N \ln 2} \frac{\lambda_{1,n}}{\lambda_{1,n} + p_{1,n}} + \alpha_1 + \sum_{k=2}^{K} \alpha_k \frac{1}{N \ln 2} \frac{\lambda_{1,n}}{\lambda_{1,n} + p_{1,n}} = 0, \tag{3.11}$$

$$\frac{\partial L}{\partial p_{k,n}} = \frac{1}{N \ln 2} \frac{\lambda_{k,n}}{\lambda_{k,n} + p_{k,n}} + \alpha_1 - \alpha_k \frac{\gamma_1}{\gamma_k} \frac{1}{N \ln 2} \frac{\lambda_{k,n}}{\lambda_{k,n} + p_{k,n}} = 0. \tag{3.12}$$

For a single user *k*, the optimal power allocation scheme can be derived from the (3.11) and (3.12). For m$^{\mathrm{th}}$ and n$^{\mathrm{th}}$ Eigen-channels set belonging to Ω_k , we may deduce the following,

$$\frac{\lambda_{k,m}}{\lambda_{k,m} + p_{k,m}} = \frac{\lambda_{k,n}}{\lambda_{k,n} + p_{k,n}}. \tag{3.13}$$

We further assume that $\lambda_{k,1} \leq \lambda_{k,2} \leq \ldots\ldots\ldots \leq \lambda_{k,n}$. Thus, the above equation can be modified to calculate the power allocation for a single user k over n$^{\mathrm{th}}$ channel

$$p_{k.n} = p_{k.1} + \frac{\lambda_{k,n} - \lambda_{k,1}}{\lambda_{k,n}\, \lambda_{k,1}}, \tag{3.14}$$

where k = 1,2….K, and n=1,2,……T. Therefore, the Eigen-channels with high channel-to-noise ratio (CNR) are allotted more power, as in water filling algorithm. This process of distributing power can be seen as water filling algorithm in frequency domain. Therefore the total power allotted to user *k* can be calculated as

$$P_{k,total} = \sum_{n=1}^{T_k} p_{k.n} = T_k p_{k.1} + \sum_{n=2}^{T_k} \frac{\lambda_{k,n} - \lambda_{k,1}}{\lambda_{k,n}\,\lambda_{k,1}}, \tag{3.15}$$

where T_k are the set of Eigen-channels allocated to the k^{th} user. Therefore, the power assignments for each user can be calculated from eqns. 3.14 and 3.15. The constraints discussed in the optimization problem formulation are used to know the total power allocated to each user. Using (3.13) and (3.15), the proportional data rate constraints ratio can be seen as following, for every $k=1,2,\dots.K$

$$\frac{1}{\gamma_1}\frac{T_1}{N}\left(\log_2\left(1 + \lambda_{1,1}\,\frac{P_{1,total} - A_1}{T_1}\right) + \log_2 B_1\right)$$
$$= \frac{1}{\gamma_k}\frac{T_k}{N}\left(\log_2\left(1 + \lambda_{k,1}\frac{P_{k,total} - A_k}{T_k}\right) + \log_2 B_k\right) \forall\, k \,\epsilon\, K. \tag{3.16}$$

The Total power assigned to the k^{th} user is given by (3.15), and the constants A_k and B_k are defined as:

$$A_k = \sum_{n=2}^{T_k} \frac{\lambda_{k,n} - \lambda_{k,1}}{\lambda_{k,n}\,\lambda_{k,1}}, \tag{3.17}$$

$$B_k = \left(\prod_{n=2}^{T_k} \frac{\lambda_{k,n}}{\lambda_{k,1}}\right)^{\frac{1}{T_k}}, \tag{3.18}$$

These constants depend only on allocated Eigen-channel terms Ω_k's and are defined solely for the purpose of materializing frequency allocation scheme. The cost function assumes that the Eigen-channel power gains for each user satisfies the condition: $\lambda_{k,1} \leq \lambda_{k,2} \leq \dots\dots\dots \leq \lambda_{k,T_k}$. This implies that the number of elements in setΩ_k is equal to number of channels allocated for k^{th} user, i.e., T_k, and quantity A_k being positive always.

Weights are applied to the channels such that all the users get equal opportunity. Then the effect of applying weights to the channels on the sum-rate of the system is investigated by obtaining a cost function using Lagrange multipliers technique [12]. Thereby, The use of equally-weighted capacity sum as the optimizing function as in (3.10), and introducing the scheme of proportional fairness into the system (by adding a set of nonlinear constraints) gives a benefit of explicitly controlling the capacity ratios among various users, while ensuring each user has his target data rate.

Using the derived cost function the total power allocation ($P_{k,total}$) for a particular user can be found, which helps in calculating the power allocations for the individual Eigen-channels as

$$p_{k,1} = (P_{k,total} - A_k)/T_k, \tag{3.19}$$

$$p_{k,n} = p_{k,1} + \sum_{n=2}^{T_k} \frac{\lambda_{k,n} - \lambda_{k,1}}{\lambda_{k,n}\,\lambda_{k,1}}. \tag{3.20}$$

The derivative of cost function specifies a set of (K-1) simultaneous nonlinear equations, which are used to calculate $P_{k,total}$ and $p_{k,n}$ in order to achieve maximum throughput and satisfy various constraints (QoS, data rate etc).

3.2 Proposed Resource Allocation Scheme for MIMO-OFDMA Systems

Channel assignment and power allocation over assigned Eigen-channels are the two main tasks of resource allocation algorithms for any given system. The two assumptions that are made with regards to the proposed scheme for MIMO-OFDMA systems are

Assumption-1: We assume that the MIMO-OFDM transmitter has instantaneous CSI. Based on this information the MIMO channel matrix is resolved in to parallel, non-interfering SISO channels through SVD of the channel matrix, as shown by Telatar [4]. SVD yields parallel channels (depending on minimum of Tx, / Rx antennas) with gains corresponding to the Eigen-values of the sub channel power gain matrix, as will be discussed in next Section.

Assumption-2: Proportionality rate constraints are assumed based on the user's data rate requirements (either fixed/variable data rates). We try to consider both the cases and compare their results.

3.2.1 Sub-carrier Allocation

When a MIMO-OFDMA system is considered, the channel power gain for a user k in sub-carrier n_s becomes a matrix instead of a scalar value as in OFDMA systems. Thereby, in order to perform sub-carrier allocation we make use of simple greedy type allocation algorithm as in [9], over Eigen-channels obtained from SVD of sub-carriers power gain matrix. For the current system we assume, that for every frequency sub-carrier, all active users in the system transmit their feedbacks CSI over the feedback channel before they are allocated to respective users based on proportional data rate criteria. To adapt to channel variations, we have to decompose the MIMO channels into non-interfering parallel channels using SVD, as follows

$$\boldsymbol{H}_{k,n_s}^{H}\boldsymbol{H}_{k,n_s} = \boldsymbol{E}_{k,n_s}\boldsymbol{D}_{k,n_s}\,\boldsymbol{E}_{k,n_s}^{H}\,, \tag{3.21}$$

where $\boldsymbol{D}_{k,n_s} = \text{diag}\,\{\lambda_{k,s}, s \in$ [1, 2…min(M_t , M_r)]}, i.e., (set of Eigen values), of user k, over n_sth sub-carrier. We refer to these parallel non-interfering channels as Eigen mode channels or Eigen-channels in this thesis. While assigning Eigen-channels, we make sure that the user who has the least achieved proportional data rate has the priority to choose the best channel. We use a criteria, in order to incorporate proportionality constraints, giving priority to the users who have least achieved proportional data rate, as in [8]. These data rates upon which the Eigen-channel assignments are made, are calculated from the instantaneous CSI while assuming equal power distribution over each Eigen-channel of all sub-carriers, (i.e., $p_{k,n} = p_{equal}$). As discussed earlier, the MIMO channel matrix is resolved into independent parallel channels, therefore for a given user its data rate can be computed as

$$R_k = \sum_{n=1}^{T} \frac{\rho_{k,n}}{N} . \log_2\left(1 + \frac{\lambda_{k,n}\, p_{k,n}}{N_0}\right), \tag{3.22}$$

where N_0 is the noise power and $\rho_{k,n}$ represents the element of the Eigen-channel allocation matrix as discussed earlier in Section 3.1.3. The algorithm used to allocate Eigen-channels is briefly described below:

1) *Initialization:* $R_k=0$, $\Omega_k = \emptyset$, for all *k= 1,2,….K* and *S={1,2….T}.*
2) *for k=1 to K,*
   i) Find Eigen-channel n satisfying $\lambda_{k,n} \geq \lambda_{k,v}$ for all *v ϵ S.*
   ii) Let $\Omega_k = \Omega_k \cup \{n\}, S = S - \{n\}$, update R_k based on (3.22).
3) *While* $S \neq \emptyset$,
   i) Find k such that it satisfies $R_k / \gamma_k \leq R_w / \gamma_w$ for all $1 \leq w \leq K$.
   ii) After computing *k, find* Eigen-channel n satisfying $\lambda_{k,n} \geq \lambda_{k,v}$ for all *v ϵ S*.
   iii) After computing Eigen-channel n and user *k*, let $\Omega_k = \Omega_k \cup \{n\}, S = S - \{n\}$, update R_k based on (3.22).

The algorithm makes an attempt to provide each user with channels that have high CNR, to the extent that is possible. The user who has least achieved proportional data rate is given the priority to select the channel for transmission. As we assume equal power allocation, the proportional fairness obtained after Eigen-channel allocation is coarse.

Thereby, we make an effort to achieve proportional fairness in strict sense while maximizing the overall systems capacity in the power allocation algorithm, discussed in next Section.

3.2.2 Power Allocation

Once these Eigen-channels are allocated, the next task is to distribute the power over these Eigen-channels in order to maximize the overall systems capacity given by (3.8). The resource allocation algorithm for power allocation solves the (*K-1*) nonlinear equations of the power optimization problem, obtained from the derivative of cost function in (3.16) by defining a new parameter X_k, given by

$$X_k = 1 + \lambda_{k,1} \frac{\left(P_{K,total} - A_k\right)}{T_k}. \tag{3.23}$$

Thus total power for each user is given by

$$P_{k,total} = A_k + \frac{T_k\,(X_k - 1)}{\lambda_{k,1}}. \tag{3.24}$$

By substituting this parameter X_k in cost function (3.16), we obtain

$$X_k = \frac{\left[\left(X_j B_j\right)^{\gamma_k T_j / \gamma_j T_k}\right]}{B_k}, \forall\, j,k \in \{1,2,\ldots.K\}. \tag{3.25}$$

To solve for X_j we use (3.25) and invoke the total power constraint defined in (3.4), deriving

$$\sum_{k=1}^{K} \left\{ A_k + \frac{T_k}{\lambda_{k,1}} . \left[\frac{[\left(X_j B_j\right)^{\gamma_k T_j / \gamma_j T_k}]}{B_k} - 1 \right] \right\} - P_{total} = 0. \tag{3.26}$$

Therefore, the procedure devised to obtain optimal power allocation over the assigned set of Eigen-channels is discussed in detail as following

1) For a given set of Eigen-channel frequency allocations Ω_k $\forall$ k = 1, 2… K, the corresponding A_k and B_k (parameters defined in (3.17) and (3.18) to quantify the cost function) are calculated.
2) Then the inequality: $\sum_{k=1}^{K} A_k \leq P_{total}$ is verified, If the inequality is not satisfied, a set of Ω_k are selected corresponding to the largest A_k (where k = 1, 2, …, K), the Eigen-channel with the smallest power gain $\lambda_{k,n}$ is dropped, and the set Ω_k is updated, A_k and B_k are re-calculated. After that, the above inequality is checked again. We consider this particular inequality because we have to make sure that for a given user, the corresponding A_k is less than or equal to the final total user power allocation. Therefore, variable X_k must always be larger than one.
3) If the inequality is satisfied, User index j is selected such that corresponding $(B_j)^{\frac{T_j}{\gamma_j}} \geq (B_k)^{\frac{T_k}{\gamma_k}}$ for all $k \neq j$ and k = 1, 2, …, K. The theoretical possible range for X_j are all values between 1 and $1 + \lambda_{j,1} (P_{K,total} - A_j)/T_j$. Then if (3.26) has different signs when X_j assumes the two extreme values of its range, then there exists a valid solution X_j between these extreme values, otherwise the Eigen-channel frequency allocation sets are updated again and the step 2 is repeated.
4) When a valid solution for (3.26) is guaranteed, it is used to solve for X_j, which is then used for finding all X_k's for all $k \neq j$ and k = 1, 2, …, K from (3.25).
5) Therefore, the corresponding total user power allocation $P_{k,\text{total}}$ for all k = 1, 2, …, K is evaluated from (3.24).
6) Once the total power for each user is computed, this power is distributed across all the Eigen-channels allocated to that user using waterfilling technique as discussed

earlier in Section 3.1.4. Thus, the individual Eigen-channel power allocations $p_{k,n}$ for all $n \epsilon \Omega_k$ are computed from (3.20).

The capacity for each user is computed based on these power and channel allocations and summed to obtain the overall throughput of the system as in (3.8). To evaluate the systems performance, Jain's Fairness index is used, which is defined as following

$$\text{Fairness Index} = \frac{\left[\sum_{k=1}^{K} \Gamma_k\right]^2}{K \left[\sum_{k=1}^{K} \Gamma_k^2\right]} \; ; \quad \forall\, \Gamma_k = \frac{R_k}{\gamma_k} \tag{3.27}$$

If the proportionality data rate constants $(\gamma_{1,}\gamma_2 \dots, \gamma_k)$ are satisfied in strict sense by the allocation scheme then all Γ_k's are equal to 1, and if the proportional rate constraints are satisfied in typical sense then all Γ_k's are > 0.5 [45].

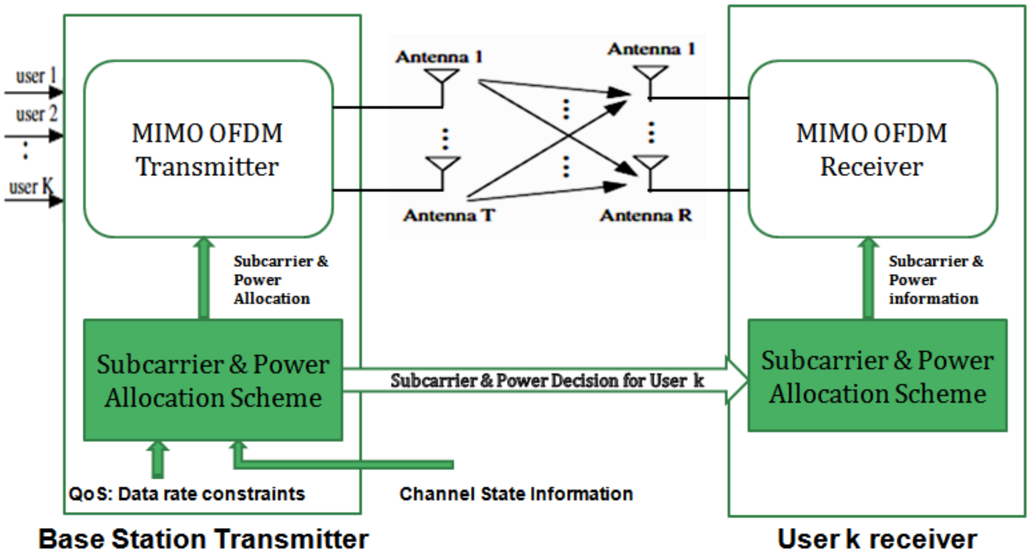

Figure 3.5: Proposed system model for MIMO-OFDMA system.

Figure 3.3, shows how the data streams for different users is modulated and transmitted by the MIMO-OFDMA transmitter at the base station depending on the power and subcarrier allocation information. The subcarrier and power assignment decisions are sent to users over a dedicated feedback channel, to assist users in demodulating the received data stream.

In order to depict the above proposed algorithm more comprehensibly we make use of the flow chart diagram in Figure 3.4. The flowchart describes how various inputs are obtained, and utilized to perform channel allocation and transmit power distribution in an optimal manner.

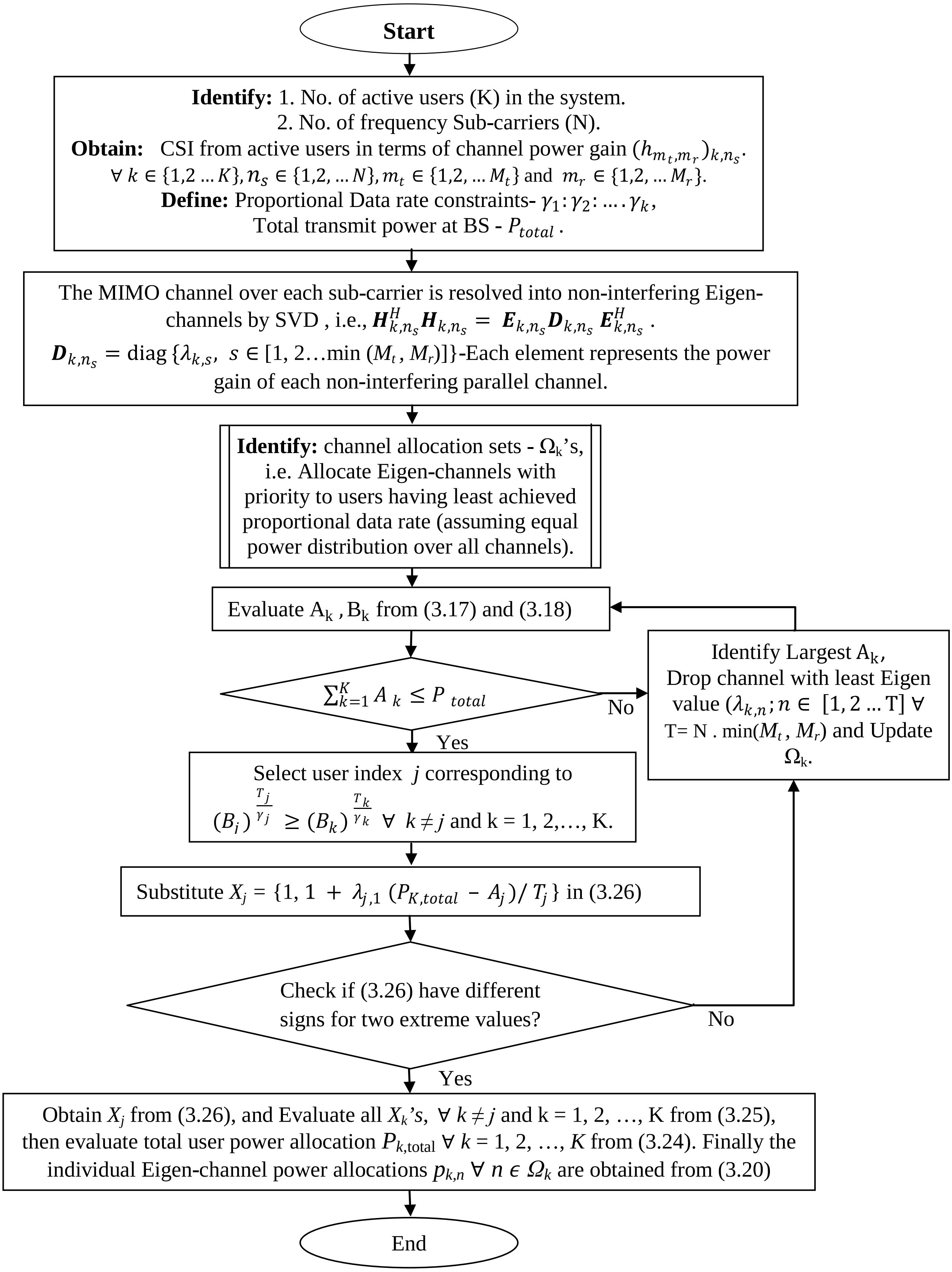

Figure 3.6: Flow chart explaining the proposed resource allocation algorithm.

3.3 Joint Resource Allocation Scheme for MIMO-OFDMA systems without strict Fairness constraint

For a system that doesn't have strict proportionality fairness constraint to be satisfied among users we proposed a joint power and sub-carrier allocation algorithm as in [23], and [6]. The main purpose while devising this algorithm was to see to what extend the overall systems capacity can be improved when fairness constraints are relaxed and how the fairness index is affected when users have diverse data rate requirements.

The MIMO channel power gain matrix obtained for each user over each sub-carrier is decomposed into parallel non-interfering channels as discussed in Section 3.1.3. The obtained parallel channels are quantified in terms of Eigen-values. The joint resource allocation algorithm proposed for MIMO-OFDMA systems is discussed below:

1. For frequency sub-carrier allocation, the user demanding the maximum data rate is given the priority to select the channel with dominant Eigen value.
2. With each Eigen-channel allocated to a user a preset amount of power is also allotted to the user, i.e., $\frac{P_{total}}{T}$,where T=N. m$in(M_t , M_r)$ and $\frac{P_{total}}{T}$ is the fraction of total power equally distributed throughout the bandwidth.
3. When all the users are allotted with their respective channels, the accumulated power for each user is distributed over these channels by means of water filling technique.
4. The channels are allocated to each user based on priority unless they achieve their minimum required data rate.
5. Thus, the systems overall capacity and Jains fairness index are evaluated by, (3.8) and (3.27) to gauge the performance of the algorithm.

Figure 3.5 shows the flow chart that gives a further insight into the functioning of this joint resource allocation algorithm.

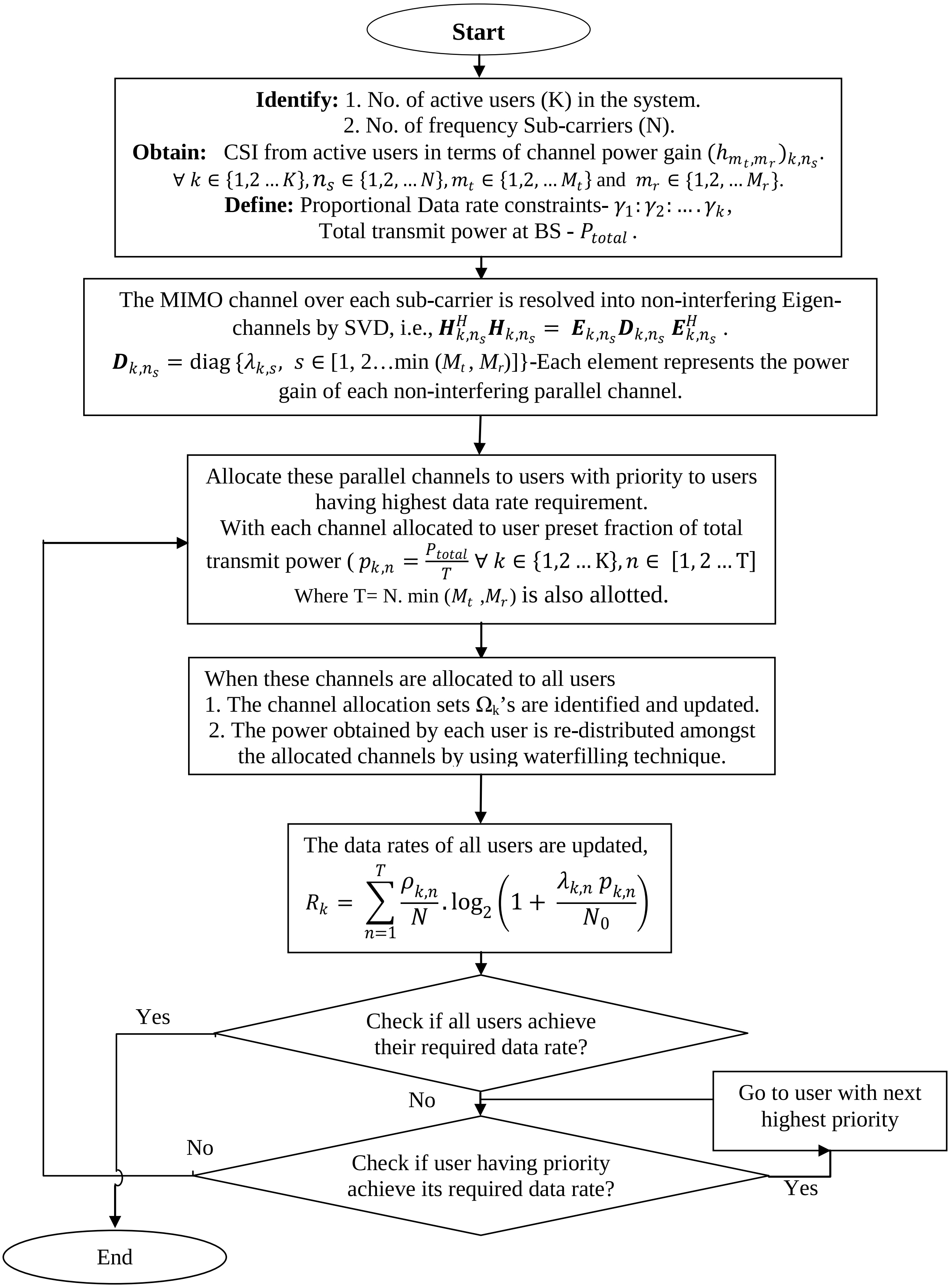

Figure 3-7: Flow chart explaining the joint resource allocation algorithm.

3.4 Simulation Results

To evaluate the performance of the proposed resource allocation scheme (will be referred to as "*Proposed*" in results), and the joint resource allocation scheme (will be referred to as "*Joint*" in results), we make use of MATLAB software and simulate the above discussed algorithms. The Proposed algorithm's main aim is to optimize the power allocation among all users. As in a major emphasis is given on power distribution over the strong channels assigned to users (by dropping weak channels) utilizing the optimal water-filling technique. Therefore, to evaluate this algorithms performance, we compare it against an algorithm where the sub-carrier allocations are done in a manner similar to the proposed scheme and transmit power is distributed equally across all the Eigen-channels [9]. As flat transmit power distribution is considered in this scheme we refer to it as "*Flat*" in results.

Table 3.1 gives details of the parameters used for simulation. The simulation results are obtained for a users varying gradually from 2 to 16, with 64 sub-carriers, noise PSD of -80 dBW/Hz, total transmit power of 1 Watt, and a total bandwidth of 1 MHz .

Table 3.1: Parameters used for simulation of MIMO-OFDMA resource allocation algorithms.

Total transmit Power	**1 Watt**
Noise PSD	**- 80 dBW/Hz**
Number of Sub-carriers	**64**
Systems Bandwidth	**1 MHz**
Number of Users in system	Varying from **2-16.**
No. of Antennas at BS (M_t)	**1**(*for SISO*), **2**(*for 2x2 MIMO*) and **4**(*for 4x4 MIMO*).
No. of Antennas at Users mobile set (M_r)	**1**(*for SISO*), **2**(*for 2x2 MIMO*) and **4**(*for 4x4 MIMO*).

The following are results obtained for different variations in proportionality rate constraints. The systems total capacity, minimum user's capacity, and average user's capacity plots are considered for evaluating the performance along with fairness index plots. For comparison, the performances of the resource allocation schemes proposed in [27], are also included. In [27], the system was investigated with and without the need for fairness among users, where fairness was modeled as maximum number of allowable channel assignments per user. Another unique aspect of the algorithm proposed in [27] is The schemes proposed in [27] make use of bisection method [40] to evaluate the optimal water level for power distribution.

Figures 3.8 to 3.11 are obtained when the proportionality data rate constant ratios, (i.e., $\gamma_1:\gamma_2:\ldots..\gamma_k$) are chosen to be random, i.e., all users have different data rate requirements.

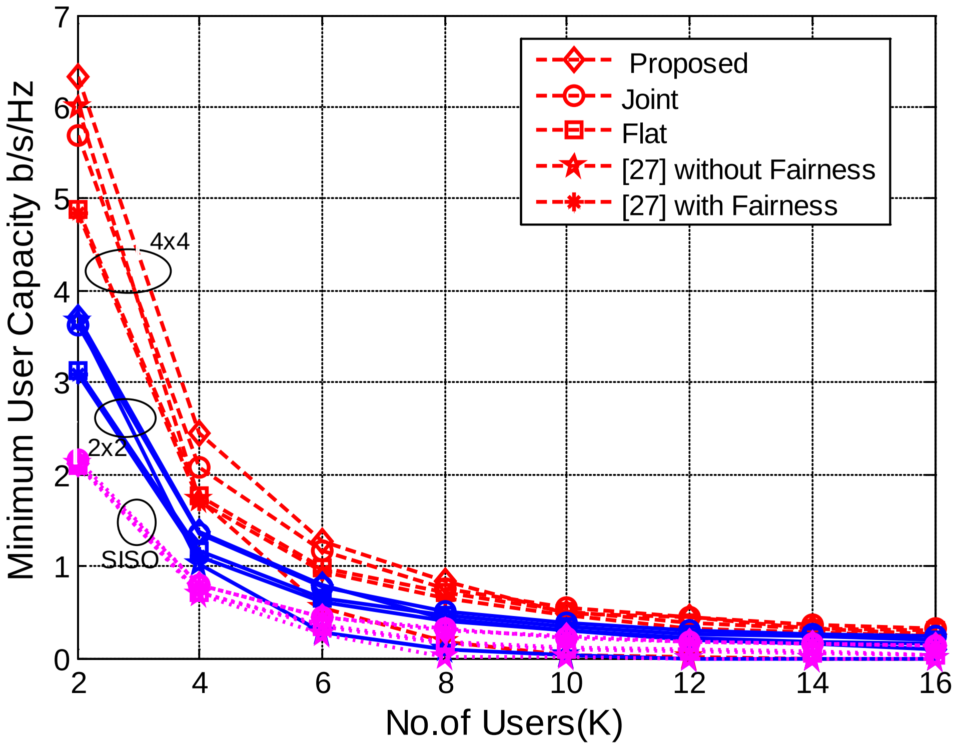

Figure 3.8: Minimum Users capacity for random proportionality constraints ratio.

Figure 3.8, shows the minimum user's capacity plots of different algorithms, for OFDMA, 2x2 OFDMA and 4x4 OFDMA systems. As can be seen from Figure, in all the cases, the minimum user capacity diminishes as the number of users in the system increase. However one can deduce that the proposed algorithm provides better minimum user capacity when compared to other schemes. In Figure 3.8, we can lucidly observe that for 4x4 OFDMA systems, the minimum users' capacity provided by proposed scheme is higher than the other schemes until there are 8 active users in the system, and there onwards the minimum users' capacity continuously diminishes as the number of users increase. This shows that the proposed resource scheme is able to provide better level of fairness among users when compared to joint resource allocation scheme. Moreover, minimum users' capacity for the scheme in [27] (without fairness constraints) is zero, when there are more than 10 users in the system. This is because there is no restriction on the number of sub-channels that can be occupied by a user, thereby, the users with poor channel conditions are penalized.

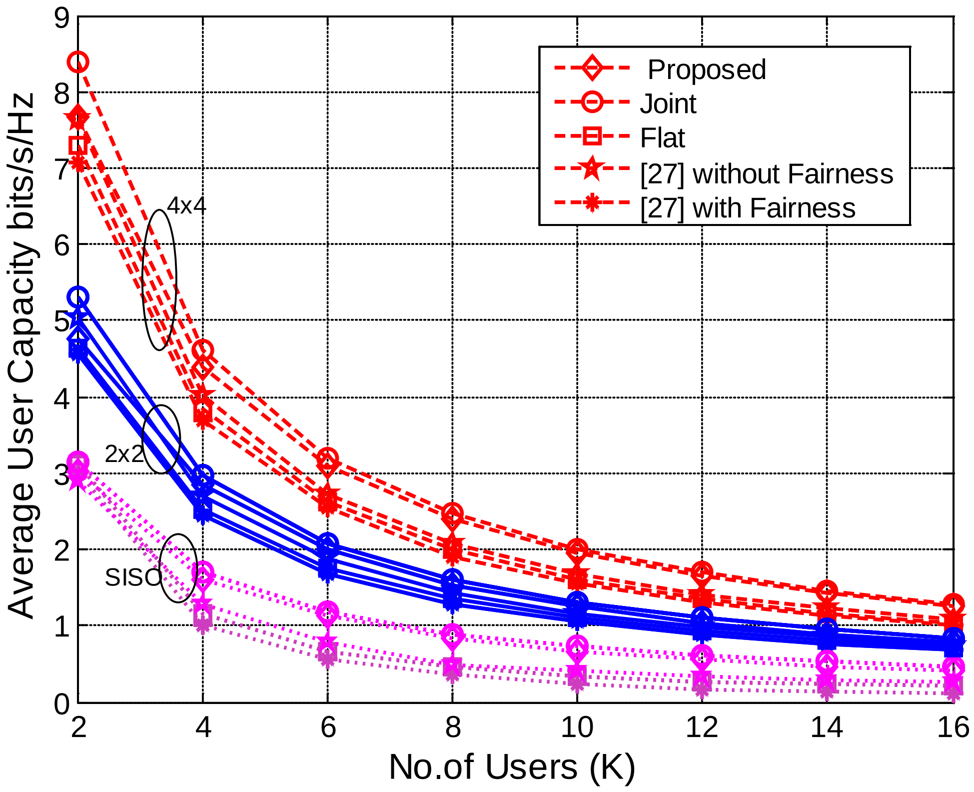

Figure 3-9: Average users capacity for random proportionality constraints ratio.

Figure 3.9, shows the simulation results for average users capacity obtained for various schemes over OFDMA, 2x2 OFDMA and 4x4 OFDMA systems. The plot shows that the pattern followed by the average users' capacity for all the schemes is similar to that of minimum user's capacity, i.e., the average users' capacity decreases with an increase in number of active users in the system. However in average users' capacity plot the joint scheme performs better than the proposed scheme in all the three systems. This shows that the total systems capacity obtained by the proposed resource allocation scheme is lesser than that of the joint resource allocation scheme, because in minimum users capacity plot the proposed scheme performs better while in average users capacity plot the joint scheme performs well.

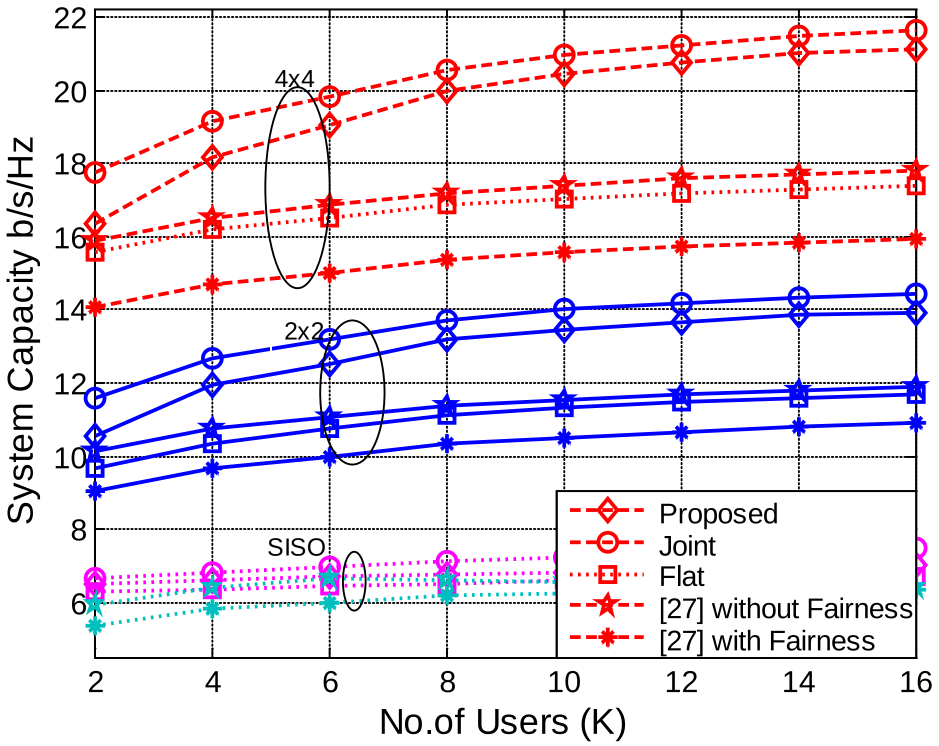

Figure 3.10: Systems overall capacity for random proportionality constraints ratio.

Figure 3.10, gives us the simulation results of the overall systems capacity, (i.e., summation of all users achieved capacity when they are served respectively) for the discussed schemes in OFDMA, as well as MIMO-OFDMA (2x2 and 4x4) scenarios. Total capacity results play a vital role in judging the systems overall performance. For all the scenarios it can be observed that the Joint scheme performs better than the Proposed scheme in terms of systems overall capacity, although there is smaller difference in their overall system capacities when active users in the system increase. As can be seen from Figure 3.10, when there are more than 10 users in the system there is lesser difference between the achieved capacity levels of the schemes (Proposed and Joint) for all scenarios. The difference between the overall systems capacity levels for proposed and flat schemes gives a fair depiction of the gain obtained when the power is distributed in an optimal manner by the proposed algorithm instead of equally distributing them over all the channels.

Figure 3.10, also shows us the gain obtained by the overall systems capacity when there are more number of antennas at the receiving as well as transmitting ends. For, 10 active users in the system the gain obtained by the proposed scheme for 2x2 MIMO-OFDMA system is 1.8 times (approximately) more than that of OFDMA system. Similarly the gain obtained by 4x4 MIMO-OFDMA systems for proposed scheme is 3 times(approximately) the OFDMA systems and 1.6 times(approximately) the 2x2 MIMO-OFDMA systems, when there are 10 active users in the system.

From Figure 3.10, it can be observed that, when the resource allocation scheme in [27], takes into account the fairness constraints the sum capacity is affected severely. For a 4x4 MIMO-OFDMA system with 10 active users, the sum capacity for the scheme in [27] with fairness drops significantly from 17.5 bits/s/Hz to 15.8 bits/s/Hz. This implies that introducing fairness constraints leads to significant capacity decrease.

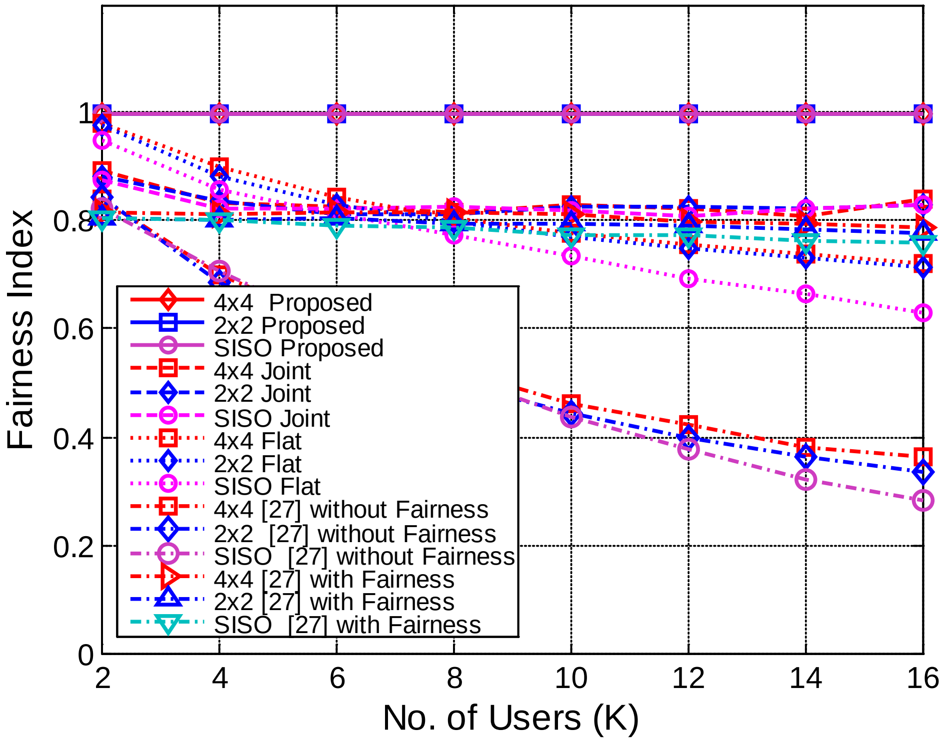

Figure 3.11: Fairness Index for random proportionality constraints ratio.

Figure 3.11 gives us the Fairness index plot for the discussed schemes under various scenarios. The fairness index in the results are obtained by means of Jains fairness index, defined and discussed in equation 3.27. Although the proposed scheme did not achieve the better sum capacity (from Figure 3.10) when compared to other schemes it is successful in achieving strict level of fairness, (i.e., it strictly satisfies the proportionality data rate constraints) as can be seen in Figure 3.11. On the other hand the joint and flat schemes are unable achieve acceptable fairness when compared to the proposed scheme, where the proportionality constraint constants ratio vary randomly. From Figures 3.10 and 3.11 one can come to a conclusion that there is always a fair amount of trade-off between the overall achieved systems capacity and level of proportional fairness.

It is also interesting that the fairness index of the scheme in [27] considering fairness constraints is close to flat resource allocation scheme. With fairness taken into consideration (for the scheme in [27]), the dominating effect of users with good channel conditions is limited in a way that the sub-carriers were allocated to all users instead. Thereby, the scheme in [27] was able to achieve acceptable level of fairness by taking into account the fairness constraints. However, the defined fairness constraints do not assist the scheme in achieving strict level of fairness among users, as is the case with proposed scheme.

We repeated the simulation results for different variations in proportionality constants ratios, the major differences in results were observed in fairness index plots while the other capacity plots were almost similar. Apart from that the fairness index plot also plays a vital role evaluating systems performance to judge the schemes adherence to the defined proportionality constraints. Therefore, we consider only the fairness index plots (Figures 3.12 to 3.16) for different variations of proportionality constraint constants.

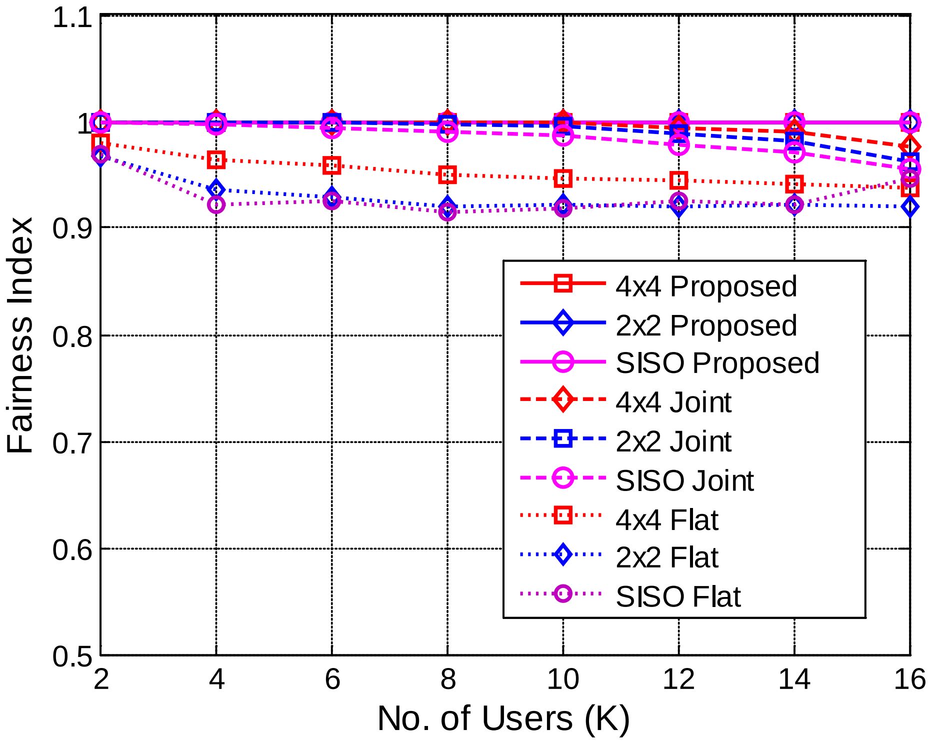

Figure 3.12: Fairness Index when all users have equal data rate requirements.

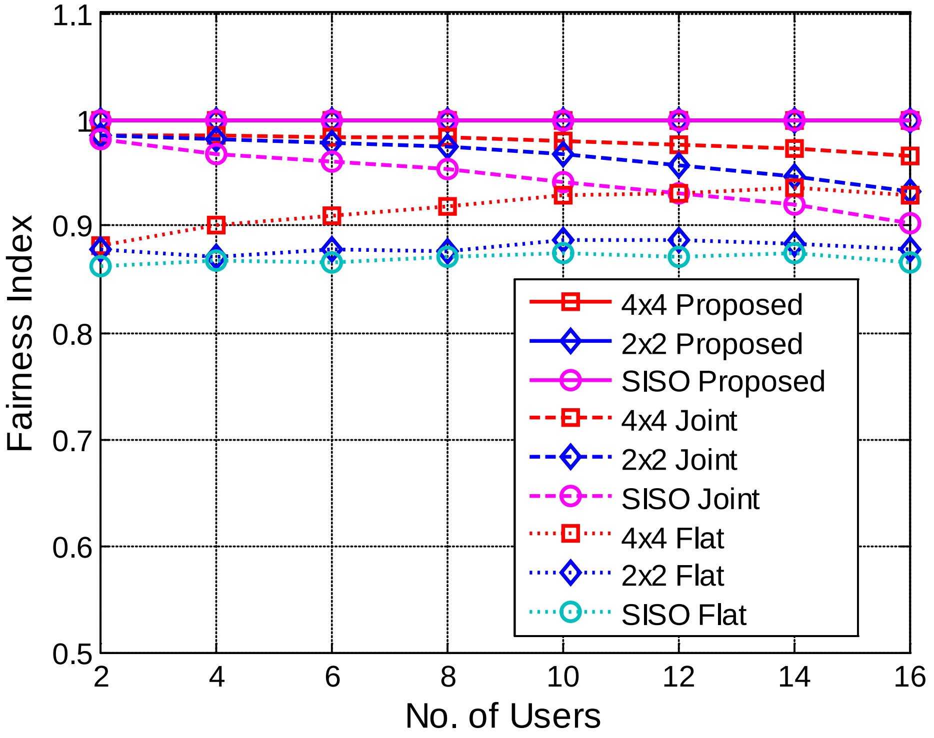

Figure 3.13: Fairness Index when proportionality rate constants for half of the users are considered to be 1/8 times of the other half of the active users in system.

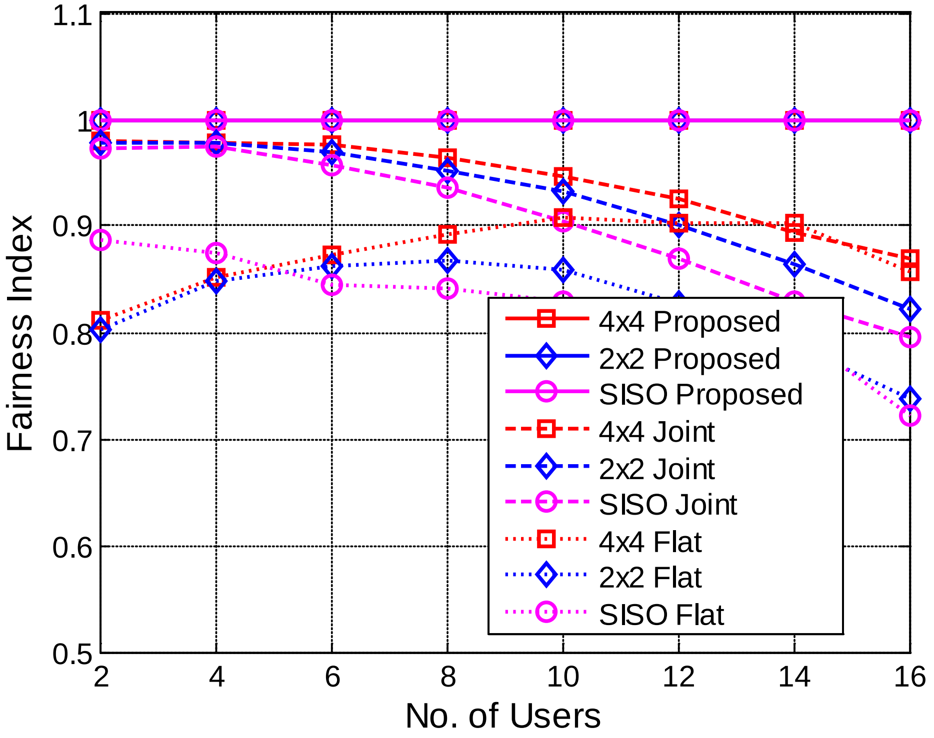

Figure 3.14: Fairness Index when proportionality rate constants for half of the users are considered to be 1/16 times of the other half of the active users in system.

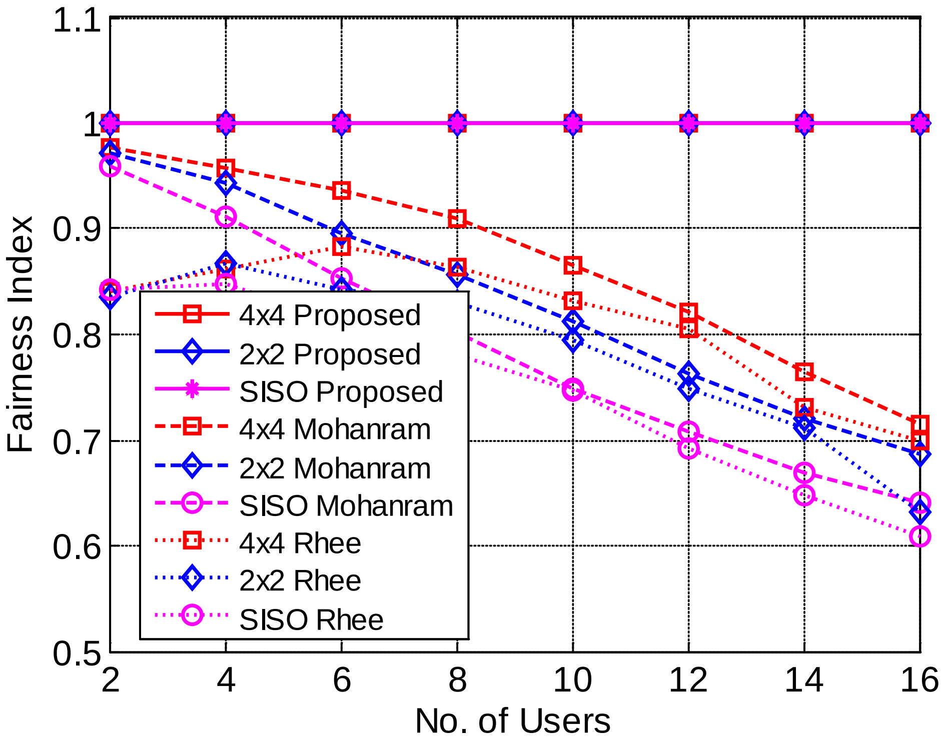

Figure 3.15: Fairness Index when proportionality rate constants for half of the users are considered to be $1/32$ times of the other half of the active users in system.

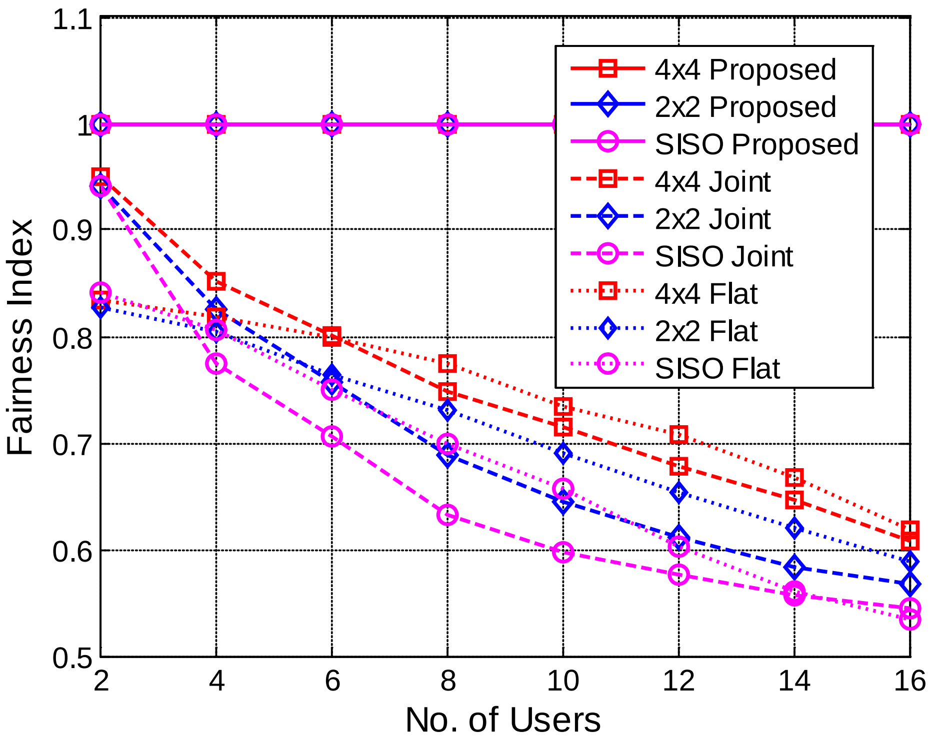

Figure 3.16: Fairness Index when proportionality rate constants for half of the users are considered to be $1/64$ times of the other half of the active users in system.

In Figure 3.12, the proportionality rate constants ratio for all users is considered to be equal, i.e., $\gamma_1 : \gamma_2 : \dots\dots\dots\dots \gamma_k = 1 : 1 : 1 \dots\dots 1$. In Figure 3.13, the proportionality rate constants for half of the users are considered to be $1/_8$ times of the other half of the active users in system. In Figure 3.14, the proportionality rate constants for half of the users are considered to be $1/_{16}$ times of the other half of the active users in system. In Figure 3.15, the proportionality rate constants for half of the users are considered to be $1/_{32}$ times of the other half of the active users in system. In addition, in Figure 3.16, the proportionality rate constants for half of the users are considered to be $1/_{64}$ times of the other half of the active users in system.

When Figures 3.12 to 3.16 are carefully analyzed, we can approach to the conclusion that the performance of the joint resource allocation scheme deteriorates excessively as one half of the active users systems demand proportionately in large portion when compared to the other half. In Figure 3.12, where all users demand equal data rate, the joint scheme has acceptable level of fairness index that is very much closer to 1 for most of the time. The level of fairness index gradually becomes unacceptable when one half of the users demand proportionately higher data rates, i.e., from Figure 3.13 to 3.16. In Figure 3.16, where the one half of active users demand data rates 64 times the other half of the active users in system the level of fairness index for joint resource allocation scheme is even worse than the flat scheme. Whereas for all the variation in proportionality constraint constants the proposed resource allocation scheme satisfies the proportional data rate constraints in strict sense, i.e., the fairness index in always equal to 1 in all scenarios. Therefore the proposed scheme has best performance in terms of fairness, although it negotiates to some extent with systems total capacity when compared to other schemes.

3.5 Conclusions

In this Chapter, we analyzed the resource optimization problem for MIMO-OFDMA systems. Later, a rate-adaptive resource allocation algorithm was proposed for MIMO-OFDMA systems. This algorithm performs sub-carrier allocation and optimal power allocation in order to maximize the overall systems capacity, whilst achieving strict fairness levels among active users of the system. We also proposed an extension to a joint resource allocation scheme for OFDMA systems found in literature [6, 23, 46, 47], to MIMO-OFDMA systems. A comparison of simulation results of these schemes show that the proposed scheme has best performance in terms of fairness, although it negotiates to some extent with systems total capacity. Similarly, the comparison of the existing schemes with proposed scheme reveal that our power allocation routine can provide much better capacity gain while ensuring strict level of fairness among users.

Chapter 4

Resource Allocation for Practical Systems

In this chapter, we discuss various practical schemes that provide the practical means of implementing and accomplishing the benefits offered by MIMO-OFDMA systems. We begin our discussion with the Vertical Bell Laboratories Layered Space-Time (V-BLAST) scheme since it is the simplest, followed by the Space Time Block Coding (STBC) scheme, and then the Multi-Layered Space Time Coding (MLSTBC) scheme. For each scheme, we describe the encoding mechanism, detection algorithms used, with emphasis on the ones based on the zero-forcing detection criteria. We then analyze and compare the performance of these practical schemes in a downlink scenario for the proposed resource allocation scheme.

4.1 Vertical Bell Laboratories Layered Space Time (V-BLAST)

Layered space time coding was introduced for the first time by Foschini [44] in 1996, and since then is seen as the most powerful scheme suitable for applications with high transmission rates. Some of the layered space time coding schemes are Horizontal Bell Laboratories layered space time code (HBLAST) [2], Vertical BLAST (V-BLAST) [44], and Diagonal BLAST (DBLAST) [2]. In these transmission schemes a number of independent sub-streams are transmitted simultaneously that are equivalent to the number of transmitting antennas available. In this Section, we discuss about the various details about the architecture of V-BLAST coding scheme. We also discuss the detection algorithm for V-BLAST coding technique based on zero-forcing detection criteria.

4.1.1 V-BLAST Encoder

The V-BLAST architectures encoder is shown in Figure 4.1, where each information bit-stream is demultiplexed as parallel sub-streams based on number of transmit antennas. All the sub-streams are modulated by M-ary constellation, and interleaved before being transmitted through respective antennas. The number of layers in V-BLAST depends on the number of transmit antennas (M_t) available at the transmitters end, the spatial rate obtained is nM_t [2]. As each layer is restricted to a transmit antenna, V-BLAST can be used for applications with diverse data rates and multiple users simultaneously. Based on the detection algorithm deployed at the receivers end, the spatial diversity of V-BLAST systems vary in range $[1, M_r]$, where M_r represents the number of antennas available at the receivers end. For example, when interference cancellation, suppression are used for detection the foremost layer achieves a spatial diversity of $M_r - M_t + 1$. This is due to the fact that other layers are seen as interference and are suppressed while detecting the first layer. Moreover the last layer achieves a spatial diversity of M_r, as all the previously detected layers were removed from this layer [48].

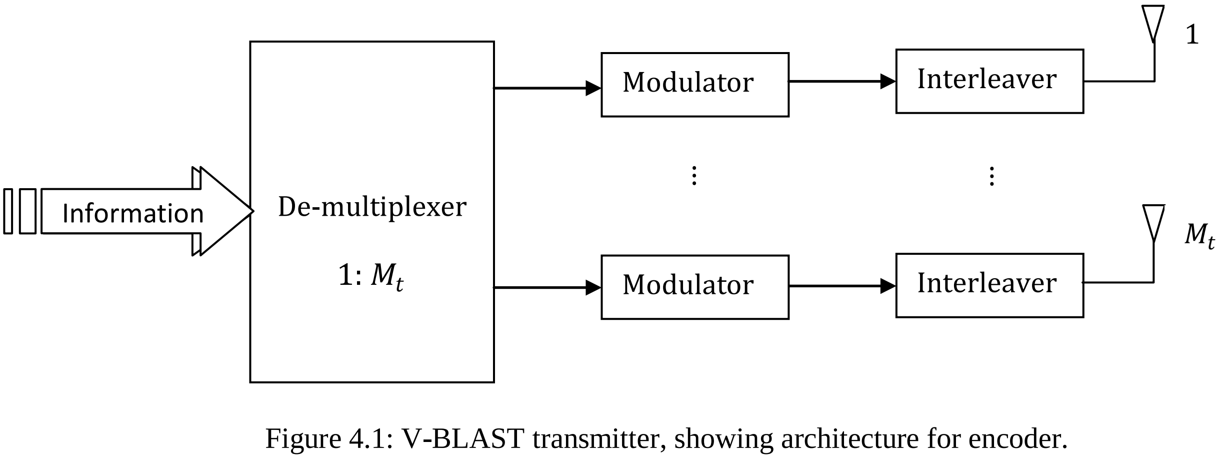

Figure 4.1: V-BLAST transmitter, showing architecture for encoder.

4.1.2 Zero-Forcing Detection for V-BLAST Systems

The detection algorithm based Zero-Forcing (ZF) criteria [42] is the most commonly used detection technique in V-BLAST systems, as it is the least complex detection procedure. In this technique when each layer is detected the interference caused by other undetected layers is suppressed, generally termed as interference suppression. To further improve the performance of the detection technique, interference suppression is merged with interference cancellation. Interference cancellation cancels out the effect of detected layers from the received signal to nullify its interference on the layers yet to be detected.

For a given user the signal received from various transmit antennas can be represented as

$$\boldsymbol{Y} = \sqrt{(SNR)_r}\,.\boldsymbol{H}_n\,\boldsymbol{X} + \boldsymbol{N}_{AWGN}\ , \tag{4.1}$$

where $\boldsymbol{H}_n$ represents the MIMO channel matrix of size M_t x M_r, X represents the matrix of transmitted sub-streams from all transmit antennas and is of size M_t x $\mathrm{S_t}$ (where $\mathrm{S_t}$ is length of the sequence transmitted from each antenna), $\boldsymbol{N}_{AWGN}$ represents the additive white Gaussian noise (AWGN) matrix of size S_t x M_r, and $(SNR)_r$ is the average signal to noise ratio for each receiver antenna. According to Horn and Johnson [49], for $M_t \leq M_r$, the channel matrix can be represented using QR factorization rule as in [49].

$$\boldsymbol{H}_n = \boldsymbol{R}\,\boldsymbol{Q} \tag{4.2}$$

where $\boldsymbol{Q}$ is a unitary matrix and $\boldsymbol{R}$ is a lower triangular matrix, both having same dimensions as that of $\boldsymbol{H}_n$. The matrix $\boldsymbol{Q}$ consists of rows that are orthonormal to each other, and exhibits the property $\boldsymbol{Q}\,\boldsymbol{Q}^H = \mathbf{I}$ where $\mathbf{I}$ represents an identity matrix. Multiplying (4.1) with $\boldsymbol{Q}^H$ results in following,

$$\overline{\boldsymbol{Y}} = \sqrt{(SNR)_r}\,.\boldsymbol{X}\,\boldsymbol{H}_n\,\boldsymbol{Q}^H + \boldsymbol{N}_{AWGN}\,\boldsymbol{Q}^H = \sqrt{(SNR)_r}\,.\boldsymbol{X}\,\boldsymbol{R} + \overline{\boldsymbol{N}_{AWGN}}\,. \tag{4.3}$$

The $(k,j)^{th}$ element of $\overline{\boldsymbol{Y}}$, represents the symbol being transmitted at time *k* from j^{th} transmit antenna and is given by

$$\overline{y_j}(k) = \sqrt{(SNR)_r}\,.\sum_{i=j}^{M_t} r_{i,j}\,x_i(k) + \overline{n_j}(k), \tag{4.4}$$

$$\overline{y_j}(k) = \sqrt{(SNR)_r}\,.r_{j,j}\,x_i(k) + \sqrt{(SNR)_r}\,.\sum_{i=j+1}^{M_t} r_{i,j}\,x_i(k) + \overline{n_j}(k). \tag{4.5}$$

where the first term of (4.5) represents the desired symbol and the second term represents the interference. The lower limit on *i* is *j* as **R** is a lower triangular matrix, as such interference from the layers *1,2,….j-1* is suppressed, and the interference from remaining detected layers can easily be cancelled. Therefore, representing $\boldsymbol{H}_\mathrm{n}$ in the QR form is essential in suppressing interference from other layers. The interference from layer *j* that is to be cancelled can be represented as $\sum_{i=j+1}^{M_t} r_{i,j}\,\widehat{x_i}(k)$. Thus (4.5) can be re-written as following with soft decision information

$$\overline{y_j}(k) = \sqrt{(SNR)_r}\,.\,r_{j,j}\, x_i(k) + \sqrt{(SNR)_r}\,.\sum_{i=j+1}^{M_t} r_{i,j}\,[x_i(k) - \widehat{x_i}(k)] \;+\overline{n_j}(k) \qquad (4.6)$$

Equation (4.6) is based on the assumption that if all the hard decisions for detected layers are correct then the next layer to be detected will be interference free.

4.1.3 Ordered Zero-Forcing Detection for V-BLAST Systems

As observed from the ZF detection criterions, the layer first detected is least reliable with a diversity order of $M_r - M_t + 1$ as the interference from other layers is suppressed at the instance of detection [50]. While the layer detected at last is the most reliable one with diversity order of M_r, as the interference from all detected layers is cancelled at the instance of detection and not suppressed as in previous layers detection [48]. Thus, the diversity order for j^{th} layer is given by, $M_r - M_t + j$ which is not desirable in many cases.

To get rid of this problem, a general approach found in literature is to order the received data stream sequences based on power, i.e., from strongest to weakest layers, and begin the detection process with the strongest data stream sequence. This can be done by sorting the rows of $\boldsymbol{H}_n$ based on their squared norms, i.e., the row that has highest value is taken as M_t^{th} row. Then the same procedure as discussed in previous Section can be followed to complete the detection process.

4.1.4 Capacity formulation for V-BLAST OFDMA systems

The instantaneous capacity of a V-BLAST system with M_t layers, received using zero forcing detection algorithm [51] is given by,

$$C_{VBLAST}^{ZF} = \sum_{j=1}^{M_t} \log_2\left(1 + \frac{(SNR)_r}{M_t\,\left\|W_{ZF,j}\right\|^2}\right), \qquad (4.7)$$

$$W_{ZF,j} = [(\boldsymbol{H}_n)_j{}^H \ (\boldsymbol{H}_n)_j]^{-1} \, (\boldsymbol{H}_n)_j{}^H. \tag{4.8}$$

Equation (4.7) gives the V-BLAST capacity for single user, where $W_{ZF,j}$ the ZF projection vector of jth is layer and $\|W_{ZF,j}\|$ is the froebinus norm of this projection vector [42].

For a V-BLAST-OFDMA system, where we have multiple users in the system accessing the same BS simultaneously, the total capacity of the system is given by,

$$C^{ZF}_{\text{V-BLAST-OFDMA}} = \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{j=1}^{M_t} \log_2\left(1 + \frac{(SNR)_r}{M_t \left\|W_{ZF,j}\right\|^2}\right), \tag{4.9}$$

where K represents total number of users in the system and N represents total number of sub-carriers available, $(SNR)_r$ is the average SNR per receive antenna and can be expressed as $p_{k,n}(j)/N_0$, where $p_{k,n}(j)$ is the power allocation done respectively to user k, over sub-carrier n for the j^{th} layer and N_0 is the noise power. As explained in Chapter 3, the MIMO channel can be decomposed into parallel non-interfering channels, in the similar manner we decompose the V-BLAST channel but instead of considering the Eigen-values we take into account the post processing SNR's (SNR_{post}) for each decomposed parallel channel. The value for post processing SNR's is given by

$$SNR_{post} = \frac{(SNR)_r}{M_t \left\|W_{ZF,j}\right\|^2}\,. \tag{4.10}$$

Once the post processing SNR's are calculated, the sub-carrier allocation and the power allocation are done based on the proposed algorithm described in Chapter 3.

4.2 Space Time Block Codes (STBC)

Space time block coding is an effective way of achieving transmit and receive diversities, providing a practical approach for implementing transmit-receive diversity offered by MIMO systems. In addition to this, STBC can be efficiently decoded by means of simple processing techniques.

4.2.1 Alamouti Scheme

Alamouti scheme is a transmit diversity scheme introduced by Alamouti in 1998 [52], proposed for a system with two transmit antennas. Let us consider two symbols x_1, x_2 that are transmitted in two different time slots, as shown in Table 4.1. In the first time slot symbol x_1 is transmitted from first antenna and symbol x_2 is transmitted from second antenna, while symbols $-x_2{}^*$ and $x_1{}^*$ are transmitted in second time slot from the first and second antennas respectively. In two time slots, two symbols are transmitted resulting in a transmission rate of 1 [52].

Table 4.1: The encoding and transmission sequence for Alamouti transmit diversity scheme [52].

	Time slot -2	**Time slot -1**
Antenna 1	$-x_2{}^*$	x_1
Antenna 2	$x_1{}^*$	x_2

In [2], the author considered two cases to design the optimal receiver for this scheme. For a single antenna receiver, the received signals vector was considered to be as following

$$\mathbf{Y} = \begin{bmatrix} \mathrm{y}_1(1) \\ \mathrm{y}_1^*(2) \end{bmatrix} = \sqrt{\mathrm{SNR}}\,.\begin{bmatrix} \mathrm{h}_{1,1} & \mathrm{h}_{1,2} \\ \mathrm{h}_{1,2}^* & -\mathrm{h}_{1,1}^* \end{bmatrix} \begin{bmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \end{bmatrix} + \begin{bmatrix} \mathrm{n}_1(1) \\ \mathrm{n}_1^*(2) \end{bmatrix} \qquad (4.11)$$

where $h_{1,1}$ and $h_{1,2}$ are the two elements of the transmission channel matrix, (i.e., h_{M_r,M_t}, fading coefficients as described in previous Chapter) and are supposed to be the same for two successive time slots. The elements $n_1(1)$ and $n_1^*(2)$ are the AWGN variables with a variance of $N_0/2$ per dimension.

The transmission matrix is orthogonal in nature as it satisfies the following condition

$$\boldsymbol{H}_{2\text{x}1}^{H}\,\boldsymbol{H}_{2\text{x}1} = \begin{bmatrix} \left|h_{1,1}\right|^2 + \left|h_{1,2}\right|^2 & 0 \\ 0 & \left|h_{1,1}\right|^2 + \left|h_{1,2}\right|^2 \end{bmatrix}. \tag{4.12}$$

Therefore, the received symbols were decoded with this receiver for a 2x2 system. This detection technique was easily extendable to a system having multiple receive antennas, as following

$$\boldsymbol{Y} = \begin{bmatrix} y_1(1) \\ \vdots \\ y_j(1) \\ y_1^*(2) \\ \vdots \\ y_j^*(2) \end{bmatrix} = \sqrt{SNR}\,.\begin{bmatrix} h_{1,1} & h_{1,2} \\ \vdots & \vdots \\ h_{j,1} & h_{j,2} \\ h_{1,2}^* & -h_{1,1}^* \\ \vdots & \vdots \\ h_{j,2}^* & -h_{j,1}^* \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1(1) \\ \vdots \\ n_j(1) \\ n_1^*(2) \\ \vdots \\ n_j^*(2) \end{bmatrix}, \tag{4.13}$$

where $j = 1,2 \ldots\ldots M_r,$ and M_r represents the total number of receiving antennas. The elements $y_j(l)$ and $n_j(l)$ represent the symbol received and AWGN at j^{th} receive antenna and l^{th} timeslot, respectively. The optimal way to combine the received symbols from M_r parallel channels (each pertaining to a receiving antenna) is to make use of maximal ratio combining. Furthermore this transmit diversity scheme can also extend to a system having more than two antennas, by the means of space time block codes defined on the basis of orthogonal design theory [53].

4.2.2 STBC Encoder

Let us consider that "n x k" bits arrive at encoder and it selects k symbols from Q(which is a signal constellation set of cardinality 2^n). These k symbols are mapped to t x M_t matrix known as orthogonal transmission matrix, represented by $\boldsymbol{X}$. Where each column represents the symbols transmitted from corresponding antenna, and each row represents the symbols transmitted in their respective time slot. As in t time slots k symbols are transmitted, the transmission rate of STBC is given by,

$$\mathrm{R_s} = \frac{\mathrm{k}}{\mathrm{t}} \text{ symbols per time slot.} \tag{4.14}$$

For orthogonal STBC, the only case in which the transmission rate of 1 (maximum rate) is achieved is in a system having two transmit antennas. Alamouti scheme discussed above is a good example of this type, which is able to achieve a rate of 1. In [53] the codes transmitting at a rate of ½, and ¾ were defined for systems having three and four antennas respectively.

4.2.3 Detection procedure for STBC

The receiver makes a decision after analyzing the received signals for complete block length duration of t time slots. Considering the channel state information of the MIMO channel to be invariable for the complete block length, the received signals over t time slots can be represented in the matrix form as following,

$$[\,\mathbf{Y}\,]_{t \times M_r} = \sqrt{SNR}\,.[\,\mathbf{H}\,]_{M_r \times M_t}\,[\,\mathbf{X}\,]_{t \times M_t} + [\,\boldsymbol{\eta}\,]_{t \times M_r}\,. \tag{4.15}$$

For orthogonal space time block codes the decoding process can be performed in two steps as mentioned below [50]:

Step 1: The received vectors are decoupled over the complete block length into estimates of transmitted symbols, by means of maximal ratio combining.

Step 2: Then maximum likelihood detection of these estimates of the transmitted symbols are done separately.

As, mentioned earlier in eq. 4.15 the received signal vector can be concisely re-written as

$$\widehat{\boldsymbol{Y}} = \sqrt{SNR}\;\widehat{\boldsymbol{H}}\,\boldsymbol{X} + \widehat{\boldsymbol{\eta}}. \tag{4.16}$$

$\widehat{\boldsymbol{Y}}, \widehat{\boldsymbol{H}}$ and $\widehat{\boldsymbol{\eta}}$ represents respective terms in estimation stage. As $\widehat{\boldsymbol{H}}$ is orthogonal in nature the estimates of the transmitted symbols can easily be achieved by decoupling received symbols after performing one-to-one transformation, i.e., by multiplying $\widehat{\boldsymbol{Y}}$ with $\widehat{\boldsymbol{H}^H}$. This procedure is known as maximal ratio combining which maximizes SNR of the estimated symbol [50].

$$\widehat{\boldsymbol{X}} = \widehat{\boldsymbol{H}^H}\widehat{\boldsymbol{Y}} \; = \; \sqrt{SNR}\,\widehat{\boldsymbol{H}^H}\;\widehat{\boldsymbol{H}}\,\boldsymbol{X} + \widehat{\boldsymbol{H}^H}\;\widehat{\boldsymbol{\eta}}. \tag{4.17}$$

For 2x2 system, as represented in (4.13), the above equation results in following

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} = \sqrt{SNR} \begin{bmatrix} |h_{1,1}|^2 + |h_{1,2}|^2 + |h_{2,1}|^2 + |h_{2,2}|^2 & 0 \\ 0 & |h_{1,1}|^2 + |h_{1,2}|^2 + |h_{2,1}|^2 + |h_{2,2}|^2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \widehat{\boldsymbol{H}^H}\;\widehat{\boldsymbol{\eta}} \tag{4.18}$$

Thereafter the estimates of symbols obtained are detected using maximum likelihood detector, which detects each symbol separately. Therefore, in order to detect $\hat{x}_1$ the detector chooses a symbol q_i belonging to signal constellation Q if the following condition is satisfied [36].

$$\begin{aligned} &\left(|h_{1,1}|^2 + |h_{1,2}|^2 + |h_{2,1}|^2 + |h_{2,2}|^2 - 1\right) |q_i|^2 + d^2\,(\hat{x}_1, q_i) \\ &\qquad \leq \left(|h_{1,1}|^2 + |h_{1,2}|^2 + |h_{2,1}|^2 + |h_{2,2}|^2 - 1\right) |q_k|^2 + d^2\,(\hat{x}_1, q_k);\ \forall\, i \neq k \end{aligned} \tag{4.19}$$

where $d^2\,(\hat{x}_1, q_k)$ represents the Euclidean distance between $\hat{x}_1$ and q_k .

4.2.4 Capacity formulation for STBC OFDMA systems

Let us consider a scenario where transmitter and receiver are equipped with multiple antennas, and the channel gains are represented by the channels matrix **H**. For an orthogonal space time block code of rate R_s, the instantaneous capacity is given by [54]

$$C_{STBC} \; = \; R_s\ \log_2\left(1 + \frac{SNR}{M_t}\ \|\boldsymbol{H}\|_f^2\right). \tag{4.20}$$

where M_t represents number of transmit antennas, and $\|\boldsymbol{H}\|_f^2$ is the squared Frobeinus norm of channel matrix.

For a STBC-OFDMA system, where we have multiple users in the system accessing the same base station simultaneously, the total capacity of the system is given by,

$$C_{\text{STBC-OFDMA}}^{ZF} = R_s \sum_{k=1}^{K} \sum_{n=1}^{N} \log_2\left(1 + \frac{SNR}{M_t} \left\|\boldsymbol{H}_{k,n}\right\|_f^2\right). \tag{4.21}$$

where K represents total number of users in the system and N represents total number of sub-carriers available. SNR is the signal to noise ratio and can be expressed as $p_{k,n}/N_0$, where $p_{k,n}$ is the power allocation done respectively to user k, over sub-carrier n and N_0 is the noise power. The overall power gain of channel matrix between user k, over sub-carrier n is represented by the value $\left\|\boldsymbol{H}_{k,n}\right\|_f^2$ based on which sub-carrier and power allocations are done in accordance with the proposed algorithm, as described in Chapter 3.

4.3 Multi-Layered Space Time Block Codes

From Section 4.2 and Section 4.3 it is clear that practical scheme like V-BLAST is an efficient spatial multiplexing technique where as STBC is a scheme that helps in achieving maximum transmit diversity. Thus there was an inspiration to merge these schemes to take benefits of both, giving rise to a new scheme known as multilayered space time code. The multilayered space time coding scheme was first considered by Tarokh et.al [55], with the aid of space time trellis codes (STTC). Later on various advantages of STBC over STTC made it suitable to design a layered architecture with STBC, like minimum number of antennas required at the receiver, short code length, orthogonal arrangement etc.

Therefore, In a MLSTBC scheme antennas at the transmitter side are divided among subgroups and from each of this subgroup an independent signal that is coded using STBC scheme is transmitted.

4.3.1 MLSTBC encoder

The MLSTBC transmitter has G independent and synchronized parallel STBC encoders as in Figure 4.2. Each STBC encoder transmits through a subgroup of M_g transmit antennas.

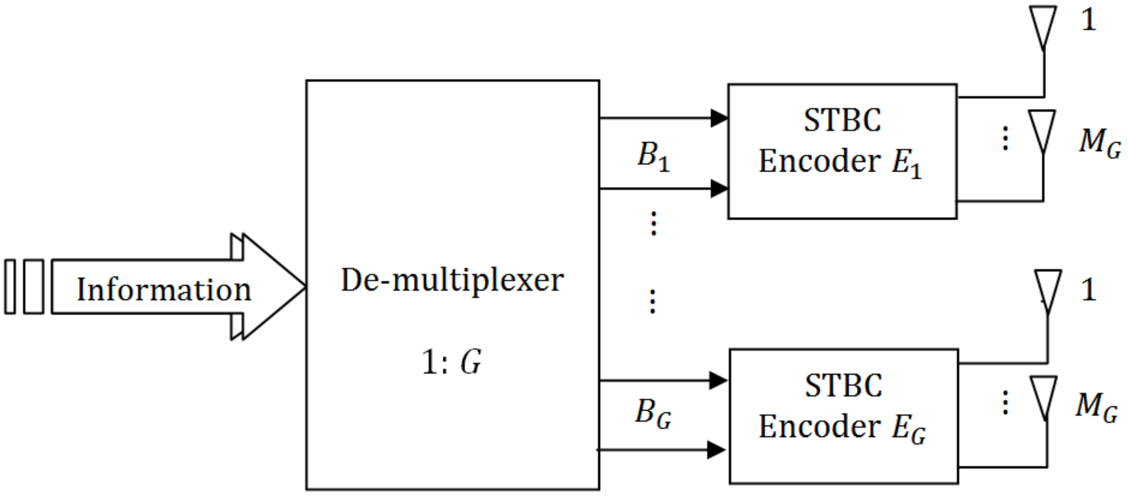

Figure 4-2: MLSTBC transmitter, showing architecture for encoder

The channel between transmitter and receiver is considered to be Rayleigh flat fading MIMO channel, as discussed in Chapter 3. There are G x M_G number of transmit antennas available at the transmitter.

4.3.2 Detection Procedure for MLSTBC systems

The received symbols matrix over the total length T of STBC can be represented as [42]

$$\boldsymbol{Y} = \boldsymbol{HS} + \boldsymbol{V} = [\boldsymbol{H}_1 \ \boldsymbol{H}_2 \ \dots \ \boldsymbol{H}_G] \begin{bmatrix} \boldsymbol{S}_1 \\ \boldsymbol{S}_2 \\ \vdots \\ \boldsymbol{S}_G \end{bmatrix} + \boldsymbol{V}, \tag{4.22}$$

where $\boldsymbol{H}_g$ represents the channel matrix for g^{th} group and is of the order M_R x M_G (M_R gives total receive antennas), $\boldsymbol{S}_g$ represents the STBC of g^{th} group of order M_G x T and $\boldsymbol{V}$ stands for the AWGN matrix over STBC length *T*. As STBC has short code length the received matrix is rearranged by the receiver into a vector as that of single STBC, which results in discrete MIMO model [50] (resembling V-BLAST) as following

$$\boldsymbol{y} = \widehat{\boldsymbol{H}}\mathbf{x} + \boldsymbol{\eta} = [\widehat{\boldsymbol{H}}_1 \ \widehat{\boldsymbol{H}}_2 \ \dots \ \widehat{\boldsymbol{H}}_G] \begin{bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \\ \vdots \\ \boldsymbol{x}_G \end{bmatrix} + \boldsymbol{\eta}, \tag{4.23}$$

where $\boldsymbol{y}$ is the received vector of order $M_R\,.T$ x 1, $\boldsymbol{H}_g$ represents the orthogonal channel matrix for g^{th} group which is of the order $M_R.T$ x M_G, $\boldsymbol{x}_g$ represents the symbols transmitted from g^{th} group of order M_G x 1 and $\boldsymbol{\eta}$ stands for the AWGN vector of order $M_R\,.T$ x 1.

4.3.3 Serial Group Interference Nulling and Cancellation Detection

In a group interference cancellation detection technique every single code is decoded independently considering all other codes as interference that can be suppressed and cancelled. This technique is very much similar to the detection technique used for BLAST systems where interference suppression and cancellation is done simultaneously. For a system having perfect channel state information, the main aim of detection algorithm is decode the desired groups signal in presence of interference from other groups, and then cancel the contribution of already decoded signals from it. This process is repeated for all layers in a serial manner hence known as serial group interference nulling and cancellation (SGINC) detection. This detection technique was initially proposed by Tarokh et.al [55] as an extension to V-BLAST scheme. The SGINC detection technique is able to perform in best manner when the layers are arranged in descending order based on highest signal power, i.e., from highest to lowest signal power.

Let us assume that g^{th} group is detected first, the detection algorithm computes orthonormal bases for null-space of $\boldsymbol{\mathcal{H}}_g$, given by

$$\boldsymbol{\mathcal{H}}_g = \begin{bmatrix} \hat{\mathrm{H}}_1 & \dots & \hat{\mathrm{H}}_{g-1} & \hat{\mathrm{H}}_{g+1} & \dots & \hat{\mathrm{H}}_G \end{bmatrix}. \tag{4.24}$$

The orthonormal bases for $\boldsymbol{\mathcal{H}}_g$ denoted by $\boldsymbol{\mathcal{N}}_g$, the received signal after nulling for g^{th} group can be represented as [50],

$$\widetilde{\boldsymbol{y}}_g = \boldsymbol{\mathcal{N}}_g\, \boldsymbol{y} = \widetilde{\boldsymbol{H}}_g\, \boldsymbol{x}_g + \widetilde{\boldsymbol{\eta}}_g, \tag{4.25}$$

where $\widetilde{\boldsymbol{H}}_g$ represents channel matrix resulting from nulling. Once the desired g^{th} group signal is decoded the contribution of this group is deducted from (4.23) and the detection procedure is repeated for each layer in serial manner. In literature we come across various ordering criterions, but the best ordering criteria is the one based on Frobenius norm of the channel matrix obtained after nulling, i.e., $\widetilde{\boldsymbol{H}}_g$. Therefore, layer having maximum $\left\|\widetilde{\boldsymbol{H}}_g\right\|_F^2$ is the one that will be detected first [42].

4.3.4 Capacity formulation for MLSTBC OFDMA systems

Let us consider a scenario where transmitter and receiver are equipped with multiple antennas, and the channel gains are represented by the channels matrix **H**. For a G layered space time block code of rate R_s, the instantaneous capacity [42] is given by

$$C_{MLSTBC} = R_s \sum_{g=1}^{G} \log_2\left(1 + \frac{SNR}{G.M_G}\left\{\frac{\|\widetilde{\boldsymbol{H}}_g\|_f^2}{T}\right\}\right), \tag{4.26}$$

where M_G represents number of transmit antennas per layer, (i.e., sub-group of STBC encoder), $\|\widetilde{\boldsymbol{H}}_g\|_f^2$ is the squared Frobenius norm of channel matrix after nulling, and T represents the length of STBC.

For a MLSTBC-OFDMA system, where we have multiple users in the system accessing the same base station simultaneously, the total capacity of the system is given by,

$$C_{MLSTBC-OFDMA} = R_s \sum_{k=1}^{K}\sum_{n=1}^{N}\sum_{g=1}^{G} \log_2\left(1 + \frac{SNR}{G.M_G}\left\{\frac{\|(\widetilde{\boldsymbol{H}}_g)_{k,n}\|_f^2}{T}\right\}\right). \tag{4.27}$$

where K represents total number of users in the system and N represents total number of sub-carriers available. SNR is the signal to noise ratio and can be expressed as ${p_{k,n}}/{N_0}$,

where $p_{k,n}$ is the power allocation done respectively to user k, over sub-carrier n and N_0 is the noise power. The overall power gain of channel matrix obtained after nulling between user k, over sub-carrier n is represented by the value $\left\|(\widetilde{\boldsymbol{H}}_g)_{k,n}\right\|_f^2$ based on which sub-carrier and power allocations are done in accordance with the proposed algorithm, as described in Chapter 3.

4.4 Simulation Results

In this Section we compare various detection algorithms like V-BLAST, STBC and MLSTBC in a multi-user scenario in the perspective of proposed resource allocation algorithm as discussed in above Sections. We consider that base station and each user is equipped with equal number of antennas, (i.e., here it is four antennas resulting in 4x4 systems, for all simulation results in this Section). For a 4x4 MLSTBC, each STBC encoder is equipped with two transmit antennas resulting in two sub-groups, (i.e., G=2) , and uses Alamouti code for encoding as discussed in Section 4.3, with an STBC length of 2, (i.e., T =2).

All the simulation results analyzed in this Section are obtained for a users varying gradually from 2-16, with 64 sub-carriers, noise power spectral density (PSD) of -80dBW, total transmit power of 1 Watt, and a total bandwidth of 1 MHz .

Table 4.2: Parameters used for simulation of V-BLAST-OFDMA, STBC-OFDMA and MLSTBC-OFDMA based resource allocation algorithms.

Total transmit Power	1Watt
Noise PSD	- 80 dBW/Hz
Number of Sub-carriers	64
Systems Bandwidth	1MHz
Number of Users in system	Varying from 2-16.
Symbol Transmission Rate (R_s)	$^3/_4$ for 4x4 systems(STBC) and 1 for 2x2 systems(STBC/MLSTBC).

In Figure 4.3, the total capacity of the system is calculated for each of the practical scheme, while gradually increasing number of users from 2 to 16 and obtaining the overall systems capacity at each instance. This is later plotted against the number of active users in the system to compare how the total capacity is influenced with increasing number of users. Figure 4.3, shows that V-BLAST scheme with zero forcing detection in particular when the received sequences are sorted based on power before detection is able to provide high system capacity as the number of users increase. V-BLAST is able to perform better than other schemes in terms of capacity for the reason that it has highest spectral efficiency achieved by transmitting multiple data streams simultaneously from multiple antennas and it is also due to multi-user diversity.

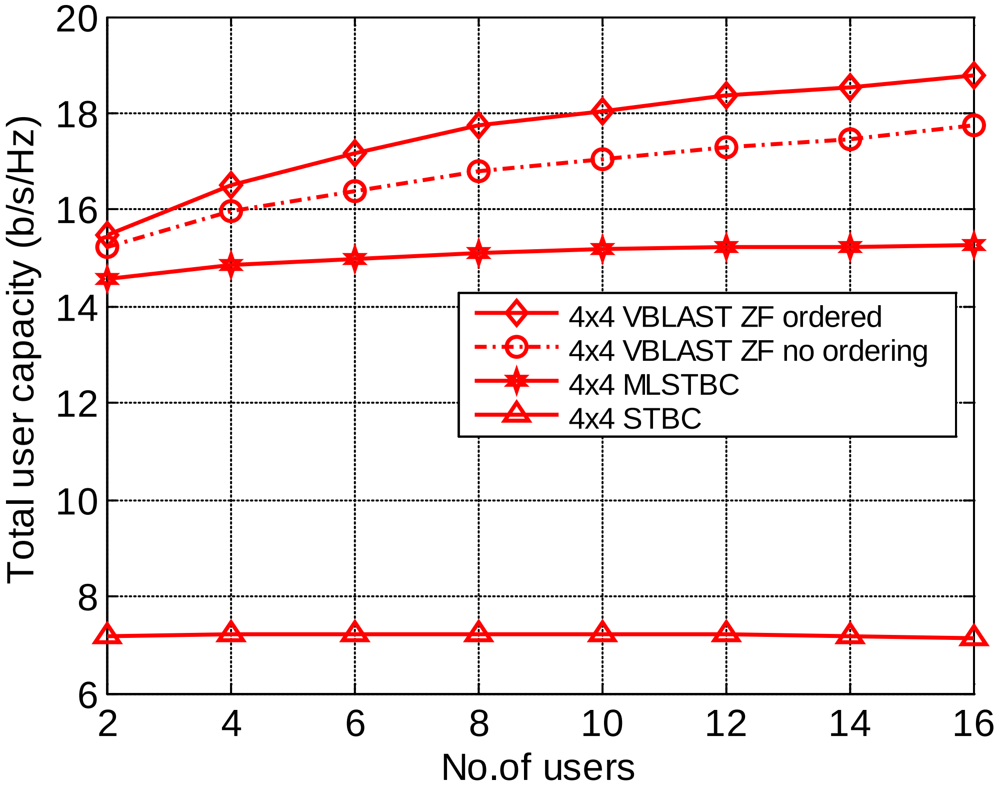

Figure 4.3: Overall systems capacity versus number of users for various practical schemes (in 4x4 MIMO-OFDMA scenarios).

In Figure 4.3, when there are ten users in the system, V-BLAST scheme with zero forcing detection after sorting (ZF-sorted) the received bits is able to achieve a total capacity of 18 bits/s/Hz, while for the V-BLAST scheme with ZF detection without ordering achieves a total capacity of 17.3 bits/s/Hz. This difference shows that there is an acceptable level of gain obtained when the detection process begins with the strongest layer (after being sorted). For ten active users in the system, STBC scheme is only able to achieve an overall capacity of 7.4 bits/s/Hz. This is because STBC scheme is not able to achieve spectral efficiency as it is transmission diversity scheme and achieves transmitting diversity gain by transmitting the same data streams on multiple transmitting antennas. Thereby, STBC is able to bring improvement in error performance by means of diversity gain.

MLSTBC is a scheme that can be seen as coalesce of V-BLAST and STBC, that is able to achieve much higher capacity and data rate compared to STBC and much improved reliability when compared to V-BLAST. The total capacity achieved by MLSTBC scheme for ten active users in the system is 15.4 bits/s/Hz which is much higher when compared to STBC scheme. The main difference in V-BLAST and MLSTBC is that MLSTBC has better spatial diversity than V-BLAST and V-BLAST has more layers, with same number of antennas at the transmitting and receiving ends.

In Figure 4.3, it can also be observed that for V-BLAST scheme the rate at which the systems overall capacity increases with respect to users is highest, when compared to others, i.e., as the number of users in the systems increase the total capacity also increases gradually. This is because with the increase in number of users, higher spectral efficiency is obtained thereby gradually improving the overall systems capacity. Similar is the case with MLSTBC scheme, but the rate at which the capacity increases is less than that for V-BLAST, as the effect of spectral efficiency is reduced due to the impact of MLSTBC's spatial diversity.

The Figure 4.4, shows the spectral efficiency of various practical schemes when the proposed resource allocation scheme is applied to them. We consider 4x4 MIMO-OFDMA systems with ten active users for all simulations of these practical schemes, i.e., V-BLAST, STBC and MLSTBC. The simulation results show us that there are multiple crossovers in capacities of various schemes that are function of SNR. At low SNR's the overall systems capacity, for V-BLAST scheme is lower than that of STBC and MLSTBC schemes. For SNR values less than 16.5dB in Figure 4.4, the capacity curve for STBC is better than MLSTBC and in turn MLSTBC's capacity curve is better than that for V-BLAST scheme. This is because the STBC and MLSTBC schemes are capable of providing more diversity at low SNR's, which achieves better capacity for these schemes when compared to V-BLAST scheme. Therefore at 16.5dB SNR the crossover of capacity occurs among V-BLAST, STBC and MLSTBC schemes. Thereby at high SNR values the capacity of V-BLAST improves considerably which is much higher than that for MLSTBC and the capacity for MLSTBC is superior to that for STBC.

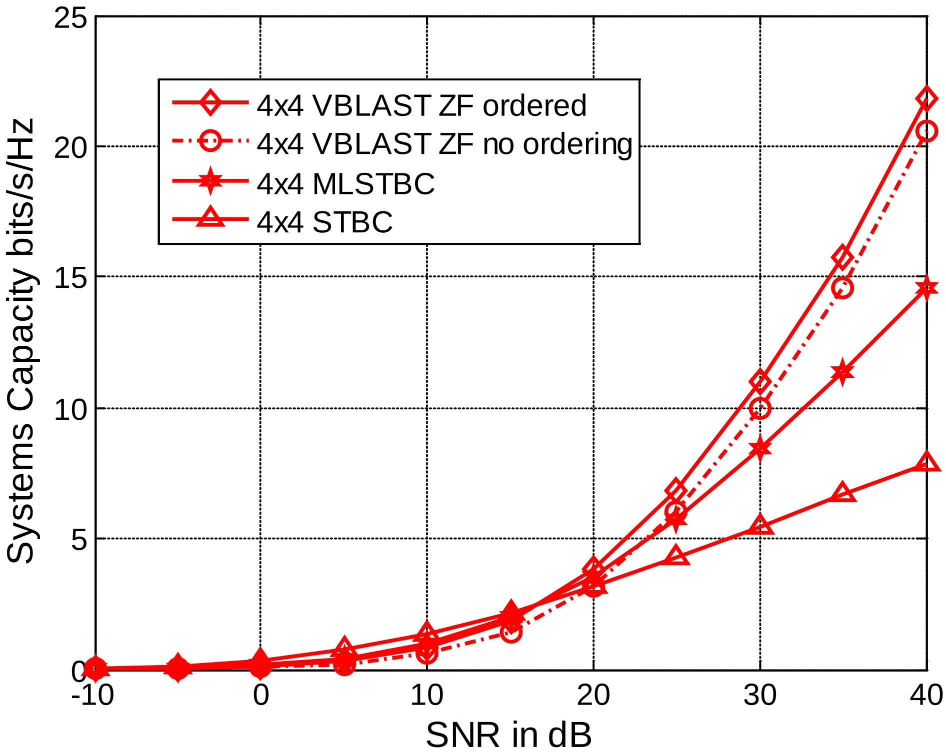

Figure 4.4: Overall systems capacity versus SNR in dB of various practical schemes (in 4x4 MIMO-OFDMA scenarios) for 10 active users in system.

For the V-BLAST scheme where the detection is performed without sorting the crossover of capacities occur at a SNR of 23dB. Furthermore, on analyzing the Figure 4.4, we can conclude that the rate of increase in total capacity for V-BLAST is faster than MLSTBC, as it is a full spectral multiplexing scheme.

Figure 4.5, gives the capacity complementary cumulative distribution function (CCDF) plots of various practical schemes for 4x4 MIMO-OFDMA systems. This plot shows that at low outage probabilities and low SNR the capacity of V-BLAST is lesser compared to STBC and MLSTBC. Which reaffirms the fact that STBC and MLSTBC provides better diversity that enhances the capacity at lower SNR’s.

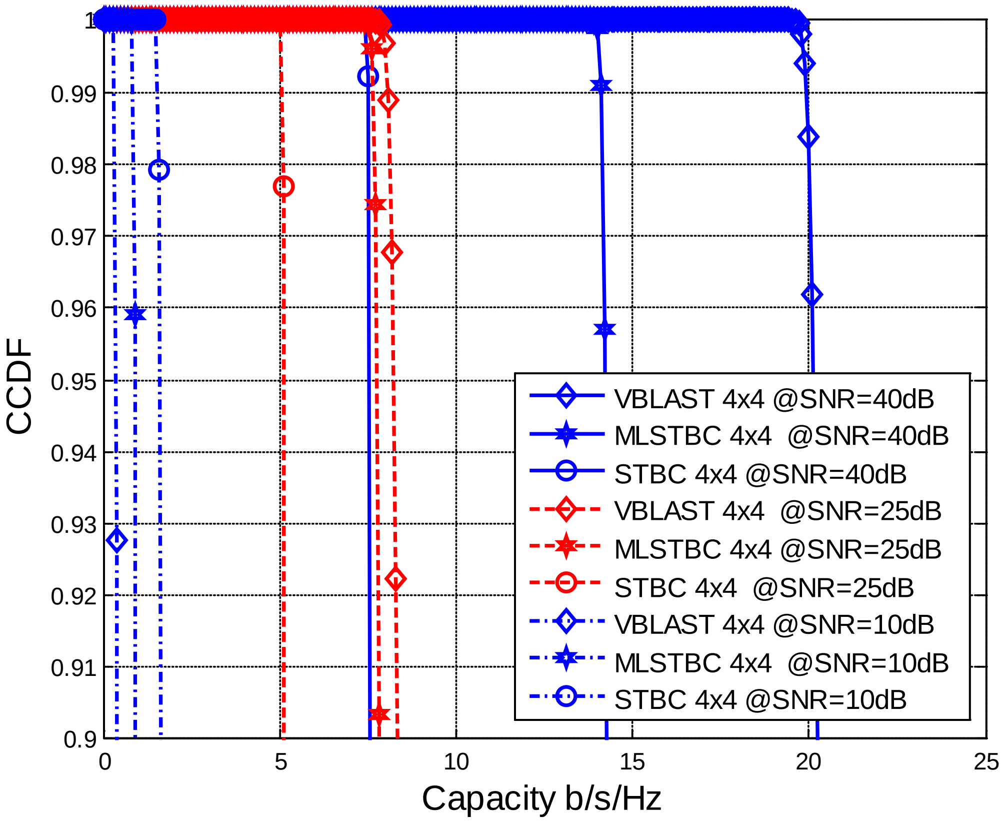

Figure 4.5: Complementary CDF versus Overall systems capacity of various practical schemes (in 4x4 MIMO-OFDMA scenarios) for 10 active users in system.

Whereas at high SNR’s the total capacity of system increases drastically for V-BLAST scheme, that is much higher than MLSTBC which is in turn higher than STBC at high SNR. The Figure 4.5, clearly explains this by means of capacity CCDF plots obtained at three different SNR’s, i.e., 10dB, 25dB and 40dB. For 10dB SNR, at low outage probabilities the capacity of V-BLAST is lesser than MLSTBC and STBC, whereas at

40dB SNR, the capacity of V-BLAST is much higher than MLSTBC and STBC, as can be seen in Figure 4.5.

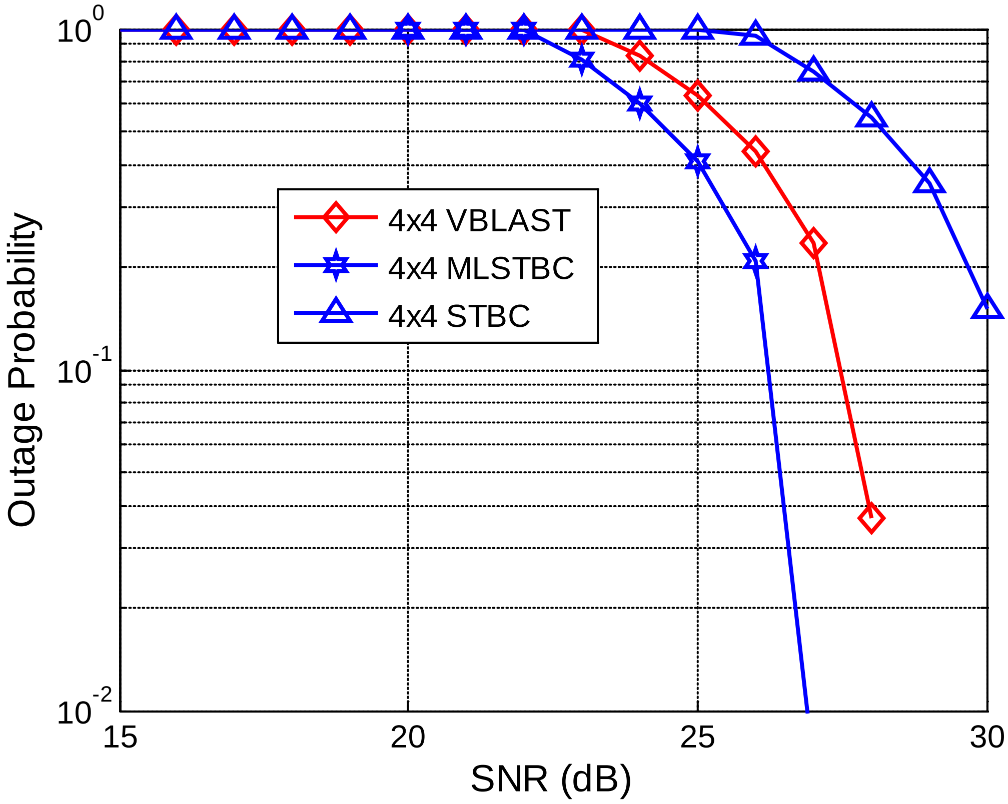

Figure 4.6: Outage probability as a function of SNR at 5 bps/Hz for various practical schemes (in 4x4 MIMO-OFDMA scenarios) for 10 active users in system..

Figure 4.6 gives the outage probability plots for various practical schemes as a function of signal to noise ratio at 5 bits/s/Hz efficiency. These results also show that MLSTBC scheme is able to provide better diversity than V-BLAST scheme even in multi-user access scenario. For a 4x4 MIMO-OFDMA system with one user, MLSTBC has two layers and each layers transmit diversity is two. At MLSTBC schemes receiver end, the foremost detected layer has a diversity, (i.e., receive diversity) of three as one antenna is used by detector to null out interfering layer and remaining antennas are used to endow with diversity.

These transmit and receive diversities increases with the increase in number of users in the systems as the number of receive antennas increase. Also MLSTBC scheme is more power proficient than STBC scheme at low and moderate SNR’s, which is a consequence of diminishing gains at high diversity orders. Thereby use of several antennas to achieve spatial multiplexing doesn’t hinder the performance of the system. Whereas for a 4x4 V-BLAST-OFDMA system there exist four layers and it has no transmission diversity. Furthermore, the foremost detected layer has zero receive diversity as the detection scheme utilizes all the other receiver antennas to null out the interfering layers.

4.5 Conclusions

In this chapter, we discussed various practical schemes like V-BLAST, STBC and MLSTBC that provide practical means of implementing and accomplishing the benefits offered by MIMO systems, along with their detection approaches. We then analyzed and compared the performance of these practical schemes with the proposed resource allocation algorithm in a downlink scenario for MIMO-OFDMA systems. Capacity formulations for these systems were analyzed to identify the factors that can improve the systems total capacity, based on these factors the proposed algorithm was modified accordingly to achieve higher spectral efficiencies for these practical schemes.

After analyzing the results of MATLAB simulation, it can be concluded that in a MIMO-OFDMA scenario V-BLAST scheme has higher overall systems spectral efficiency at high SNR’s. Whereas at low outage probabilities, and at low and moderate SNR’s MLSTBC has better performance in terms of overall systems spectral efficiency. It can also be concluded that MLSTBC has more number of layers than STBC, and is more power proficient even in multi-user access scenario when compared to V-BLAST scheme.

Chapter 5

Adaptive Modulation-Bit Loading Schemes

Adaptive modulation is an important technique that increases data rates when compared to their counterpart non adaptive uncoded schemes. Adaptive modulation and bit loading techniques aid us in enhancing as well as evaluating the performance of dynamic resource allocation schemes [56]. To perform adaptive modulation it is assumed that the receiver and transmitter have complete information about channels condition well in advance. Hence while, for each user over the assigned sub-channel appropriate modulation scheme can be selected that suits best its channel conditions in order enhance the systems performance. In this Chapter, purpose of introducing adaptive modulation is to maximize the achievable system bit error (BE) performance, whilst retaining the specified target BER such that desired quality-of-service is guaranteed [56]. For time varying wireless channels, adaptive modulation techniques can track and adapt to instantaneous changes in the channel in order to increase reliability and spectral efficiency of the system [57].

Thereby tracking and adapting to the instantaneously changing channel conditions it can be ensured that the most proficient modulation scheme is employed, such that the system achieves higher data rates, and have increased reliability when compared to non-adaptive schemes.

In this Chapter, adaptive modulation schemes are proposed which assist us in giving a practical approach to the assumptions made in resource allocation scheme devised in third Chapter. We fore mostly focus on adapting to various modulation schemes in order to satisfy the minimum bit error rate performance. We also explore the spatial domain aspect of the downlink system. OFDM converts frequency selective fading channel into a set of parallel flat-fading ones, while a space division multiple access (SDMA) technique can be implemented on each sub-carrier to further enhance the systems throughput [26, 58]. The various spatially distinguishable users are multiplexed on to the same time slot and frequency channel by SDMA with the help of precoding techniques [26].

In this Chapter we proposed two schemes, firstly an adaptive modulation resource allocation scheme for multi-user MIMO-OFDMA-SDMA systems in a downlink scenario. Multi-user diversity can be exploited both in frequency domain as well as spatial domain when the OFDMA and SDMA techniques are combined [58]. Thus the MIMO-OFDMA-SDMA systems can enhance the degrees of freedom in dealing with richly scattered channels and facilitates in proposing an adaptive modulation scheme for MIMO-OFDMA systems. Secondly we propose an adaptive resource allocation scheme for MIMO-OFDMA system, using V-BLAST algorithm implementation based on ZF detection with symbol cancellation in contrast to the MIMO-OFDMA-SDMA scheme which employs precoding. This scheme is proposed to improve the performance of MIMO-OFDMA system while having low computational complexity [59]. Finally, we compare simulation results of these schemes to conclude which one performs better while adapting to appropriate modulation schemes so as to maintain the required bit error rate performance. As mentioned we consider two different adaptive systems in this Chapter, and analyze their performance while maintaining systems target BER as 10^{-3}.

5.1 Adaptive Modulation- Bit loading scheme for MIMO-OFDMA-SDMA systems

In this Section we propose dynamic resource allocation algorithm for a multi-user MIMO-OFDMA-SDMA downlink system. The main objective is to evaluate the systems performance under strict bit error rate constraints, apart from other constraints discussed in Chapter 3. The resource allocation algorithm for such a system can be divided into two steps. In first step as per the proposed algorithm in Chapter 3, the various available spatial sub channels are allocated to appropriate users and then based on the channel conditions the power is distributed among all the users across these sub-channels by means of water filling technique. Whereas in second step, depending on the signal to noise ratio of each spatial sub-channel the type of modulation to be used, and number of bits to be transmitted are decided based on some preset system performance constraints.

As discussed earlier, MIMO-OFDMA-SDMA system can achieve high data rates and enhance the systems performance as multi-user diversity can be exploited in both spatial as well as frequency domain. For such systems, before allocating the available resources it is necessary to shape the available channel as a set of parallel, independent and spectrally flat sub channels [58]. Thus, for a downlink system zero forcing or block diagonalization techniques were proposed in literature for SDMA systems to cancel the co-channel interference in multi-user systems [59, 60]. In such systems, making use of precoding techniques much of the signal processing complexities that confiscate the co-channel inter-user interference are moved to base station terminal while leaving user terminals with simple receiver systems.

5.1.1 System Model for MIMO-OFDMA-SDMA

In a multi-user downlink MIMO-OFDMA-SDMA scenario, we consider a base station and K geographically dispersed users. Where base station is equipped with M_t transmit antennas and each user is equipped with M_r receive antennas. The simplified system model can be seen in the Figure 5.1.

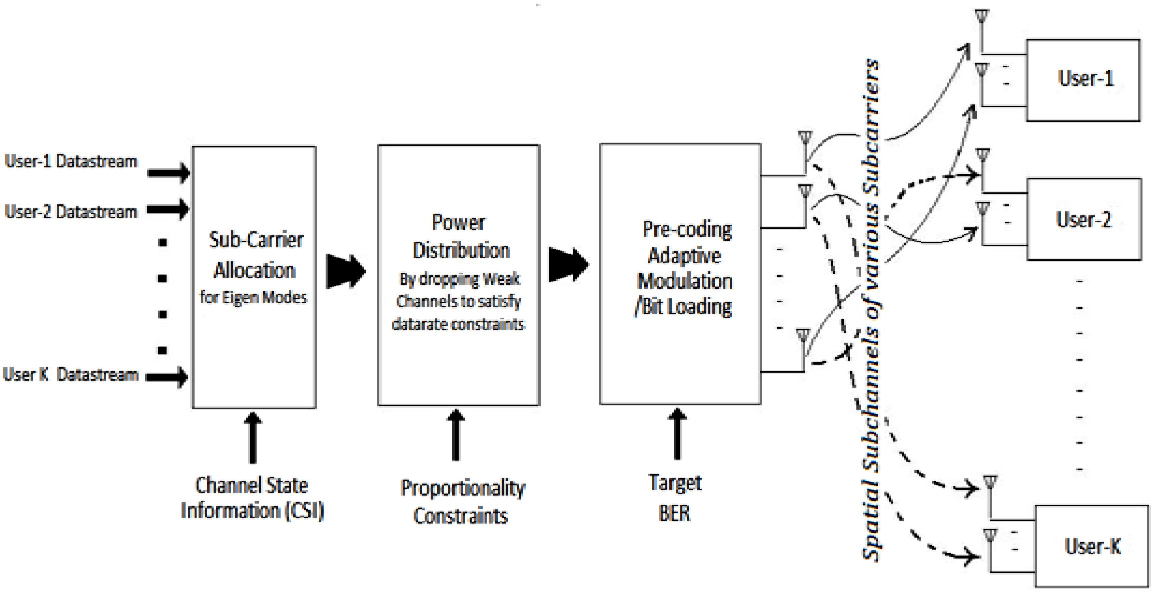

Figure 5.1: Block diagram for an adaptive loading scheme devised for MIMO-OFDMA-SDMA system in downlink scenario.

We assume that the base station is fedback by perfect channel state information from the receiving ends without any error or delay. For N OFDM sub-carriers, the MIMO channel existing between user k and base station at sub-carrier n, can be represented as $\boldsymbol{H}_{k,n}$, (i.e., same as the channel defined in Chapter 3, (3.1)). As discussed earlier after allocating sub-carrier and distributing the total available power, block diagonalization (precoding) technique is used to cancel co-channel multi-user interference. From literature it had been be noted that MIMO channels can be decomposed in to parallel non-interfering SISO channels with the help of singular value decomposition [4]. Therefore based on the Eigen values obtained after decomposition the spatial sub-channels are assigned to various users, for a more detailed description of the proposed scheme please refer Chapter 3. Now that the users are allocated over these spatial channels represented by respective Eigen values, there is a need to perform zero forcing precoding on each sub-carrier before transmitting bits or data over them. The precoding technique facilitates in cancelling out inter-user interference as well as interference resulting from adjacent antennas of the same user. Therefore, we mathematically evaluate expressions for obtaining the precoding matrix that can block diagonalize the users allocated over same sub-channel by zero forcing precoding technique, assuming all the users to be spatially compatible.

We represent the channel matrix ($\boldsymbol{H}_n$) and the precoding matrix ($\boldsymbol{M}_n$) over n^{th} sub-carrier as following,

$$\boldsymbol{H}_n = \left[\boldsymbol{S}_{1,n}^T \quad \boldsymbol{S}_{2,n}^T \quad \dots \quad \boldsymbol{S}_{G,n}^T\right]^T \tag{5.1}$$

$$\boldsymbol{M}_n = [\boldsymbol{M}_1 \quad \boldsymbol{M}_2 \quad \dots \quad \boldsymbol{M}_G] \tag{5.2}$$

where G represents number of users allocated on n^{th} sub-carrier, $(\quad)^T$ is the transpose of given matrix. While $\boldsymbol{S}_{g,n}$ $\forall$ $g\epsilon\{1,2 \dots . G\}$, represents a single-input multiple output channel matrix, i.e., its elements characterize channel gains from the given transmit antenna (assigned to respective user g) of base station to all receiving antennas at user terminal. The maximum number of users that can be assigned over a given sub-carrier in a given time slot must be less than or equal to M_t, (i.e., $\leq$ Total number of transmit antennas at base station). The received signal at sub-carrier n can be written as

$$\boldsymbol{X}_n = \boldsymbol{H}_n\boldsymbol{M}_n\boldsymbol{D}_n + (\boldsymbol{N}_{AWGN})_n \tag{5.3}$$

where $\boldsymbol{D}_n$ represents transmitted signal while $(\boldsymbol{N}_{AWGN})_n$ represents additive white Gaussian noise respectively at n^{th} sub-carrier. The received signal for user g at n^{th} sub $-$ carrier $\forall g \epsilon \{1,2, \dots G\}$, can be written as

$$\boldsymbol{X}_{g,n} = \boldsymbol{S}_{g,n} \sum_{l=1}^{G} \boldsymbol{M}_{l,n} \, \boldsymbol{D}_{l,n} + (\boldsymbol{N}_{AWGN})_{g,n}$$

$$= \boldsymbol{S}_{g,n} \, \boldsymbol{M}_{g,n} \, \boldsymbol{D}_{g,n} + \boldsymbol{S}_{g,n} \, \widetilde{\boldsymbol{M}}_{g,n} \, \widetilde{\boldsymbol{D}}_{g,n} + (\boldsymbol{N}_{AWGN})_{g,n} \tag{5.4}$$

In the above equation $\boldsymbol{M}_{g,n}$, $\boldsymbol{D}_{g,n}$ and $(\boldsymbol{N}_{AWGN})_{g,n}$ represent the precoding matrix, transmitted signal and additive white Gaussian noise of user g at n^{th} sub-carrier. Dimensions of all the matrices in above equation are same as $\boldsymbol{S}_{g,n}$. Whereas $\widetilde{\boldsymbol{M}}_{g,n}$, $\widetilde{\boldsymbol{D}}_{g,n}$ are given by following matrices:

$$\widetilde{\boldsymbol{M}}_{g,n} = [\, \boldsymbol{M}_{1,n} \quad \dots \quad \boldsymbol{M}_{g-1,n} \quad \boldsymbol{M}_{g+1,n} \quad \dots \quad \boldsymbol{M}_{G,n}] \tag{5.5}$$

$$\widetilde{\boldsymbol{D}}_{g,n} = [\, \boldsymbol{D}_{1,n}^{T} \quad \dots \quad \boldsymbol{D}_{g-1,n}^{T} \quad \boldsymbol{D}_{g+1,n}^{T} \quad \dots \quad \boldsymbol{D}_{G,n}^{T}]^{T} \tag{5.6}$$

The zero forcing (ZF) based forcing precoding technique requires $\boldsymbol{S}_{g,n} \, \boldsymbol{M}_{l,n} = 0 \; \forall g \neq l$ such that the interference is eliminated. Therefore, in order to suffice this condition $M_{g,n}$ should be positioned in null space of $\tilde{\boldsymbol{S}}_{g,n}$ which is given by

$$\tilde{\boldsymbol{S}}_{g,n} = [\, \boldsymbol{S}_{1,n}^{T} \quad \dots \quad \boldsymbol{S}_{g-1,n}^{T} \quad \boldsymbol{S}_{g+1,n}^{T} \quad \dots \quad \boldsymbol{S}_{G,n}^{T}]^{T} \tag{5.7}$$

$\tilde{\boldsymbol{S}}_{g,n}$ can also be expressed as following after singular value decomposition as in [26],

$$\tilde{\boldsymbol{S}}_{g,n} = \widetilde{\boldsymbol{U}}_{g,n} \widetilde{\boldsymbol{\Sigma}}_{g,n} \left[\; \widetilde{\boldsymbol{V}}_{g,n}^{(1)} \quad \widetilde{\boldsymbol{V}}_{g,n}^{(0)} \;\right]^{H} \tag{5.8}$$

where $(\quad)^{H}$ stands for conjugate transpose of a matrix. Considering r as the rank of $\tilde{\boldsymbol{S}}_{g,n}$, $\widetilde{\boldsymbol{V}}_{g,n}^{(1)}$ represents the first r- right singular values (RSV's) while $\widetilde{\boldsymbol{V}}_{g,n}^{(0)}$ consists of the last $M_t - r$ RSV's. As $\widetilde{\boldsymbol{V}}_{g,n}^{(0)}$ forms an orthogonal basis for null space of $\tilde{\boldsymbol{S}}_{g,n}$, and the columns of this matrix serve as precoding matrix for block diagonalization of the n^{th} sub-carrier channel [26]. Thus, the precoding matrix is given by

$$\boldsymbol{M}_{g,n} = \widetilde{\boldsymbol{V}}_{g,n}^{(0)} \tag{5.9}$$

Therefore, the downlink system reduces to G parallel non-interfering single user SISO channels at all sub-carriers, with the help of above discussed pre-processing technique. The equivalent independent channel at sub-carrier n for user g can be written as,

$$\boldsymbol{S}_{g,n}^{'} = \boldsymbol{S}_{g,n}\boldsymbol{V}_{g,n}^{(0)} \tag{5.10}$$

Therefore the channel at n^{th} sub-carrier can be expressed as

$$\boldsymbol{H}_{n}^{'} = \begin{bmatrix} \boldsymbol{S}_{1,n}^{'} \\ \vdots \\ \boldsymbol{S}_{g,n}^{'} \\ \vdots \\ \boldsymbol{S}_{G,n}^{'} \end{bmatrix} = \begin{bmatrix} s_{1,n}^{'} & 0 & 0 & \dots & 0 \\ & \ddots & & & \\ 0 & \dots & s_{g,n}^{'} & \dots & 0 \\ & & & \ddots & \\ 0 & & 0 & \dots & s_{G,n}^{'} \end{bmatrix} \tag{5.11}$$

where $s_{g,n}^{'}$ stands for non-zero term of matrix $\boldsymbol{S}_{g,n}^{'}$, which represents the equivalent independent channel for user g at sub-carrier n.

5.1.2 Adaptive Modulation – Bit loading for MIMO-OFDMA-SDMA

With the help of above discussed spatial preprocessing, a set of non-interfering parallel independent spatial sub-channels are abstracted from multi-user MIMO channels. The SNR of user g at sub-carrier n on each spatial channel can be calculated as,

$$\gamma_{g,n} = \frac{p_{g,n}\ s_{g,n}^{'}}{\sigma_{g,n}^{2}} \tag{5.12}$$

where $p_{g,n}$ and $\sigma_{g,n}^{2}$ is the power allocated and noise power of user g on n^{th} sub-carrier over the assigned spatial sub-channel respectively. Once the SNR's are computed for all users over allocated spatial sub-channels the type of modulation and number of bits to be transmitted over these channels is decided based on target bit error rate requirement for the system. For a square M-QAM modulation scheme with unitary mean energy the number of bits to be transmitted over allocated spatial sub-channel is given by following expression which was approximately derived by Goldsmith et.al in [61],

$$b_{g,n} = \log_2\left[1 - \frac{1.5\,\gamma_{g,n}}{\ln(5\,\mathrm{BER}_{\mathrm{target}})}\right] \tag{5.13}$$

where $b_{g,n}$ denotes the number of bits per symbol that are allocated over the assigned spatial sub-channel of user g over sub-carrier n. $\mathrm{BER}_{\mathrm{target}}$ is the required or target BER of the system or a user in particular in order to achieve the desired performance of the system, whilst satisfying all the QoS constraints. In our algorithm for MIMO-OFDMA-SDMA system, we set the target BER as 10^{-3} for each user over each spatial sub-channel. Such that the average BER of the whole system is less than 10^{-3}. Based on the available modulation types or schemes the value of $b_{g,n}$ obtained is truncated to the nearest available integer value.

$$\tilde{b}_{g,n} = trunc(b_{g,n}) \in \{0, 1, 2, 3, 4, 5, 6, 7, 8\} \tag{5.14}$$

The values $0, 1, 2, 3, 4, 6$ and 8 correspond to no bit transmission, BPSK, QPSK, 8-PSK, 16-QAM, 32-QAM, 64-QAM, 128-QAM, and 256-QAM respectively. Therefore, the random input bit sequences are transmitted over spatial sub-channels and are modulated according to the number of bits allocated - choice of modulation scheme.

In this adaptive loading algorithm, a modulator is needed to change the set of bits into a complex number that represents the elements of signal constellation corresponding to selected modulation type. Therefore a modulator takes input as a set of bits and gives output as constellation symbols. It is also assumed that the modulator has a finite set of rates available which instead means that only a finite set of constellations exist or are presented for modulation. Also to offer robustness alongside bit errors, Gray coded constellation sets are deployed for available modulation orders. Gray coding guarantees that if a symbol error occurs, the decoder chooses an adjacent symbol to that which transmitter anticipated to be decoded, as a result there is only a single bit error [62]. A demodulator in this scheme is expected to demodulate the received bit sequences at the receiver; to simplify the demodulator design demodulation is performed using zero forcing approach.

5.1.3 Adaptive Scheme Proposed for MIMO-OFDMA-SDMA system

We have already discussed the algorithm in preceding Sections but a briefer, more summarized discussion of the algorithm seems necessary for the readers to get an overview of the steps carried out in allocating resources and adapting to various modulation modes. The proposed scheme attempts to maximize the achievable bit error performance of each individual user as well as whole system by adaptively varying the modulation schemes used for transmission. In this proposed adaptive modulation resource allocation algorithm for MIMO-OFDMA-SDMA systems, available transmit power at the base station and noise PSD of the system the scheme proposed in Chapter 3 is used to allocate spatial sub-channels (based on eigen values obtained after SVD) to appropriate users. Once the sub-channels are allocated to users then as per the algorithm proposed in Chapter 3 the weak sub-channels are dropped in order to satisfy the proportionality rate constraints. Then the available transmission power is distributed over the available spatial sub-channels based on water filling technique as discussed earlier in Chapter 3.

Now that power is allocated to each spatial sub-channel, based on the signal to noise ratio value of each spatial sub-channel the number of bits to be transmitted over each channel is decided using (5.13) and (5.14), considering target BER as 10^{-3}. Hence while the type of modulation scheme to be used is decided accordingly. However before transmitting the modulated input sequences over these spatial sub-channels, it is necessary to perform preprocessing as discussed in Section 5.1.1 in order to block diagonalize the spatial sub-channels of the users allocated over same sub-carrier such that the interferences resulting from other users and other antennas can be suppressed by zero-forcing precoding technique. Thereafter, modulated random input data sequences are transmitted over these pre-coded channels based on bit allocations for each channel. The received signal at each user is then demodulated using a zero forcing approach and compared to the transmitted signal to detect the BER performance of each user as well as the whole system.

Following is a step by step explanation of the algorithm, after the sub-carrier allocation and power distribution is performed based on proposed scheme in Chapter 3,

Adaptive Modulation Algorithm

1. Compute signal to noise ratios for all allocated spatial sub-channels by (5.12).
2. Compute number of bits to be transmitted on each sub-channel with the help of (5.13).
3. Round off and truncate the value obtained in previous step, as in (5.14) to nearest value in set {0, 1, 2, 3, 4, 5, 6, 7 and 8} to decide on the type of modulation scheme to be selected corresponding to the available M-QAM modulation orders.
4. Before transmitting modulated input data sequences over the spatial sub-channels, the users allocated over a sub-carriers spatial channels are block diagonalized by zero forcing precoding technique described in Section 5.1.1.
5. Eqn. 5.11 gives the pre-coded sub-carrier channel over which the modulated input sequences are transmitted.

6. At each users terminal over the allocated spatial sub-channel the received signal, (i.e., given by (5.3)) is detected and demodulated to be compared with the transmitted input sequence to measure the bit error performance of whole system.

For a given SNR of the system the average BER of every user over all assigned spatial sub-channels is calculated and plotted to review the overall systems BE performance. The overall systems throughput can also be evaluated as

$$C = \frac{1}{N}\sum_{n=1}^{N}\sum_{l=1}^{G_n}\tilde{b}_{l,n} \tag{5.15}$$

where G_n represents number users allocated over spatial sub-channels of n^{th} over sub-carrier. The results obtained are discussed and compared in final Section of this Chapter.

5.2 Adaptive Modulation - Bit Loading Scheme for V-BLAST based MIMO-OFDMA systems

In this Section we propose an adaptive modulation scheme for V-BLAST detection based MIMO-OFDMA system. In contrast to the ZF precoding technique used in previous Section for devising an adaptive modulation scheme, in this Section we make use of V-BLAST algorithm based ZF detection technique to perform adaptive modulation and demodulation. The results obtained are then compared to the scheme proposed in previous Section. The details about the V-BLAST encoder and decoder have been discussed briefly in the previous Chapter. It is well established from the literature that V-BLAST based ZF detection technique with successive interference cancellation can significantly improve the systems performance with low implementation complexity [59]. A V-BLAST technique and an optimal resource allocation strategy for MIMO-OFDMA system can achieve a breakthrough with increase in spectral efficiency and improved bit error performance [63]. In zero-forcing and successive interference cancellation based V-BLAST detection scheme the nulling process creates estimates of the transmitted signal to combat interference resulting from multiple-access. Then the received layer corresponding to detected sub-stream is removed and the process continues until all the streams are detected [64].

5.2.1 System Model for V-BLAST based MIMO-OFDM

We assume a system similar to that of a MIMO-OFDMA system described in Chapter 3, where a downlink scenario is considered with K geographically dispersed users, each user having M_r receiving antennas while the base station being equipped with M_t transmit antennas. Therefore the channel matrix of user k over sub-carrier n is same multi-dimensional matrix as the one described in Chapter 3, (i.e., (3.1)), and can be denoted by $H_{k,n}$. It is also expected that the receiver has perfect CSI, i.e., each user sends an error free feedback without any delay about channels condition to the base station. Thereafter the base station allocates sub-carriers and distributes power to all users while adhering to all the constraints. The incoming data streams are divided into multiple sub streams and each antenna is supposed to transmit symbols independently. The following Figure shows a block diagram representation of the allocation process for the proposed scheme. After the sub-carrier allocation and power distribution, the input data streams are converted into parallel data streams and transmitted through available transmit antennas at the base station. At the receivers end V-BLAST receiver detects and demodulates the received streams based on ZF detection and interference nulling criteria.

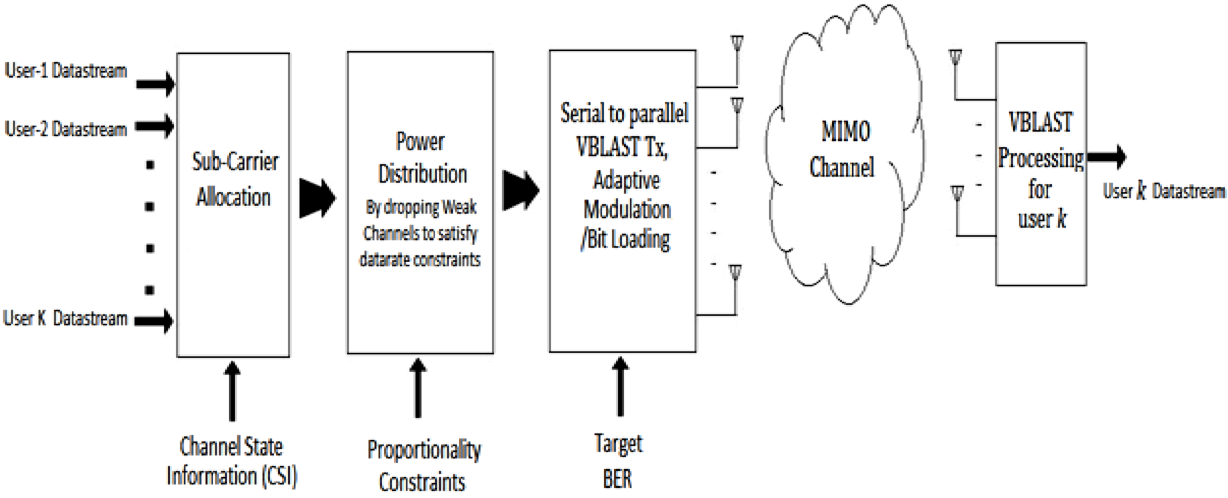

Figure 5.2: System Model for MIMO-OFDMA based on ZF V-BLAST detection technique.

It is established from the literature that the performance of spatial multiplexer with linear receiver depends on minimum SNR induced by available set of transmit antennas [59]. This implies that the transmitted symbol having least post-detection SNR dominates systems error performance.

For a given sub-carrier n, in a ZF receiver the post-processing SNR of worst n^{th} substream can be represented as following [54],

$$\gamma_{n,min}^{ZF} \geq \lambda_{min}^{ZF}(\boldsymbol{H}_n).\frac{P_t}{N_0} \tag{5.16}$$

where $\lambda_{min}^{ZF}(H_n)$ is the minimum singular value of channel matrix - $\boldsymbol{H}_n$, $\gamma_{n,min}^{ZF}$ is minimum post-processing SNR of n^{th} spatial sub-channel for ZF receiver, N_0 is the noise power and P_t is the average transmit power per antenna. Therefore, (5.14) confirms that the performance of linear receivers improves as the minimum singular value of channel increase. In [59], it is experimentally shown that the value of λ_{min} is influenced by two factors which are fading correlation of channel matrix $\boldsymbol{H}_n$ and average channel gain of channel matrix $\boldsymbol{H}_n$. The value of λ_{min} is larger for a low correlated channels when compared to high correlated channels. On the other hand channel matrix having higher average channel gain has higher minimum singular value when compared to channels having low average gain. Therefore, the minimum singular value (λ_{min}) can be taken as criteria to allocate MIMO channels to appropriate users [59], as both the factors can be considered simultaneously.

The proposed scheme in Chapter 3 is modified to allocate sub-carriers to the users based on minimum singular values of channels existing between base station and users. Therefore instead of breaking down the MIMO channel matrix into non-interfering parallel SISO channels by singular value decomposition and assigning them to users, all the MIMO channels between a user and base station over all sub-carriers can be represented by minimum singular value ($\lambda_{min}(\boldsymbol{H}_n)$). This can be used as a suitable parameter to assign n^{th} sub-carrier to k^{th} user. Based on these minimum singular values the best sub-carrier is decided for each user by means of same resource allocation algorithm proposed in Chapter 3. Thereafter the total available transmit power is also distributed among users as well using the same algorithm.

5.2.2 Adaptive Modulation- Bit Loading for V-BLAST-OFDMA system

In this scheme we adapt to various modulation schemes based on the SNR of the channel from BPSK to 256QAM. The threshold switching SNR levels are acquired experimentally such that the bit error rate is always less than 10^{-3}, as there is no closed form expression derived for such systems in literature as is available for MIMO-OFDMA-SDMA system. The use of adaptive modulation scheme can provide more data rates at high SNR.

At first we conduct experiments by considering a MIMO channel that exists between a user and base station. This channel matrix ($\boldsymbol{H}$) is supposed to be composed of samples drawn from quasi-stationary Rayleigh fading random processes that are assumed to remain constant during transmission of a complete data block. As signals in a scattering environment appear to be uncorrelated, it is assumed that complex channel gains between each transmit receive antenna pair are independent and identically distributed complex Gaussian random variable with zero-mean and unit variance. The incoming data stream to be transmitted to the user, at the base station is demultiplexed into M_t sub-streams and is transmitted through M_t transmit antennas. All the transmit antennas transmit in the same frequency channel in same timeslot simultaneously.

The data stream to be transmitted is given by $\boldsymbol{X} = \left[x_1 \;\; x_2 \; \ldots . \; x_{M_t}\right]^T$, where x_{M_t} is the data intended for M_t^{th} transmit antenna. The received signal at the user end can be expressed as

$$\boldsymbol{Y} = \boldsymbol{H}\,\boldsymbol{X} + \boldsymbol{N}_{AWGN} \tag{5.17}$$

where $\boldsymbol{N}_{AWGN}$ is the additive white Gaussian noise and is given by $\boldsymbol{N}_{AWGN} = \left[n_1 \;\; n_2 \; \ldots . \; n_{M_r}\right]^T$ where each element represents the noise at respective receive antenna.

The elements of $\boldsymbol{N}_{AWGN}$ are complex Gaussian distributed with zero mean and variance N_0. The received signal is of the form $\boldsymbol{Y} = \left[y_1 \ y_2 \ldots . \ y_{M_r}\right]^T$.

The task of a V-BLAST receiver is to estimate the vector $\boldsymbol{X}$ when $\boldsymbol{Y}$ and $\boldsymbol{H}$ are known. The detection is done sequentially in layers with ZF-SIC receiver. To detect the symbol of m_t^{th} transmission layer the receiver first nulls the interference from resulting from other layers with ZF technique, then estimates the data. Thereafter the receiver uses SIC technique to cancel out the effect of detected layer from the received signal to nullify its interference on the layers yet to be detected. The general form of the modified received symbol vector after detection of m_t^{th} layer is given by [65] as,

$$\boldsymbol{Y}_{m_t} = \sum_{j=m_t+1}^{M_t} h_j x_j + \left\{ \boldsymbol{N}_{AWGn} + \sum_{j=1}^{m_t} h_j \left(x_j - \tilde{x}_j\right) \right\} \tag{5.18}$$

where h_j represents the j^{th} column vector of the channel matrix $\boldsymbol{H}$, $\tilde{x}_j$ denotes detected symbol of j^{th} layer. The term $\sum_{j=1}^{m_t} h_j \left(x_j - \tilde{x}_j\right)$ is the interference from erroneous decisions of previously detected layers that can have a serious impact on the systems performance. Once the received signal is detected at the receiver it is then compared to the transmitted signal to know the bit error performance of the system. Therefore, experiments, (i.e., using MATLAB simulation) are conducted on the described system to know the BE performance of the ZF-SIC based V-BLAST detection scheme assuming the transmitted data to be modulated by different modulation types (M-QAM and M-PSK) independently. The obtained results are then used to determine the threshold SNR levels for a target BER of 10^{-3} which help in switching modulation types in order to adapt to the varying channel conditions, i.e., used to perform adaptive modulation – bit loading on the given channel.

5.2.3 Adaptive Scheme Proposed for V-BLAST based MIMO-OFDMA

Although the adaptive modulation procedure followed by the algorithm proposed for MIMO-OFDMA system (with V-BLAST based ZF-SIC detection) is clear from previous Sections, yet we summarize the algorithm again and brief up on the steps performed in this Section. The adaptive loading resource allocation scheme devised can be discussed in three steps namely sub-carrier allocation, power allocation and adaptive modulation-bit loading.

For sub-carrier allocation, it is assumed that the total power available at base station is distributed equally over all available sub-channels. The rate of each user in a given sub-channel is calculated using following MIMO capacity calculation [54],

$$C_k^{MIMO} = \sum_{n \, \epsilon \, \Omega_k} \sum_{l=1}^{r} \frac{1}{N} \log_2 \left(1 + \frac{p_t}{M_t N_0} \lambda_{k,n,l}\right) \tag{5.19}$$

where Ω_k represents the set of sub-carriers allocated to the given user, r denotes the rank of the MIMO channel over n^{th} sub-carrier, $\lambda_{k,n,l}$ is the Eigen value of l^{th} spatial channel of sub-carrier matrix and p_t is the transmit power each sub-carrier after assumed equal distribution. The algorithm used to allocate sub-carriers is briefly described below

Sub-carrier Allocation:

1. *Initialization:* C_k*=0,* $\Omega_k = \emptyset$, for all *k= 1,2,….K* and *S={1,2….N}.*
2. *for k=1 to K*
    - *i.* Find n satisfying $\left|\lambda_{\min(k,n)}\right| \geq \left|\lambda_{\min(k,v)}\right|$ for all $v \, \epsilon \, S$.
    - *ii.* Let $\Omega_k = \Omega_k \cup \{n\}, S = S - \{n\}$, update R_k based on (5.19).
3. *While* $S \neq \emptyset$
    - i. *Find k* such that it satisfies $C_k / \gamma_k \leq C_w / \gamma_w$ for all $1 \leq w \leq K$.

ii. After computing k, *find* n satisfying $\left|\lambda_{\min(k,n)}\right| \geq \left|\lambda_{\min(k,v)}\right|$ for all $v \epsilon S$.

iii. After computing n and K, let $\Omega_k = \Omega_k \cup \{n\}, S = S - \{n\}$, update C_k based on (5.19).

The above procedure is repeated until all the sub-carriers are allocated to existing users in MIMO-OFDMA system. Once the sub-carriers are allocated the available power is distributed over the allocated sub-carriers to users using the same procedure as described in Chapter 3, Section 3.2.2. Now, that sub-carrier and power allocations have been performed these assignments are taken as reference to decide on the modulation type to be used on each sub-carrier. Following is a brief discussion about the adaptive loading algorithm, after the sub-carrier allocation and power distribution is done.

Adaptive Modulation Algorithm

To reduce complexities at the receivers end, same number of bits, (i.e., modulated using same modulation type) are transmitted from all the transmit antennas at base station for a given user k over sub-carrier n.

1. Compute the minimum SNR among the base station transmit antennas for user k over sub-carrier n,

$$\gamma_{\min(k,n)} = \frac{p_t \ \lambda_{\min\,(k,n)}}{N_0} \tag{5.20}$$

   Using (5.20), the minimum SNR values are computed for all the allocated sub-carriers.

2. Compute number of bits to be transmitted, modulation type to be used on each sub-carrier with the help of threshold levels obtained from the

experiments performed on the single user system described in Section 5.2.2, considering various modulation techniques.

3. Subsequently random set of input data sequences are transmitted over spatial sub-channels of allocated sub-carrier after being modulated by the selected modulation scheme.
4. At each user’s terminal over the allocated sub-carrier the received signal, (i.e., given by (5.18)) is detected using ZF-SIC based V-BLAST detection scheme and is demodulated to be compared with the transmitted input sequence to measure the bit error performance over the spatial channels allocated under the influence of an additional constraint, i.e., target BER constraint.

For a given SNR of the system the average BER of every user is evaluated and plotted to review the overall systems BE performance. The overall systems throughput can be computed as following

$$C = \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{r} b_{k,n,l} \tag{5.21}$$

where $b_{k,n,l}$ represents number of bits allocated over respective spatial sub-channels. The results obtained are discussed and compared in results and discussion Section of this Chapter.

5.3 Results and Discussion

In this Section the results of the proposed adaptive loading schemes are compared and analyzed. The simulation results are obtained for a system consisting of 16 active users, 64 sub-carriers with a total transmit power of 1 Watt, and a total bandwidth of 1MHz. The results are obtained while varying transmit SNR from 0 to 50dB based on which the noise power and noise PSD of the system are calculated, but the results are plotted against average SNR of the system.

Table 5.1: Parameters used for obtaining simulation results for adaptive bit loading schemes.

Total transmit Power	1Watt
Number of Sub-carriers	64
Systems Bandwidth	1MHz
Number of Users in system	16
Number of Transmit antennas	4
Number of Receive antennas	4
Target BER	10^{-3}

The two proposed schemes in Sections 5.1 and 5.2 are referred to as ZF precoding adaptive modulation (AM) scheme and ZF-SIC based V-BLAST AM scheme respectively. For the ZF precoding AM scheme the decision on the type of modulation scheme to be used and number of bits to be transmitted over spatial sub-channel is taken with the help of (5.14). The available modes of modulation for ZF precoding AM scheme are - no bit transmission, BPSK, QPSK, 8-PSK, 16-QAM, 32-QAM, 64-QAM, 128-QAM, and 256-QAM (Gray coding is used for bit mapping of available M-QAM constellations).

Whereas for ZF-SIC based V-BLAST AM scheme a set of experiments are conducted to determine the threshold values for adaptive modulation switching. For the system described in Section 5.2.2, it is considered that the base station has four transmit antennas as well as the user has four receive antennas, resulting in a 4x4 independent MIMO channel. At the users end ZF-SIC based V-BLAST detection technique is used to detect the transmitted symbols or bits. While varying the channels SNR continuously with changing noise conditions the bit error rate performances of the system are recorded for M-PSK and M-QAM modulation schemes respectively.

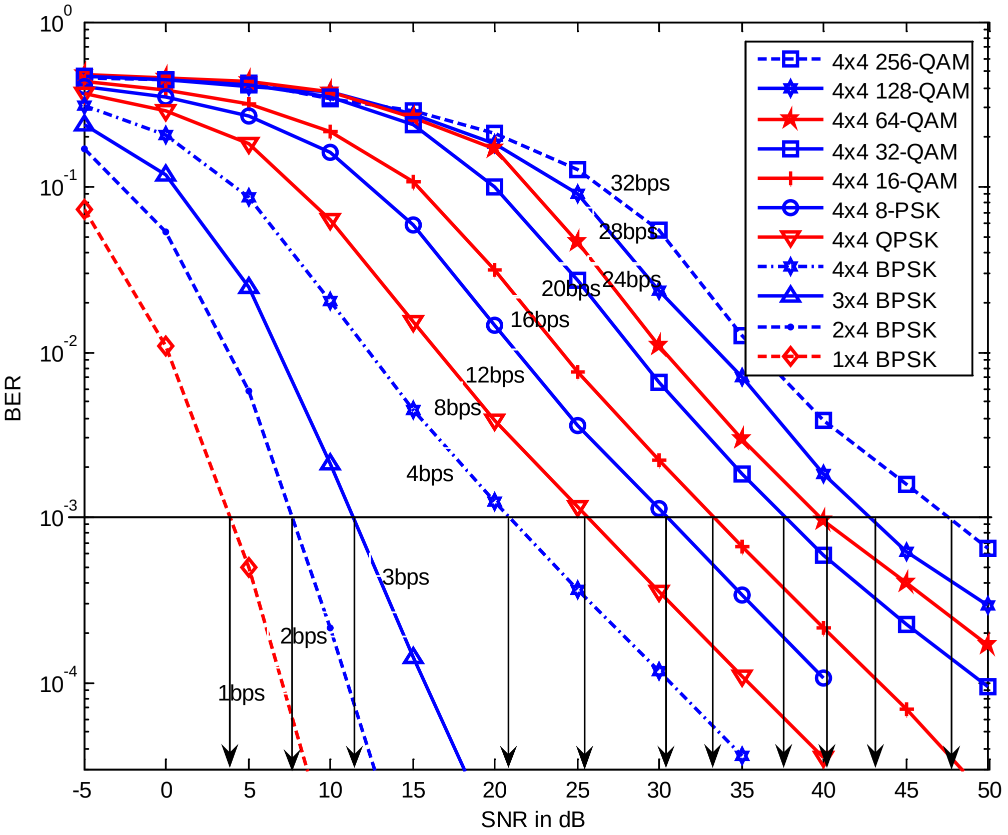

Figure 5.3: BER performance of various M-PSK and M-QAM schemes for 4x4 MIMO-OFDMA system based on ZF-SIC V-BLAST detection technique.

The BER performances of various modulation techniques are plotted on one graph as in Figure 5.3, in order to determine the threshold SNR values that identify switching levels between various modulation modes available. As can be seen in Figure, for low bit rates like 1 bits per second (bps), 2bps and 3bps modulation schemes like 1x4 BPSK, 2x4 BPSK and 3x4 BPSK are used respectively. This can also be termed as adaptive layer- adaptive modulation but it is used only for low bit rates like 1, 2 or 3 bps. The following table gives an overview of the various modulation modes available for ZF-SIC based V-BLAST AM scheme, whilst specifying the determined threshold SNR values.

Table 5.2: Modulation Modes for 4x4 MIMO systems using V-BLAST scheme

Mode	M_t	M_r	MIMO order	Modulation Type	Rate(bps)	Threshold (dB)
Mode 0	-	-	-	No Transmission	0	< 4
Mode 1	1	4	1x4	BPSK	1	< 7.5
Mode 2	2	4	2x4	BPSK	2	< 12.5
Mode 3	3	4	3x4	BPSK	3	< 21
Mode 4	4	4	4x4	BPSK	4	< 25.5
Mode 5	4	4	4x4	QPSK	8	< 30.5
Mode 6	4	4	4x4	8-PSK	12	< 34
Mode 7	4	4	4x4	16-QAM	16	< 37.5
Mode 8	4	4	4x4	32-QAM	20	<40
Mode 9	4	4	4x4	64-QAM	24	< 43
Mode 10	4	4	4x4	128-QAM	28	< 47
Mode 11	4	4	4x4	256-QAM	32	> 47

In following paragraphs we discuss on the spectral efficiency and bit error performance based on MATLAB simulation results obtained for the proposed schemes. The graphs are plotted against the average SNR values of active users in the system.

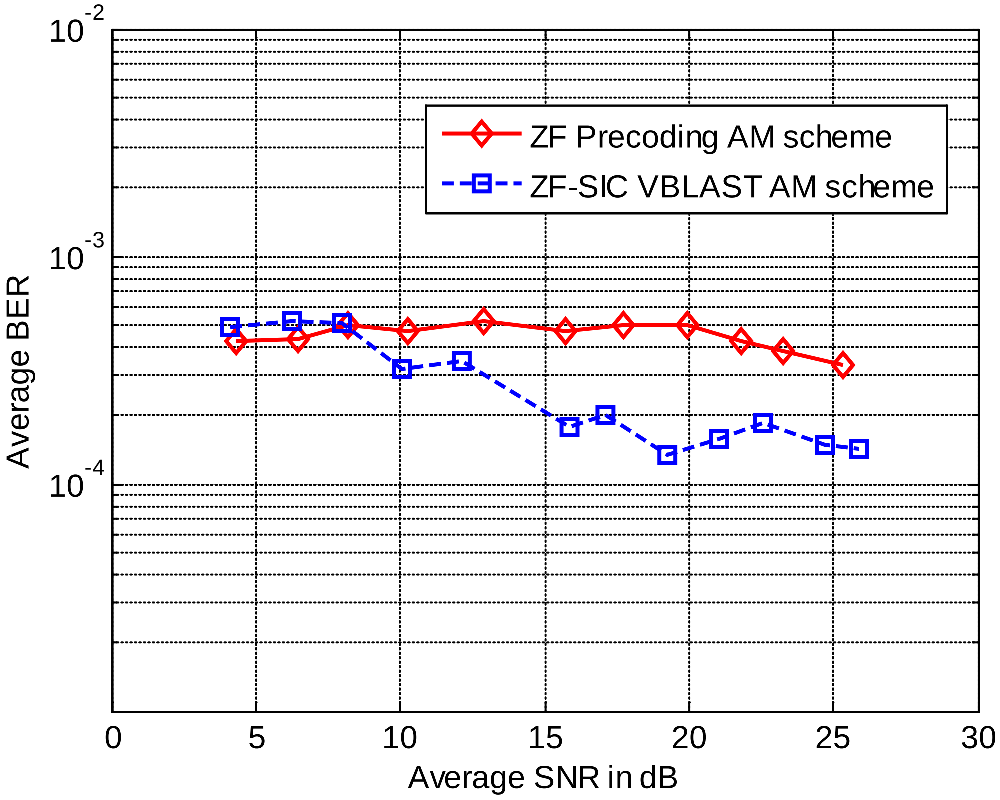

Figure 5.4: Average SNR in dB versus Average BER for a Target BER of 10^{-3}.

The average BER performances of active users for ZF precoding based AM scheme and ZF-SIC based V-BLAST AM scheme are compared in Figure 5.4, against average SNR values. The results show that both the schemes were successful in maintaining the average BER of the system less than 10^{-3} which was our systems target BER. Due to increasing computational complexities at high SNR's, BER rate curves were obtained at 10^3 Monte Carlo iterations. More number of Monte Carlo simulations will certainly smooth out the BER curves further. From Figure it is apparent that the ZF-SIC based V-BLAST detection AM scheme provides better BER performance than ZF precoding AM scheme. This is because the ZF-SIC based detection technique has the characteristics whose performance approaches that of minimum mean squared error detection technique at high SNR's, as was analyzed by [66]. It is eminent from literature that ZF-SIC based V-BLAST detection scheme has improved BER performance when compared to other ZF detection schemes [66, 67]. Whereas for ZF precoding AM scheme at low SNR's an inverted channel at transmitters end (as done by transmit ZF precoder) increases the noise power drastically thereby causing the BER performance to be degraded [68]. The average BER performance of ZF precoding AM scheme starts improving at higher SNR's (>20dB), but nevertheless it doesn't performs better than ZF-SIC based V-BLAST AM scheme. Despite of these adversities, the adaptive modulation-bit loading nature of the schemes maintains the BER performance of users less than the target BER under all conditions by adjusting the transmission rate and selecting appropriate modulation modes.

In Figure 5.5, the sum capacity for ZF precoding based AM scheme and ZF-SIC based V-BLAST AM scheme are compared. The capacities are computed with the help of (5.15) and (5.21).

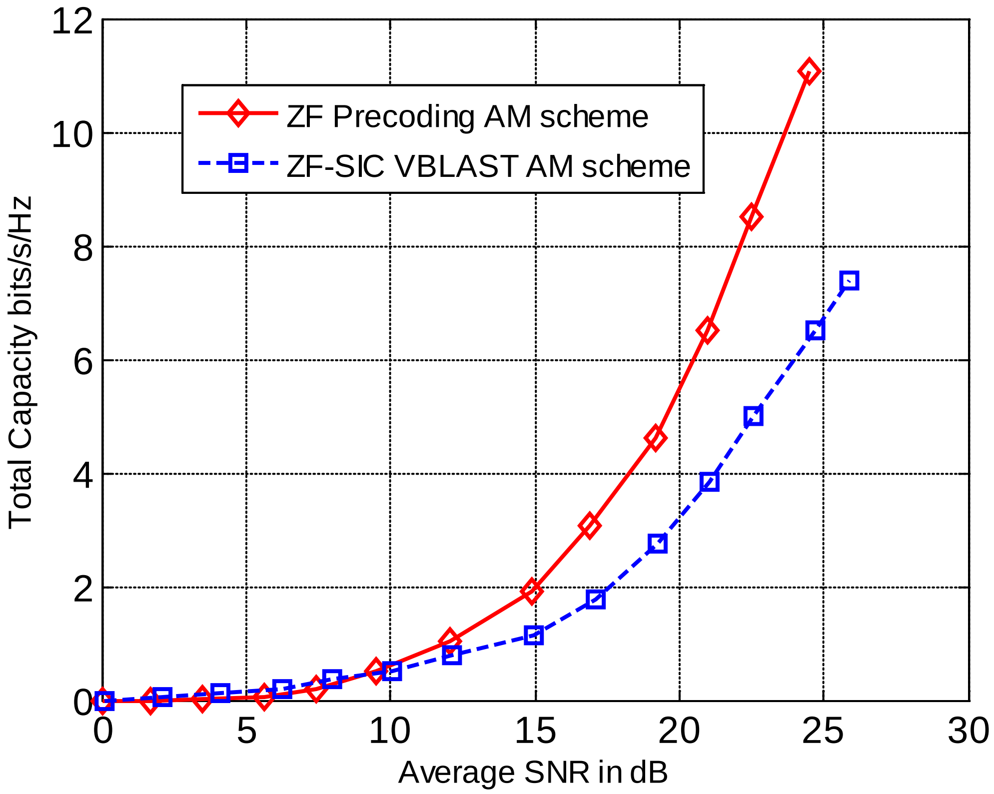

Figure 5.5: Average SNR in dB versus Total systems capacity in bps/Hz for Target BER of 10^{-3}.

In ZF-precoding AM scheme the modulation type and bits to be transmitted are decided on the channel conditions of each spatial sub-channel independently, thereby each transmit antenna transmits at different rate. Where as in ZF-SIC based V-BLAST AM scheme the modulation type and number of bits to be transmitted over all the transmit antennas is decided based on the channel conditions of weakest sub-channel, (i.e., minimum singular value), thus all transmit antennas transmit at same rate. Therefore, ZF-precoding AM scheme outperforms at higher SNR's when compared to ZF-SIC based V-BLAST AM scheme, while adaptation to modulation modes and allocation of bits depend on thresholds obtained for a target BER of 10^{-3}. On comparing the simulation results obtained in Figure 5.4 and Figure 5.5, a trade-off model between average BER performance of the system and spectral efficiency can be inferred. Hence while depending on the BER, throughput and other QoS requirements a decision can be made among the two devised schemes.

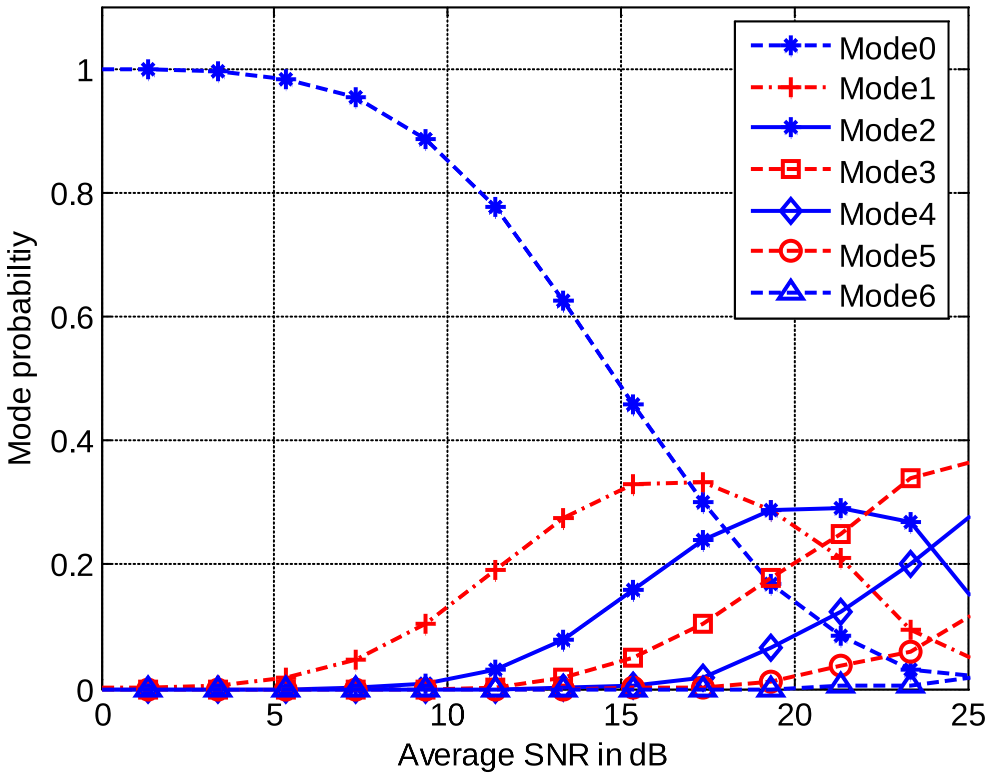

Figure 5.6: Mode probabilities for ZF precoding AM scheme at a Target BER of 10^{-3}.

In the ZF precoding based adaptive modulation scheme proposed for MIMO-OFDMA-SDMA systems, we consider the available modulation modes - no bit transmission, BPSK, QPSK, 8-PSK, 16-QAM, 32-QAM, 64-QAM, 128-QAM, and 256-QAM as Mode0, Mode1, Mode2, Mode3, Mode4, Mode5, Mode6, Mode7 and Mode8 respectively. For these defined modes the mode probabilities are plotted against the average SNR in Figure 5.6. The Figure gives a clear idea with regards to how the modes are adapted based on changing channel conditions. For instance, at average SNR of 15dB the probability that mode0 is selected is 0.46, probability that mode1 is selected is 0.32, probability that mode2 is selected is 0.17 and probability that mode3 is selected is 0.05.

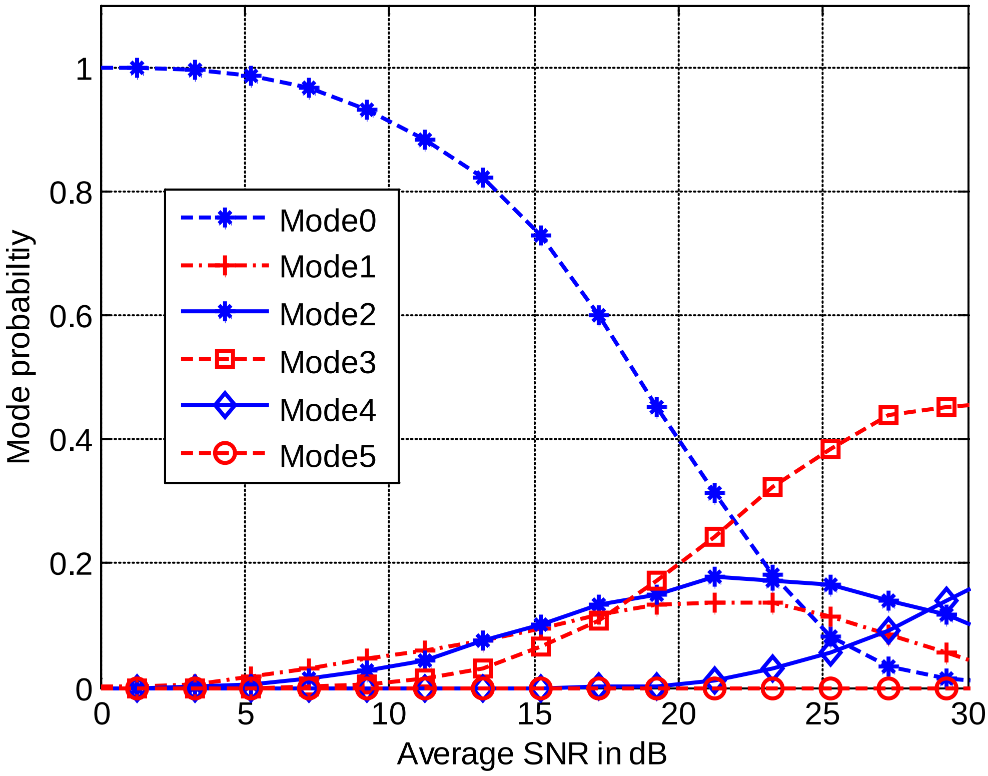

Figure 5.7: Mode probabilities for ZF-SIC V-BLAST AM scheme at a Target BER of 10^{-3}.

For ZF-SIC based V-BLAST adaptive scheme for MIMO-OFDMA systems based on available transmission schemes modes are already defined in table 5.2. For these defined modes the mode probabilities are plotted against the average SNR in Figure 5.7. The Figure gives a clear idea with regards to how the modes are adapted based on changing channel conditions.

5.4 Conclusions

In this chapter, we proposed two new adaptive modulation schemes as an extension to the scheme devised in Chapter 3. Firstly an adaptive modulation resource allocation scheme for multi-user MIMO-OFDMA-SDMA systems in a downlink scenario. Secondly, an adaptive resource allocation scheme for MIMO-OFDMA system, using V-BLAST algorithm implementation based on ZF detection with symbol cancellation in contrast to the MIMO-OFDMA-SDMA scheme which employs precoding. With the mathematical expressions and matrices the whole process of ZF-precoding or block diagonalization of a sub-carrier was explained for SDMA systems. We then analyzed these schemes in a multi-user downlink transmission scenario. Our investigations reveal that the system using a ZF precoded adaptive modulation scheme has better spectral efficiency than ZF-SIC based V-BLAST AM scheme.

Chapter 6

Conclusion and Future Research

In this Chapter, we summarize the works accomplished and the contributions made in this thesis. We also discuss on the possible future research for the thesis, with general ideas that can further enhance the scheme.

6.1 Conclusions

We have successfully proposed a resource allocation algorithm for MIMO-OFDMA systems that performs sub-carrier allocations and optimal power distribution, achieving high spectral efficiency and strict level of proportional fairness among users. We also came up with an algorithm that is able to perform better in terms of overall systems spectral efficiency but wasn’t able to achieve acceptable fairness in diverse conditions. Thereby, a typical tradeoff was observed between overall system efficiency and the level of proportional fairness among users.

Later on, we studied the performance of the proposed algorithm when subjected to practical MIMO schemes that provide practical means to accomplish the advantages provided by MIMO systems like V-BLAST, STBC and MLSTBC. From this performance analysis we could conclude that in a MIMO-OFDMA scenario, at high SNR's V-BLAST scheme has higher spectral efficiency. While MLSTBC scheme is able to perform in a better manner in terms of overall systems spectral efficiency at low outage probabilities and low, moderate SNR's. We were also able to deduce that, MLSTBC scheme has more number of layers than STBC, and is more power proficient even in multi-user access scenario when compared to V-BLAST scheme.

We also devised two adaptive modulation – bit loading schemes in previous Chapter namely ZF precoding adaptive modulation scheme for MIMO-OFDMA-SDMA systems and ZF-SIC based V-BLAST adaptive modulation scheme for MIMO-OFDMA systems. The adaptation criterion for both the schemes was set at a target BER of 10^{-3}, based on which the threshold SNR's for switching modulation modes were derived. Simulation results of these schemes elucidate trade-off between the average BER performance of the system and sum capacity of the system.

6.2 Future Research

There are some significant additions that can be done in the proposed resource allocation algorithm to reduce the complexities and cost of implementation for MIMO-OFDMA systems. One such technique is to make use of antennas selection criterions found in literature. The main drawback of employing multiple antennas is the increase in complexity and implementation cost, as each antenna is accompanied with a complete set of RF circuitry. Therefore, Antenna selection is a technique that can effectively resolve this complexity issue, while making best possible efforts to take full advantage of multiple antennas deployed at transmitter and receiver. The main aim of antenna selection is to select only a subset of antennas available at the transmitter, or receiver or both, in order to reduce the systems complexity. There are various antenna selection criterions found in literature, some of which aim at maximizing the channel capacity, i.e., Capacity-based antenna selection criteria, while some concentrate on maximizing the received SNR, i.e., Energy-based antenna selection criteria.

In this thesis, a major assumption was made with respect to CSI. It was assumed that the transmitter has complete and perfect knowledge about the CSI, in general referred to as perfect CSI. As we know that in practice it is highly impossible to have perfect CSI at the transmitter end. On the other hand, with limited channel state information at the transmitter the performance of ZF-precoding decreases depending on the accuracy of CSI. ZF-precoding requires the significant feedback overhead with respect to SNR so as to achieve the full multiplexing gain. Therefore scenarios where transmitter has unsynchronized CSI, partial CSI or no CSI can be considered to resolve issues concerning practical implementation of the resource allocation algorithm.

Nomenclature

AM	Adaptive Modulation.
AWGN	Additive White Gaussian Noise.
BER	Bit Error Rate.
BPSK	Binary Phase Shift Keying.
BS	Base Station.
CNR	Channel to Noise Ratio.
CSI	Channel State information.
D-BLAST	Diagonal Bell Laboratories Layered Space-Time.
DLL	Data Link layer.
FDM	Frequency Division multiplexing.
H-BLAST	Horizontal Bell Laboratories Layered Space-Time.
MAC	Medium Access Control.
MIMO	Multiple-Input Multiple-Output.
MLSTBC	Multi-Layered Space Time Block Codes.
MRC	Maximum Ratio Combining.
MUI	Multi-User Interference.
OFDM	Orthogonal Frequency Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
PHY	Physical Layer.
PSK	Phase Shift Keying.
QAM	Quadrature Amplitude modulation.
QoS	Quality of Service.

QPSK	Quadrature Phase Shift keying.
RF	Radio Frequency.
RSV	Right Singular Values.
SDMA	Space Division Multiple Access.
SER	Symbol Error Rate.
SGINC	Serial Group Interference Nulling and Cancellation.
SIC	Successive Interference Cancellation.
STBC	Space Time Block Code.
STTC	Space Time Trellis Code.
SVD	Singular Value Decomposition.
TF	Trade-off Factor.
WiMAX	Worldwide Interoperability for Microwave Access
ZF	Zero Forcing.

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