A Thesis for the Degree of Ph.D. in Engineering

Resource Allocation and Reduced Complexity in MIMO Wireless Communication System

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Summary

Recently, the demands for high speed internet access from the mobile wireless devices have grown very rapidly. Therefore, there is need to satisfy the demands of the capacity improvements in wireless communication systems. Fourth generation (4G) mobile technology promises the full mobility with high speed data rates for next generation mobile users. The main aim of 4G technology is to provide high speed wireless broadband services. Airport lounges, cafés, railway stations, conference arenas, and other such locations are required to have high speed internet services; in those places, 4G can play an important role. 4G is equipped with the proper arrangements at the physical layer to meet all the demands of those various scenarios. Spatial Multiplexing offers high channel capacity and transmission rate for the same bandwidth without additional power requirement by employing multiple antennas at the transmitter and receiver. Therefore, 4G like its predecessor 3G, would use the advanced versions of the Multi-Input Multi-Output (MIMO) antennas. The antennas used for the 3G system were smart enough to take care of many advanced operations at the signal level. This system must continue for 4G as well, and may even be made more sophisticated for 4G, as the number of signal-level decisions would be far greater in the case of 4G compared to 3G. There are many difficulties, however, in providing high speed wireless internet services in these environments, such as multipath fading

and the inter-symbol interferences generated by the system itself. Therefore, high data transmission is limited by Inter-Symbol-Interference (ISI). As a result, Orthogonal Frequency Division Multiplexing (OFDM) technology is used to handle this problem. OFDM uses the spectrum efficiently by spacing the channels closer together as well as it gives the ability of reducing ISI.

Users of multiuser OFDM system observe multipath fading but have independent fading parameters due to their different locations. The probability that a subcarrier in deep fade for one user may also be in deep fade for other users is quite low. Hence, multiuser system creates channel diversity as the number of user increases. Therefore, in multiuser MIMO-OFDM environment, the system needs to allocate efficiently its resources such as bits, antennas and subcarriers adaptively to the users. The resource management in 4G is much better than 3G. Optimization is present in the 3G system, but most of the optimizations are not that adaptive and dynamic. In contrast to that, 4G would have very smart adaptations in the resource management sector. Adaptive algorithms are used to provide optimization everywhere, from the modulation and coding, to the individual scalable channel bandwidth allocation. The combination of above technologies has been researched for the most promising technique for the next generation wireless systems.

Chapter 1 introduces the promising technologies of 4G such as OFDM, MIMO, efficient resource allocation in wireless communication system and reduction of complexity in that system, which can be used for the development of next generation wireless communication.

Chapter 2 presents the resource allocation scheme for Multi-Input Multi-Output Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) broadband mobile wireless communication system for next generation. In the wireless communication systems, the different data throughput requirements for each user with various kinds of services and multimedia applications might be occurred. In this case, this system should provide the service to the users with proportional data rate fairness among users in the system. It is well known that using MIMO and OFDMA together gives rise to greater system capacity. Therefore, we consider the proportional data rate fairness in the MIMO-OFDMA mobile broadband wireless system case to give the higher capacity throughput in the next generation wireless.

In chapter 3, we propose the resource allocation scheme to use the more radio frequency spectrum more efficiently by using same frequency to transmit for different user's data at the same time in the system. In chapter 2, users are separated in frequency domain but not in chapter 3. Different user's data can overlap in the same frequency at the same time. Therefore, we can use scarce spectral resources more efficiently in the MIMO-OFDM wireless communication system environments under the consideration of proportional data rate fairness constraint and QoS requirements among users in the system.

Chapter 4 describes the singular value decomposition (SVD) based reduced complexity antenna selection method for the practical MIMO communication system with linear receivers. In the conventional MIMO communication systems, most of the antenna selection methods considered are suitable only for spatially separated uni-polarized system under Rayleigh fading channel

in non-line of sight (NLOS) condition. There have a few antenna selection schemes for the cross-polarized system in LOS condition and Ricean fading channel, and no antenna selection scheme for the MIMO channel with both LOS and NLOS. In the practical MIMO channel case, influence of LOS and NLOS conditions in the channel can vary from time to time according to the channel parameters and user movement in the system. Based on these influences and channel condition, uni-polarized system may outperform a cross-polarized. Thus, we consider this kind of practical MIMO channel environment when developing the antenna selection scheme. The reduced complexity in antenna selection is proposed to give the higher throughput in the practical MIMO channel environment. In the proposed scheme, suitable polarized antennas are selected based on the calculation of SVD of channel matrix and then adaptive bit loading is applied to increase the throughput of the system under the constraint of target bit error rate (BER) and total transmit power of the MIMO system. The proposed system and selection method consider not only reducing the complexity but also the effects of adaptive modulation and total transmit power constraint under the target BER rate in the MIMO system.

Finally, chapter 5 concludes this dissertation and discusses the further study of research works.

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Chapter 1

Introduction

1.1 Today's Internet and Wireless Communication

High speed data throughput and very fast mobility in broadband mobile wireless communication system is urgently needed throughout the world because of the huge demand from today Internet users. The Internet has been growing exponentially, in both the number of users and the amount of information content points of view during these years. We can see various kinds of wireless services in nearly all of the countries in the world. The mobility of wireless services has revolutionized the way people think and live. *Seamless Wireless System* for *Everywhere and Every time* concept has given some extraordinary dimensions to the business community. Innovation and changes in wireless world make it possible to use the system that can help users to satisfy their basic needs of interpersonal communication and access to information , while the same time enjoying the freedom of wireless communication. Recently, so many mobile applications are developed and give their services over the Internet to use not only for personal usages but also for business related services. Moreover, real time sensitive data such as online gaming, IPTV and video conferencing are running as an important application in current Internet systems, where enhanced capacity and spectral efficiency need to fulfill the exponentially increasing data

traffic demand over the wireless mobile communication system. Looking at the present demand, it is clear that there is an ever increasing demand for higher bandwidths in mobile communication systems. While the target of the first generations was mobile telephony, currently deployed system aim to enhance people's lives by enabling high speed mobile access to the Internet anywhere at any time. While the integration of heterogeneous mobile and wireless access techniques may be one important aspect of the next generation (4G), a second goal is the support of even higher data rates, similar to fixed networks, as well as to provide high-quality multimedia applications at reasonable costs for multimedia mobile users.

1.2   Evolution of Mobile Wireless Communication

The gradual evolution of mobile communication systems follows the quest for high data rates (bps) with a high spectral efficiency (bps/Hz). Mobile Cellular Network evolution has been categorized to *generations* as shown in Fig. 1.1 [1.1].

1.2.1   First Generation

The first mobile communications systems were analog and are today referred to as systems of the first generation. 1G is the name which was given to the first generation of mobile telephone networks. In the first generation of mobile communications the services were mainly based on the analog communication techniques. 1G networks were the earliest cellular systems to develop, and they relied on a network of distributed transceivers to communicate with the mobile phones. Because of the analogue circuit-switched technology with FDMA (Frequency Division Multiple Access), the networks had a low traffic capacity, unreliable handover, poor voice quality, and poor security.

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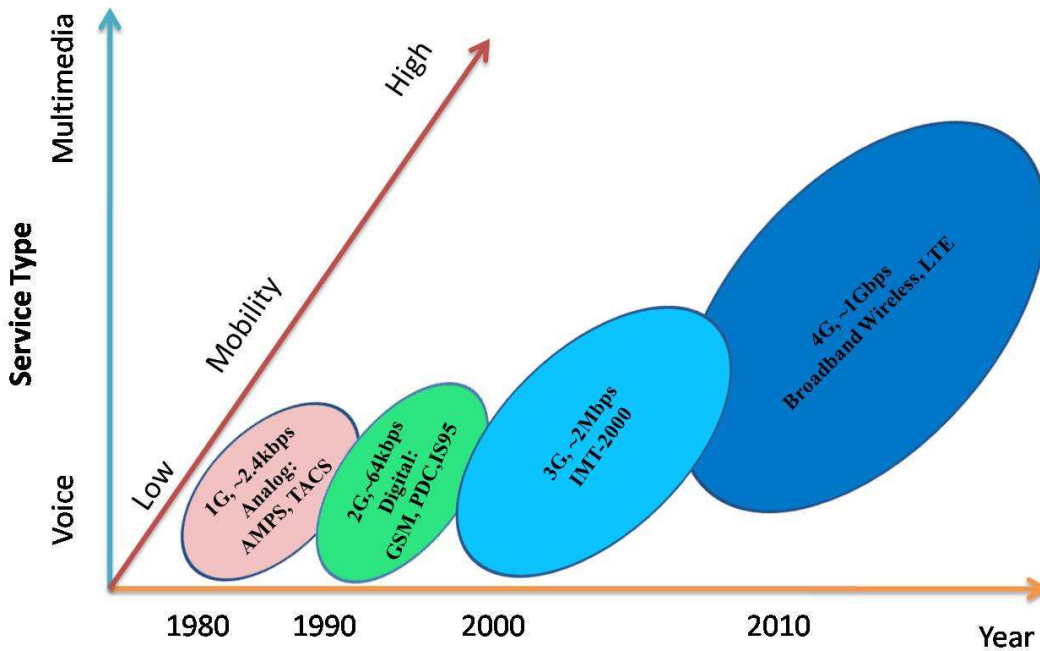
Figure 1.1: 1G to 4G

1.2.2 Second Generation

In the beginning of the 1990s, the first digital systems emerged, denoted as the second generation (2G) systems. The second generation of the mobile systems was known as 2G. 2G mobile telephone networks were the logical next stage in the development of wireless systems after 1G, and they introduced for the first time a mobile phone system that used purely digital technology. In the United States, the most popular 2G system is the TDMA/136, which is also a digital cellular system. TDMA stands for time-division multiple access. In Europe, the most popular 2G system introduced was the global system for mobile communications (GSM), which operated in the 900 MHz band or the 1,800-MHz band and supported data rates of up to 22.8 kbit/s. The European GSM technology was quite popular and now it has stretched over the whole globe. GSM was nothing more than the TDMA system of the European countries with pan-European roaming facilities. It was

a great revolution that a single phone could be used in different countries and it was the main choice in many countries. Basically GSM is a cellular system [i.e., it typically uses a single base transceiver station (BTS), which marks the center of a cell and which serves several mobile stations (MS), meaning the users]. The demands placed on the networks, particularly in the densely populated areas within cities, meant that increasingly sophisticated methods had to be employed to handle the large number of calls, and so avoid the risks of interference and dropped calls at handoffs. Although many of the principles involved in a 1G system also apply to 2G - they both use the same cell structure - there are also differences in the way that the signals are handled, and the 1G networks are not capable of providing the more advanced features of the 2G systems, such as caller identity and text messaging. 2G systems or technologies used in different countries were different. In America CDMA emerged as the main competitor of the GMS. The competition between these two 2G technologies gave rise to many new standards and technologies.

Some other versions like the Japanese PDC were also popular regionally, but later they parted with either of the two main technologies. The initial 2G or digital mobile communication systems were using lower bandwidth and the data rate was only 16 kbps (though at first it was even lower). Then the initiative was taken to provide higher data rate services through the addition of the GPRS known as 2.5G. This is a generic term used to refer to a standard of wireless mobile telephone networks that lies somewhere between 2G and 3G. The development of 2.5G has been viewed as a stepping-stone towards 3G, which was prompted by the demand for better data services and access to the Internet. GPRS was mainly used for non-voice services and the maximum data rate possible was around 160 kbps. In the evolution of mobile communications, each generation provides a higher data rate and additional capabilities, and 2.5G is no exception as it provides faster services than 2G, but not as fast or as user's demands. So EDGE or the Enhanced Data

Rates for GSM Evolution was adopted. It can be considered as the earliest broadband on the GSM framework. Some people consider EDGE to be 3G; however, this is not true, as EDGE is the 2.7G on the GSM infrastructure. And it is slower than the full 3G service. In technical terms 2.5G and 2.7G extend the capabilities of 2G systems by providing additional features, such as a packet-switched connection (GPRS) in the TDMA-based GSM system, and enhanced data rates in EDGE. These enhancements permit data speeds of 64-144 kbps, which enables these mobile phones to feature web browsing, the use of navigation and navigational maps, voice mail, fax, and the sending and receiving of large email messages. But they were not the cure for high demand of data service from the mobile users and it was expected that the evolution of the systems must be necessary and this happened sometime around the year 2000.

1.2.3   Third Generation

At first, the GSM group or the European standards making body ETSI proposed a project for the development of 3G technologies. Then some other organizations also joined them from across the globe, and the project then went on to develop a new technology which we known as the UMTS or the Universal Mobile Telecommunications System. This technology that enabled GSM to leap forward and allowed high data rate services to become possible in the GSM framework.

There has also another project where the ITU or the International Telecommunications Union was taking the leader's role. They developed the IMT 2000. At the same time the air interface access technologies were evolving very fast. WCDMA was one of them. Similarly, CDMA2000, TDSCDMA and their hybrid versions made it easy to provide the high broadband services. With all of these ingredients in place, business parties in the mobile communication systems started designing the next generation mobile systems. In

the early years of 21st century, the 3G system emerged and people welcome it with enthusiasm. Now almost all the developing countries have 3G facilities. Significant features of 3G systems are that they support much higher data transmission rates and offer increased capacity, which makes them suitable for high-speed data applications as well as for the traditional voice calls. In fact, 3G systems are designed to process data, and since voice signals are converted to digital data, this results in speech being dealt with in much the same way as any other form of data. Third Generation systems use packet-switching technology, which is more efficient and faster than the traditional circuit-switched systems, but they do require a somewhat different infrastructure to the 2G systems. Compared to earlier mobile phones generations, a 3G handset provides many new features, and the possibilities for new services are almost limitless, including many popular applications such as TV streaming, multimedia, videoconferencing, Web browsing, e-mail, paging, fax, and navigational maps. Japan was the first country to introduce the 3G system, which was largely because the Japanese PDC networks were under severe pressure from the vast appetite in Japan for digital mobile phones. Unlike the GSM systems, which developed various ways to deal with the demands for improved services, Japan had no 2.5G enhancement stage to bridge the gap between 2G and 3G, and so the move into the new standard was seen as a solution to their capacity problems. In many countries, 3G systems are currently using to provide a range of data rates, depending on the user's circumstances, providing up to 144 kbps for moving vehicles (macrocellular environments), up to 384 kbps for pedestrians (microcellular environments) and up to 2 Mbps for indoor or stationary users (picocellular environments). In contrast, the data rates supported by the basic 2G networks were only 9.6 kbps, such as in GSM, which was inadequate to provide any sophisticated digital services. Although the UMTS-based 3G and the IMT2000-based 3G had some differences, they were very similar as far as the performances and the features are concerned. So it can

be said the technologies are heading towards a common framework in which the better aspects of either will stay.

The 3G services were a grand success for both the researchers and the service providers. The coverage areas were not limited and the mobility was not restricted. The 3G systems were good enough in comparison to the 2G or the GPRS enabled 2.5G systems, but Internet related services such as video conferencing or online gaming, anything that needed higher bandwidth were either out of reach, or the quality of service was not good enough. This led to demand for a system which could give some proper solution to these needs. That condition caused research and development efforts in the telecommunications industries for the new generation mobile wireless communication technologies. While 3G systems are currently running for the data communication services, research activities on the fourth generation (4G) have already started.

1.2.4   Fourth Generation

4G was first proposed by the team who were the members of the 3GPP LTE (Third Generation Partnership Project -Long Term Evolution). The front runner among the business group was the NTT DoCoMo of Japan, the first of many business partners in this project.

4G mobile broadband wireless access system should be designed based on the characteristics of the environment in which they need to operate and the requirements of the services which are necessary to provided by these systems. Some of the development features in 4G are as follows [1.3]:

- The major change in the infrastructure for 4G will be *all packet-based system* and the technology on which it will be based is the IPv6,

- Very High data rates and support of different traffic profiles, also referred to as quality-of-service (QoS) profiles,

- High capacity (i.e., the ability to serve a high number of users),

- Efficient use of available resources, which means satisfying the increased requirements by making better use of the already available resources (e.g., spectra) than by allocating new ones,

- Operation in a hash and changeable environment of the radio channel, in which variability should be treated as usual rather than exceptional,

- Low power consumption (which applies to the construction of algorithms and the design of processors) and low power emission (meaning low levels of transmit power),

- Freedom of personalization and mobility,

- Cooperation of a number of different communication devices as well as entire systems at the same time and at the same place. This requires the ability to handle the mutual influence of devices or systems, which undoubtedly happens in such situations either by intentional or unintentional interactions. This influence is most often referred to as interference (e.g., cochannel interference),

- It is clear that future 4G air-interface technology is necessary to support the data rates in the order of 100 Mbps at full mobility, i.e., at velocities up to 200-300 km/h,

There are some other proposals for an open platform in which the new innovations and evolutions of the future can fit. One of the first technology really fulfilling the 4G requirements as set by the ITU-R will be LTE Advanced as currently standardized by 3GPP. LTE Advanced will be an evolution of the 3GPP Long Term Evolution. The higher data rates needed are for instance, achieved by the aggregation of multiple LTE carriers that are currently limited to 20MHz bandwidth and there are many such changes have been recommended.

1.3   Difference between 4G and 3G

Though the 4G is the evolved version of the 3G there are many fundamental differences between the two systems, the greatest achievements are speed enhancement and all IP based packet transmission when compared with 3G network services. The main differences between the 3G and the 4G have been listed below [1.4].

1. *The speed or data rate*: The maximum speed or the data rate of the 3G system is 2Mbps. With that speed we can definitely get a better service than the 2G system or its advanced versions like the GPRS (where the maximum possible speed is 204 Kbps). Although the 3G substantially enhanced the data rate, the data contents of the present wireless broadband services make it impossible to carry on far with the 3G system. 4G was the solution to overcome that bottleneck of the 3G technologies. In 4G the aim is to get a data rate of 100Mbps or even more in the indoor environment. In theory, 4G will be at least 50 times faster then the 3G system; this is the main difference between the 3G and 4G technologies. In other words, the bandwidth of the 4G system would be much higher than the 3G system.

2. *Packet switched infrastructure*: In 4G, the whole network will be packet switched. The IP based infrastructure will be used for the 4G system exclusively. IPv6 is the version on which the whole protocol system will govern the different kinds of switching for the data transfer. 4G switching aspects will therefore be more sophisticated and complex than the 3G system.

3. *Quality of service or Qos*: The quality of services in 4G networks is going to be much better than the 3G and its contemporary technologies. The improvement in main service factors will be due to the high broadband of the 4G systems, the improved quality of service of the IPv6 systems compared to previous IP versions, and better reception and transmission services from the smart antenna based MIMO system.

4. *Network Security*: Network security is another important aspect, one for which people are ready to pay. Network security in 4G is different from that of the 3G or 2G versions, in part because the security provided through the 4G networks is made up of two tiers. That means not only the MSC authentication is required but along with that there are some additional securities.

   We have seen the added security arrangement of the 4G systems in the OSI model. The Information Privacy Layer is there to take care of the security related aspects of the information that is exchanged in the 4G networks.

5. *Management of Resources*: The resource management in 4G is much better than 3G. Optimization is present in the 3G system, but most of the optimizations are not that adaptive and dynamic. In contrast to that, 4G would have very smart adaptations in the resource management sector. Adaptive algorithms are used to provide

optimization everywhere, from the modulation and coding, to the individual scalable channel bandwidth allocation.

1.4 Difference between 4G and Other Wireless Services

There are many personal communication systems evolving these days. Out of them the broadband services are the most popular ones. There are many kinds of broadband frameworks available today for public use, from traditional cable or wired broadband to more sophisticated systems. The most sophisticated ones are the wireless broadband services. There are many wireless broadband services like 3G, WiFi, WiMAX, etc. The main aim of these technologies is to provide broadband or high quality services to the customers at the best possible means [1.4].

1.4.1 Wireless Fidelity (WiFi)

There was a need for mobility in the local area network as well, which led to the creation of the wireless LAN. There were many challenging issues in establishing this WLAN. In order to achieve the proper mobility and flexibility a new system came into existence, which is well known as WiFi or Wireless Fidelity.

In WiFi, mobility and the range of coverage are limited; though it can provide broadband services wirelessly, the data rates are not very high. Nevertheless, it was very popular initially in the corporate sectors and universities. The main difficulties in the WiFi systems are the limited security and the difficulty of channel management.

In the corporate sector, the need for mobility was immense, and WiFi based systems were not able to fulfill the demand. Because of this, there was a need for a technology

which could take care of the mobility and provide a large range of coverage. Eventually that challenge was met and WiMAX, or Worldwide Interoperability for Microwave Access, was born.

1.4.2 Worldwide Interoperability for Microwave Access (WiMAX)

WiMAX boasts a high range of coverage, satisfactory mobility, and improved security compared to wireless communication. Sometimes WiMAX is confused with WiBro, but in reality there are some small differences, including the standards upon which they are based. IEEE developed the IEEE 802.16 standards, which include notably IEEE 802.16-2004, the first major WiMAX standard for fixed access. One year later, fixed WiMAX was superseded by IEEE 802.16e-2005 which is known as mobile WiMAX. Mobile WiMAX (802.16e) supports the mobility of 120km/h and downlink data rate of 46Mbps at 10MHz bandwidth. However, according to ITU-R definition, 4G wireless technology needs to support the data rate up to 1Gbps (indoors). Additionally, WiMAX technology (802.16e) does not support mobility very well. To achieve the requirement for 4G, IEEE 802.16 Working Group submitted its proposal for IMT-Advanced based on IEEE 802.16m, which enhances IEEE 802.16e-2005 to meet the IMT-Advanced requirements [1.5].

1.5 Orthogonal Frequency Division Multiplexing (OFDM)

The main aim of 4G technology is to Provide high speed wireless broadband services. Airport lounges, cafés, railway stations, conference arenas, and other such locations are required to have high speed Internet services; in those places, 4G can play an important role. 4G is equipped with the proper arrangements at the physical layer to meet all the demands of those various scenarios. There are many difficulties, however, in providing the high speed wireless Internet services in these environments, such as multipath fading
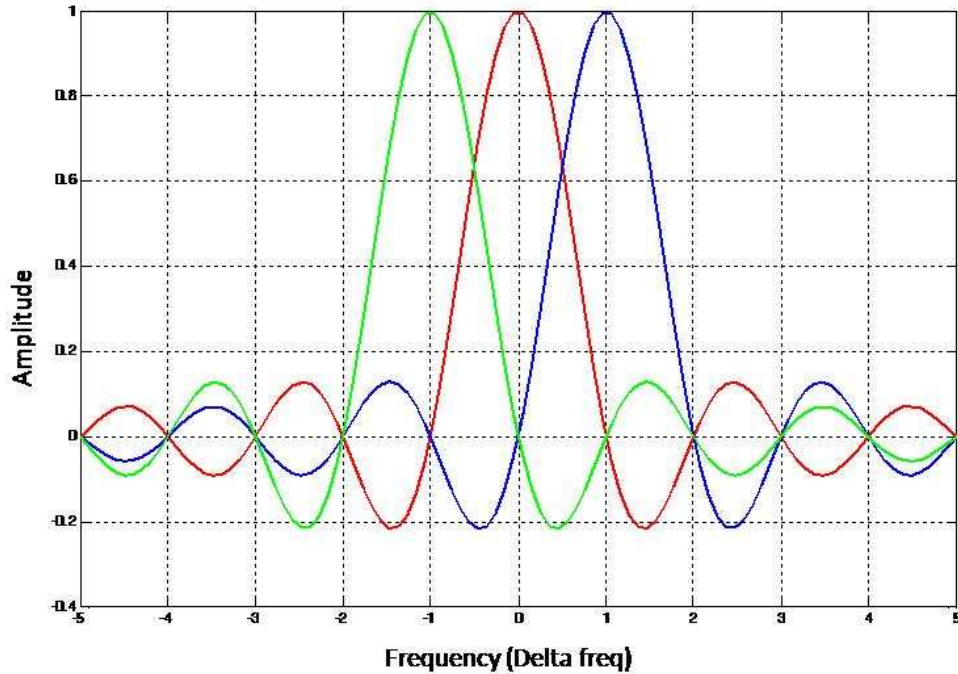
Figure 1.2: OFDM

and the inter-symbol interferences generated by the system itself. As a result, OFDM technology is used to handle this problem. OFDM is a transmission scheme that partitions the available bandwidth into N narrowband parallel subcarriers, which are overlapping but orthogonal, as shown in Fig. 1.2. This results in a high spectral efficiency.

1.5.1 Inter-Symbol Interference due to Time Delay (ISI)

In a multipath environment, the signals and their delayed versions arrive with different amount of delays. When the time delay between the different delayed signals is a large enough fraction of the transmitted signal's symbol period (actual time allotted for one symbol transmission), a transmitted symbol may arrive at the receiver during the next symbol period. This is well known as inter-symbol interference (or ISI). At higher data rates, the symbol period or duration is shorter; hence, it takes only a small time delay to

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introduce ISI. In case of broadband wireless, ISI is a big problem and reduces the quality of service significantly. In conventional situations, statistical equalization is the method for dealing with ISI, but at high data rates it is quite complex and requires considerable amount of processing power. In order to overcome frequency selective fading causing intersymbol interference, the bandwidth of each subcarrier is chosen to be sufficiently smaller than the coherence bandwidth of the channel. Therefore, OFDM is extremely robust to multipath propagation, which is one of the phenomena causing significant problems in wireless communications. OFDM appears as a better solution for controlling ISI in broadband systems like 4G. OFDM deals with this problem in a very intelligent way by introducing a guard interval before each OFDM symbol. This guard interval is the duration in which no information is transmitted. Digitally, it is nothing but a certain number of zeros transmitted between each couple of symbols. Whatever signal comes during that interval is discarded by the receiver, but when the guard interval is properly chosen then the OFDM signal can be kept undistorted.

1.5.2 Effective Use of Bandwidth through OFDM

OFDM has the ability to optimize the consumption of resources. Due to the orthogonal nature of the carriers used for different channels, it is possible to overlap the bands on each other and still recover them in the receiver without losing any quality. Because of this, OFDM is very effective in saving bandwidth. In low bandwidth systems where the demand for spectrum is very high, OFDM comes naturally as the first choice. The bandwidth saving has been shown in Fig. 1.2. Besides the above advantages, OFDM based systems provide other facilities for digitalization and protocol supports. Processes like error correction and interleaving are easily supported by OFDM. We can also use OFDM in a form of FDMA which we called OFDMA, where a user may be assigned one

or more subcarriers (equivalent to FDMA frequency channels) in order to satisfy its traffic requirements. The key advantage of OFDMA is that it allows for multiuser diversity: a subcarrier that is of low quality to one user can be of high quality to another user and can be allocated accordingly. In this way, a subcarrier is left unused only if it is low quality to all users. Moreover, this approach can be combined with adaptive modulation, where modulation levels are chosen on a per-subcarrier basis according to the observed channel conditions in order to further increase spectral efficiency. Therefore OFDM/OFDMA is currently one of the key element of the majority of the modern communication systems, including Broadband Wireless Access (BWA), cable access (xDSL), digital audio and video broadcasting (DAB and DVB), and WLANs (802.11, HiperLAN, 802.16).

1.6 Multiple-Input Multiple-Output (MIMO)

4G like its predecessor 3G would use the advanced versions of the MIMO Antennas. The antennas used for the 3G system were smart enough to take care of many advanced operations at the signal level. This system must continue for 4G as well, and may even be made more sophisticated for 4G, as the number of signal-level decisions would be far greater in the case of 4G compared to 3G. MIMO technology is also one of the key technologies for the fourth generation mobile broadband wireless access technology. In ideal conditions (uncorrelated high rank channel) the MIMO capacity scales roughly linearly as the number of Tx/Rx antennas although the effect of channel correlation is to decrease the capacity and, at some point, this is the dominant effect. However, the radio spectrum available for wireless services is extremely scarce. As a consequence, a prime issue in current wireless systems is the conflict between the increasing demand for wireless services and the scarce electromagnetic spectrum. Spectral efficiency is therefore of primary concern in

Figure 1.3: MIMO

the design of future wireless data communication systems with the very limited bandwidth constraint. The current need for increased capacity and interference protection in wireless multiuser systems is at present treated through, among the other techniques, limited micro diversity features at cell sites, sectorization, and switched multibeam schemes. These techniques fall into the category of exploiting the spatial characteristics of wireless channels. Slowly but steadily, more sophisticated fully adaptive antenna arrays are being considered instead as a cost-effective higher performance solution for the base station. The use of multiple antennas at the receiver can significantly increase the channel capacity by exploiting the spatial diversity, for example, to combat fading and to perform interference cancellation. If simultaneous spatial diversity is employed both at the transmitter and the receiver as shown in Fig. 1.3, then a MIMO channel naturally arises with the additional property that several substreams can be opened up for communication within the MIMO channel (this is the so-called multiplexing gain). This particular scenario has gained a significant popularity due to recent studies indicating a linear increase in capacity with the number of antennas [1.6] and [1.7].
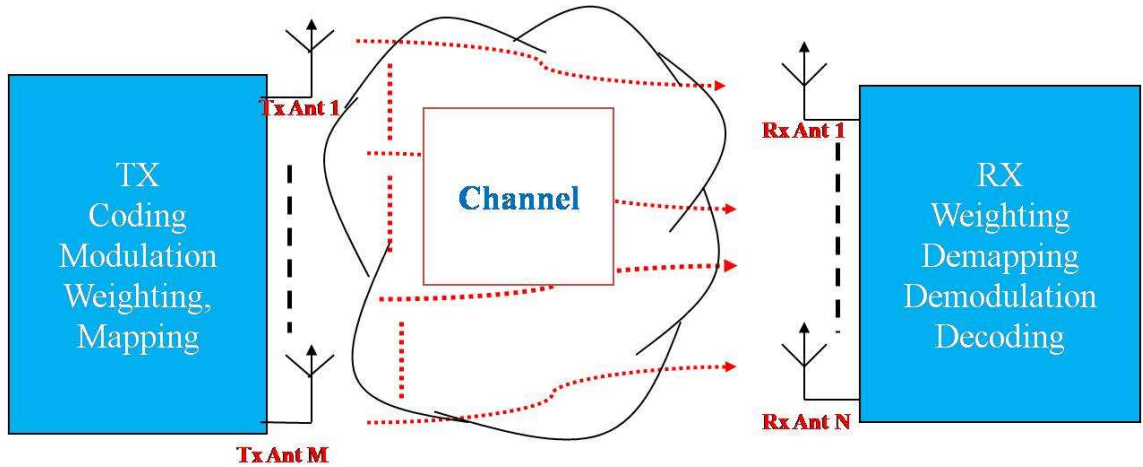
Figure 1.4: MIMOChannel

1.6.1 Shannon's Capacity Formula

Shannon's capacity formula approximated theoretically the maximum achievable transmission rate for a given channel with bandwidth B, transmitted signal power P and single side noise spectrum N_o, based on the assumption that the channel is white Gaussian (i.e., fading and interference effects are not considered explicitly).

$$C = B.\log_2\left(1 + \frac{P}{N_oB}\right) \tag{1.1}$$

In practice, this is considered to be a SISO scenario (single input, single output) and Equation 1.1 gives an upper limit for the achieved error-free SISO transmission rate. If the transmission rate is less than C bits/sec (bps), then an appropriate coding scheme exists that could lead to reliable and error-free transmission. On the contrary, if the transmission rate is more than C bps, then the received signal, regardless of the robustness of the employed code, will involve bit errors.

For the case of multiple antennas at both the receiver and the transmitter ends (Fig. 1.4), the channel exhibits multiple inputs and multiple outputs and its capacity can be estimated

by the extended Shannon's capacity formula, as described in next subsection.

1.6.2 General Capacity Formula

We consider an antenna array with n_t elements at the transmitter and an antenna array with n_r elements at the receiver. The impulse response of the channel between the jth transmitter element and the ith receiver element is denoted as $h_{i,j}(\tau,t)$. The MIMO channel can then be described by the $n_r \times n_t$ $\mathbf{H}(\tau,t)$ matrix:

$$\mathbf{H}(\tau,t) = \begin{bmatrix} h_{1,1}(\tau,t) & h_{1,2}(\tau,t) & \cdots & h_{1,n_t}(\tau,t) \\ h_{2,1}(\tau,t) & h_{2,2}(\tau,t) & \cdots & h_{2,n_t}(\tau,t) \\ \vdots & \vdots & \ddots & \cdots \\ h_{n_r,1}(\tau,t) & h_{R,2}(\tau,t) & \cdots & h_{M_R,n_t}(\tau,t) \end{bmatrix}, \tag{1.2}$$

The matrix elements are complex numbers that correspond to the attenuation and phase shift that the wireless channel introduces to the signal reaching the receiver with delay τ. The input-output notation of the MIMO system can now be expressed by the following equation:

$$\mathbf{y}(t) = \mathbf{H}(\tau,t) \otimes \mathbf{s}(t) + \mathbf{u}(t) \tag{1.3}$$

where $\otimes$ denotes convolution, $\mathbf{s}(t)$ is a $n_t \times 1$ vector corresponding to the transmitted n_t signals, $\mathbf{y}(t)$ is a $n_r \times 1$ vector corresponding to the n_r received signals and $\mathbf{u}(t)$ is the additive white noise.

If we assume that the transmitted signal bandwidth is narrow enough that the channel response can be treated as flat across frequency, then the discretetime description corresponding to Equation 1.3 is

$$\mathbf{r}_\tau = \mathbf{H}\mathbf{s}_\tau + \mathbf{u}_\tau \tag{1.4}$$

where $\mathbf{H}$ is the $n_r \times n_t$ channel matrix, $\mathbf{s}_\tau$ is a $n_t \times 1$ vector corresponding to the transmitted n_t signals, $\mathbf{r}_\tau$ is a $n_r \times 1$ vector corresponding to the n_r received signals and $\mathbf{u}_\tau$ is the additive white noise.

The capacity of a MIMO channel was proved in [1.9] that can be estimated by the following equation:

$$C = \max_{tr(\mathbf{R}_{ss}) \leq p} \log_2 \left[\det \left(\mathbf{I} + \mathbf{H} \mathbf{R}_{ss} \mathbf{H}^H \right) \right] \tag{1.5}$$

where $\mathbf{H}$ is the $n_r \times n_t$ channel matrix, $\mathbf{R}_{ss}$ is the covariance matrix of the transmitted vector $\mathbf{s}$, $\mathbf{H}^H$ is the transpose conjugate of the $\mathbf{H}$ matrix and p is the maximum normalized transmit power. Equation 1.5 is the result of extended theoretical calculations.

Two methodologies have been developed to exploit the capacity offered by the presence of several transmit and receive antennas in a telecommunication system. The first method exploits the additional diversity of multiple antennas, namely spatial diversity, to combat channel fading. This method is performance oriented. It targets improving the reliability of the link, which can be achieved by the transmission and reception of several replicas of the same information through independent fading paths and, hence, reduces the probability of simultaneous signal fades. The provision of replicas of the same information at the receiver is referred to as diversity. The number of independent receptions of the same information at the receiver is defined as the *diversity order* or the *diversity gain* of the system. In a MIMO system, the diversity order is equal to the product of the number of transmit and receive antennas, if the channel between each transmit-receive antenna pair fades independently [1.8].

the transmit and receiver antennas form $M_T \times M_R$ independent radio links and, hence, can provide a maximum or full diversity gain equal to this product. Diversity techniques are particularly interesting in the case of a severely rich fading environment, but the targeted transmitted rate is equivalent to that of a SISO system. In other words, the additional

antennas of the MIMO system are used to support the transmission of a SISO system. Diversity methods are traditionally used in Base Stations (BS). In the downlink, the BS transmits from two or more antennas, while in the uplink the BS receives information via several receive antennas. The diversity approach is particularly important for systems having a relatively small number of transmit antennas that operate at low SNR values. A major drawback of a MIMO system is that the transmitted signals from distinct antennas must be decorrelated, and hence, the antenna elements must be sufficiently separated. It has been shown in the literature that the spacing between antenna elements must exceed half the wavelength of the transmitted signals. In practice, the spading exceeds by three and even ten times the signal's wavelength. Therefore, the diversity schemes are popular to mobile/portable devices that have size limitations.

In MIMO systems that target maximizing the transmission and reception diversity, the channel coding is named according to the domains where diversity is applied. Usually, diversity is applied to two or more domains. Hence, we have Space-Time (ST) coding, Space-Frequency (SF) coding and Space-Time-Frequency (STF) coding.

The methodology described previously is suboptimal for MIMO systems with a large number of transmit antennas when operating at high SNR regimes. Since the capacity of a MIMO system increases according to the number of antennas, this capacity augmentation can be exploited differently for MIMO systems that have no limitations on the number of antennas. There are the other methods to exploit the capacity of a MIMO system, which are throughput oriented. In this case, the target of the system is to transfer the maximum possible information data. These techniques are particularly interesting for the case of a Line of Sight (LOS) environment, where the channels have practically no fading. This approach is known as Spatial Multiplexing (SM) or Layer Space-Time (LST). The number of extra degrees of freedom available for communication in a MIMO system is
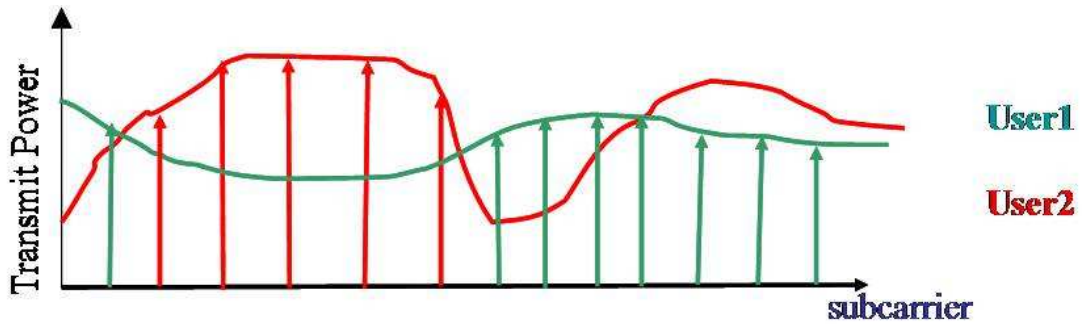
Figure 1.5: Resource Allocation

then equal to the minimum between the number of transmit antennas and the number of receive antennas. Several efforts have been made recently in the literature to combine the two methods described in this section. Some hybrid encoding schemes have been suggested. A trade off between diversity and multiplexing has been presented in [1.10].

1.7 Multiuser Diversity and Resource Allocation Principles

Although MIMO and OFDM technologies are strong enough for the efficient usage of wireless resources for a single user wireless communication system, they are not enough for multiuser multiple access wireless communication system. It is possible to enhance the effective usage of wireless resources in the multiuser broadband wireless communication systems by applying the wireless resources allocation management principles to achieve multiuser diversity. Wireless access systems are often considered to be the weakest link of the entire communication chain. This is not only due to the difficulty and unpredictable behavior of the radio channel but also due to the fact that radio resources are much more limited and scare than cable resources. The problem is that while the demand for more traffic increases at a very high pace, the availability of new spectra increases at a much lower pace. This problem can be solved without allocating new resources but by

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making better use of the available ones. That is the basic idea of relationship between multiple access and resource management.

The main task for multiple access techniques is to allow multiple users to communicate by sharing the finite physical resources of a system, such as time, bandwidth, and transmit power. One form of multiuser diversity in bandwidth and transmit power domain is shown in Fig. 1.5. Sharing involves not only creating separable links for multiple communications but also reuse of available resources in order to increase their utilization. Reuse means that at the same time instant more than one user is assigned the same resource (e.g., a frequency channel or a time slot). Therefore, these multiple users influence each other, sometimes causing problems, as in the case of cellular systems but sometimes bringing benefits, as in the case of embedded modulation systems. In wireless communications, as in real life, when sharing of finite resources to satisfy individual needs (i.e., QoS) is involved, it is always related to the management of these resources since the sharing should be done in a fair and efficient way. The following general approaches to radio resource management can be identified [1.3].

1.7.1 Fixed Resource Allocation

Fixed resource allocation is historically the oldest approach to the problem of resource management. Here, certain resources (such as frequency channel or time slots) are assigned permanently to certain users. This approach is still present in contemporary communication systems. For example, in GSM where one of the options for frequency planning is to assign a frequency permanently to transceivers at certain base stations. This is the worst-case design aiming to provide a minimum carrier-to-interference (C/I) ratio over the majority of a system's service area. Obviously, fixed resource allocation, though

simple and not requiring the knowledge of the environment is a waste of resources for most of the time when the worst-case assumption is too stringent.

1.7.2 Random Resource Allocation

In the random resource allocation scheme, resources are either randomly allocated or randomly accessed. Examples of randomly accessed time resources are multiple access schemes based on ALOHA and its derivatives (CSMA/CA, CSMA/CD). Examples of randomly allocated frequency resources are spread spectrum (SS) techniques, such as frequency hopping (FH) or direct sequence (DS) SS. These SS systems can also be treated as interference averaging techniques, and usually they provide better performance than fixed resource allocation. Their advantages stems for the fact that without having a detailed knowledge of the environment on average, it is better to allocate resources randomly, since the negative effect of the environment (noise, interference, channel attenuation) will be averaged over all users without risking that some of them are significantly affected, as is the case of fixed resource allocation.

1.7.3 Adaptive Resource Allocation

The allocation process in adaptive scheme is based on the detailed knowledge about the environment and the user's requirements; the resource manager makes decisions about which resource should be allocated to which user. In this way, resources are allocated according to their quality and users' needs. One of the examples of adaptive resource allocations is dynamic channel allocation (DCA) [1.11], where a channel from a common pool is allocated to a user based on the measured C/I status. Adaptive resource

allocation operating in the interference limited environment can also be named as interference avoidance. These methods provide an even better performance than the interference averaging methods. Here, adaptation is seen as the key success factor [1.12]. The drawback of these methods is necessary to obtain detailed information about the environmental conditions. If we will consider about the adaptive resource allocation techniques in the multiuser MIMO-OFDMA wireless communication system, then in this multiuser MIMO-OFDMA wireless communication system, users might be faced with multipath fading but have independent fading parameters due to their different locations. The probability that a subcarrier in deep fade for one user may also be in deep fading for the other users is quite low. Hence, multiuser system creates channel diversity as the number of user increases. Therefore, in multiuser OFDM environment, the system needs to allocate bits as well as subcarriers adaptively to the users. Adaptively assigning resources to each user based on the channel condition can give better performance compared to the other two schemes, which is called multiuser diversity.

1.7.4 Proportional Fairness Resource Allocation Schemes in MIMO-OFDM System

The most important features in the next generation mobile broadband wireless access is to give the much higher data rate and support of different traffic profiles for different users with different channel condition in the wireless communication system. In this case, one algorithm is required which can give the proportional data rate fairness among users with different level of services in the wireless communication system under the constraint of scare wireless resources. Therefore, the base station should allocate the resources based on the proportional fairness among users in the system for a given time interval. Proportional fairness implies that each user should get the predetermined subscribed amount

of system resources. The tradeoff between maximizing the system throughput and maximizing the proportional data rate fairness among users in the system should be concerned carefully. If only system throughput maximization is desired then resources get allocated to users with good channels while starving users with poor channels might be occurred. That's why , we will emphasize on the research work which can give the better system performance (i.e., better BER for same throughput) under the constraint of total available transmit power and proportional data rate fairness among users in the particular wireless communication. There have a lot of papers which considered to give the fairness among users in the system. But, most of them considered only in MIMO or OFDMA field [1.13]-[1.18].

It is well known that using MIMO and OFDMA together gives rise to greater system capacity. That's why, we will emphasize on the MIMO-OFDMA related research work to give the higher data throughput than SISO system. But, research of resource allocation for multiuser MIMO OFDM environments with different data throughput requirements for each user is still an open research field, though some researchers studied about rate fairness among users in the MIMO-OFDMA system [1.19][1.20][1.21] and [1.22]. But, these schemes have some weak points to use the system resources efficiently. They did not consider about the various channel conditions in the wireless system. They just chose the best carriers for each user and then applied the fixed allocation of power and bits to all of the allocated subcarrier. If they want to use the system resources efficiently, they have to use the adaptive bit and power loading. But if they applied this adaptive bit and power loading to the system, they could not give the guarantee for proportional data rate fairness among users in the system. Because their resource allocation scheme assigned the resources without considering various channel condition in frequency and space domain

of the system. Therefore, most of the system resources might be wasted without using efficiently. If we consider different channel conditions for different users with adaptive bits, power and subcarrier allocation scheme more appropriately, the usage of system resources will be more efficient. In our proposed scheme, we can use not only the system resources efficiently but also give the guarantee for proportional data rate fairness among users in the system. In chapter 2 and 3 we propose a subcarrier, bit and power allocation scheme for MIMO-OFDM wireless communication systems to maximize the total throughput under the constraints of total transmit power and proportional data rate fairness among users in the system.

1.8   Antenna Selection in MIMO Systems

MIMO systems, which employ multiple transmit and receive antenna elements, substantially improve the data rates that can be transmitted over the channel and the reliability with which they can be received without any additional bandwidth. Higher data rates are achieved by transmitting multiple data streams simultaneously using spatial multiplexing techniques. For spatially uncorrelated channels, the data rates even increase linearly with the minimum of the number of transmit and receive antenna elements [1.23]. Increased reliability is achieved by exploiting spatial diversity to significantly reduce the probability that the channel is in a deep fade. Orthogonal space-time block codes and space-time trellis codes are examples of diversity techniques tailored to MIMO systems. A single input multiple output (SIMO) system, which combines the many received copies of the transmitted signal to improve reliability, is another example of a spatial diversity system. While MIMO systems perform impressively, an important practical problem arising with

the deployment of multiple is the cost of the hardware and signal processing complexity, power consumption, and component size in the transmitter and the receiver associated with every additional antenna [1.3]. One of the main culprits behind this increase in complexity is that each receive antenna element requires a dedicated radio frequency (RF) chain that comprises a low noise amplifier, a frequency down-converter, and an analog-to-digital converter, and each transmit antenna element requires an RF chain that comprises a digital-to analog converter, a frequency up-converter, and a power amplifier. Moreover, processing the signals received in spatial multiplexing schemes or with STTCs calls for sophisticated receivers whose complexity increases, sometimes exponentially, with the number of transmit and receive antenna elements. This increase in complexity has inhibited the widespread adoption of MIMO systems. For example, the third-generation cellular system specification (3GPP) currently supports only an optional two antenna space-time transmit diversity scheme and does not require the handsets to have more than one antenna element [1.25]. Sophisticated techniques that employ spatial multiplexing or support more antenna elements have met with considerable opposition in 3GPP. While the adoption of MIMO has made headway in the next-generation wireless network, which aims to transfer raw information at rates greater than 100 Mbps in high mobility outdoor environment and 1Gbps in low mobility indoor environment, complexity considerations are likely to make the adopted MIMO scheme with a small number of antenna elements. Antenna selection is a solution that addresses some of the complexity drawbacks associated with MIMO systems. It reduces the hardware complexity of transmitters and receivers by using fewer RF chains than the number of antenna elements. While the antenna elements are typically cheap, and in some cases are just a patch of copper, the RF chains are considerably more expensive. In antenna selection, a subset of the available antenna elements is adaptively chosen by a switch, and only signals from

the chosen subset are processed further by the available RF chains. Given its promise as a low-complexity solution, antenna selection has received considerable attention recently. It has been considered at the transmitter (transmit antenna selection [TAS]), at the receiver (receive antenna selection [RAS]), and at both the transmitter and the receiver (transmit and receive antenna selection [T-RAS]). Its performance has been explored from various angles such as capacity and outage for spatial multiplexing systems, and diversity order and array gain for space-time coded systems. The ***diversity order*** quantifies the effectiveness in avoiding deep fades and is defined as the slope of average symbol error probability vs. input signal to noise ratio (SNR) curve for high SNRs. The ***array gain*** quantifies the improvement in average SNR seen at the combiner output when signals received by the multiple antenna elements are combined. As we shall see, antenna selection - for a variety of MIMO techniques - achieves the full diversity inherent in the system at the expense of a small loss in array gain compared to a full complexity system, i.e., a system that can always allocate RF chains to each and every antenna element. Another way of stating this is that for the same number of RF chains, using additional antenna elements with antenna selection outperforms a system that lacks additional antenna elements. Antenna selection has been found to modify, on a fundamental level, the optimum Gaussian signaling required to transmit information at the maximum possible rate. Considerable effort has also been spent to develop various criteria, both optimal (but complicated) and suboptimal (but simple), to implement antenna selection algorithms. However, the antenna selection solution depends, of course, on the signaling scheme, the receiver architecture, the optimization criteria and the nature of channel knowledge available. There have two criteria for antenna selection:

- 1. Maximum information rate (VBLAST in spatial multiplexing MIMO system)
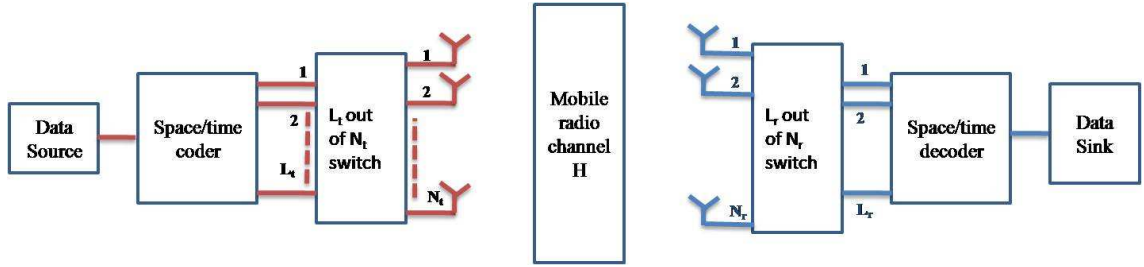
Figure 1.6: Antenna Selection Model

- 2. Minimum error (such as OSTBC transmission in MIMO system)

Between these two criteria, we will focus on the maximizing of information rate in the spatial multiplexing MIMO system to fulfill the demand of high data throughput in next generation mobile users.

1.8.1 Implementing Antenna Selection: Criteria and Algorithms

Let N_t and N_r denote the number of antenna elements that are available (but not necessarily used every time) at the transmitter and receiver, respectively. Let L_t and L_r denote the number of RF chains at the transmitter and receiver, respectively. We always have $1 \leq L_t \leq N_t$ and $1 \leq L_r \leq N_r$. A block diagram representation of antenna selection at the transmitter and the receiver is given in Fig. 1.6. The transmitted signal, of size $N_r \times 1$, is denoted by $\mathbf{x}$. The signal, $\mathbf{y}$, of size $N_r \times 1$, received by the N_r antenna elements is given by

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{1.6}$$

where $\mathbf{n}$ represents noise and the matrix $\mathbf{H}$, of size $N_r \times N_t$, denotes the instantaneous channel state. Unless otherwise mentioned, the elements of $\mathbf{H}$ are assumed to be independent of each other. In case of TAS, $N_t L_t$ elements of $\mathbf{x}$, which correspond to the transmit antenna elements not chosen, will be 0. The noise vector, $\mathbf{n}$, of size $N_r \times 1$, is a zero-mean

complex white Gaussian random vector. To simplify notation, we shall use **x** to also denote the $L_t \times 1$ transmit vector and **y** to denote the $L_r \times 1$ receive vector that correspond to only the selected transmit and receive elements, respectively. The notation shall be obvious from the context. The total power transmitted from all the antennas is denoted by p. Without loss of generality, we shall assume that each element of **n** and **H** has unit variance. Therefore, the average SNR of the signal input to any receive antenna element equals p/L_t when the power is equally allocated among the L_t transmit elements.

In TAS, the transmitter needs to examine $\binom{N_t}{L_t}$ possibilities to choose the best subset of L_t antenna elements out of the N_t available. Similarly, in RAS, the receiver needs to examine $\binom{N_r}{L_r}$ possibilities. In the case of T-RAS, the number of possibilities balloons to $\binom{N_t}{L_t} \binom{N_r}{L_r}$, and coordination between the transmitter and receiver is required to choose the optimal transmit and receive antenna subsets. The combinatorial increase in the number of possibilities makes an exhaustive search impractical even for moderate values of N_t and N_r.

Therefore, it is necessary to develop the reduced complexity in antenna selection algorithm for the MIMO systems although there have a large number of sub-optimal selection algorithms and heuristics with varying levels of complexity have been proposed in the literature [1.26] and [1.3]. The complexity of antenna selection will depend on receiver architecture (Maximum Likelihood or Zero Forcing etc..), transmission schemes such as diversity or spatial multiplexing systems, kind of the channel environments and polarization of the antennas etc. Most of these previously proposed algorithms are mostly considered for uni-polarized antenna in rich scattering multi-path channel environments. But, in the real world condition, we might face with not only non-line-of-sight (NLOS) condition but also with line-of-sight condition. In that case, we should consider to use the cross-polarized antenna to reduce the correlation effects in the spatial multiplexing

MIMO systems. Therefore, we emphasized on the development of reduced complexity antenna selection for spatial multiplexing MIMO system with dual-polarized antennas. Therefore, the complexity reduction in antenna selection scheme is proposed in chapter 4.

1.9 Position of the Research and Contributions in this Dissertation

This section briefly describes the position of the research in the mobile broadband wireless communication area and the contributions in this dissertation. The research in this dissertation mainly focuses on three research directions: proportional data rate fairness resource allocation for downlink MIMO-OFDMA wireless communication system and proportional data rate fairness resource allocation for uplink multiuser MIMO-OFDM wireless communication system and reduced complexity in the antenna selection method for MIMO wireless communication system. Figure 1.7, 1.8 and Table 1.1 provide an overview of the motivation of the research, how they are related in the mobile wireless communication system.

As shown in Fig. 1.7, there are three principal research areas in wireless communication system. In the OFDM related research area, we can do subcarrier allocation research work or we can consider how to reduce the Peak to Average Power Ratio (PAPR) or how to reduce the guard interval in the OFDM system etc. In this research area, we can also get some advantages and disadvantages for the wireless communication system. As for the advantages, the wireless system is robust to be used in the ISI related channel condition and the disadvantages are increasing in PAPR and frequency offset error in the wireless system.

If we are doing research works in the MIMO area, we can choose some research works such as channel estimation, antenna selection, polarization or receiver design to improve the overall performance of the MIMO system. By using MIMO system, we can also improve the capacity or BER performance of the wireless system without increasing the transmit power or the available bandwidth of the wireless system. That is one of the advantages of using MIMO technology in the wireless system. On the other hand, wireless system is limited to use only in the flat fading channel condition if we apply the spatial MIMO technology in that system and there will be increasing in hardware cost and complexity in the MIMO wireless system and these are some of the disadvantages of the MIMO technology in the wireless communication system.

The last part of research area in this dissertation is the resource allocation area. We can get the advantages of diversity and effective usage of system resources if we use the resource allocation techniques in the wireless communication system. But it has also a disadvantage of increasing in complexity for the wireless communication system.

Although there are some disadvantages in each area A, B and C, we can remove some of the disadvantages in each research area if we combine these technologies as shown in the middle of Fig. 1.7. There has overlapping areas in the middle of Fig. 1.7, and we can get some advantages such as: degree of freedom in more dimension, we can use the wireless system not only in the narrow band flat fading condition but also in the wide band frequency selective fading condition and efficient usage of system resources in more dimension condition.

Therefore, I am doing research works in these overlapping areas and chapter 2 and 3 are research works related to the middle of overlapping areas A and B and C as shown in Fig. 1.8. At first, I propose the resource allocation scheme for MIMO-OFDMA down-link wireless system under the proportional data rate fairness among user in the system.

By using this proposed method, we can use the system resources more efficiently in the frequency domain as well as space domain and because of this efficient usage of system resources, the BER performance can be improved under the proportional data rate fairness requirement among user in the system. In this proposed method, users are separated in the frequency domain to distinguish their data in the wireless system. By using this kind of user separation, we can reduce the complexity of proposed method but it will also limit the usage of same frequency for different user at the same time. If we can use same frequency for different user at the same time, the total system capacity will be increased according to the number of transmit and receive antennas in the MIMO wireless system. Therefore, we propose another resource allocation scheme for the multiuser MIMO-OFDM uplink system under the proportional data rate fairness requirement among users in the system. This time, users are not separated in the frequency domain. Therefore, they can transmit their different data into the same frequency at the same time based on the number of receive antenna in the base station system. Because of this overlapping in the frequency domain, we can use system resources more efficiently in this proposed method.

In the Fig. 1.7, we already mention that the combine effect of research areas A and B and C will be increase the system complexity and that is one of the disadvantages in proposed methods in chapter 2 and 3. In the mobile wireless communication system, base station has to compute channel estimation, channel coding, subcarrier, bit and power allocation etc for each user in the system and this will cause the high computational complexity in the base station. Therefore, it is necessary to reduce the complexities in each step of the wireless communication system as much as possible to reduce the over all processing time for the mobile wireless system. Therefore, we also propose the reduced complexity scheme for the antenna selection in the MIMO wireless communication system in chapter 4. Moreover, antenna are one of the resources of wireless communication

OFDM Area (A)
Resource Allocation: Bit and Power Distribution, Subcarrier Selection, User Selection.
PAPR (Peak to Average Power Reduction),
GI (Guard Interval)
Channel : Channel Estimation, Pilot symbol insertion, Preamble, Doplar Frequency

Advantages : Robust for ISI

Disadvantages: PAPR, Frequency Offset

Advantages : Degree of freedom in more dimension, Combat to ISI, Wide-band. Improve capacity and BER.

Disadvantages : Increase Complexity

MIMO Area (B)
Resource Allocation: *Antenna Selection, User Selection, Power Distribution*
Channel: Channel Estimation, *NLOS case, LOS case*
Angular : AOA, AOD, SDMA
Antenna Polarization: *Uni, Cross, Circular*
Transmission Type: Beam Forming, *SVD, Spatial Multiplexing*, STBC
Receiver Design: ZF, MMSE, OSIC, PIC, *ML, ZF-OSIC*
User: *Single User, Multiuser (MIMO-BC, MIMO-MAC)*

Advantages: Improve capacity or BER without additional transmit power or bandwidth.

Disadvantages: Flat fading, narrow band, Intersymbol interference ISI. Increase Complexity, Hardware Cost, Processing Time.

Advantages : Diversity, Efficient Usage
Disadvantages : Complexity

Resource Allocation Area (C)
Type: Fixed, Random, *Adaptive*
Resources: *Tx Power, Frequency (Subcarrier or Subchannel), Antenna,*
Modulation: Fixed or *Adaptive*
Emphasized on: Max Cap, Min BER, Equal Fairness, *Proportional Fairness*
Complexity: Optimal (High), *Sub-optimal (Low)*
User: *Single User, Multiuser*

Advantages: Efficent usage of system resources, Improve capacity or BER.

Disadvantages: Increase Complexity

Figure 1.7: Position of research works in the broadband mobile wireless communication field.

system and if we are selecting the antennas in the MIMO system, we can also call this antenna selection as one of the resource allocation methods in the wireless communication system. Therefore, overlapping area of B and C is related to chapter 4 as shown in figure 1.8.

Chapter 2: Resource Allocation for MIMO OFDMA System (A&B&C)

Proportional Fairness, Multiuser, MIMO, OFDM, SVD, Adaptive Bit Loading, Spatial Multiplexing.
Down Link (uplink also possible), Users are separated in freq domain.
Motivation: To improve the system capacity and BER performance under PRF requirements

Chapter 3: Resource Allocation for MIMO OFDM System (A&B&C)

Proportional Fairness, Multiuser, MIMO, OFDM, SVD, Adaptive Bit Loading, Spatial Multiplexing.
Uplink, Selected users can share same freq at the same time.
Motivation: Same as chapter 2. (one more thing: more efficient for freq; domain)

A (OFDM Area)
B (MIMO Area)
C (Resource Allocation)

A
A & B
A & C
A & B & C
B
B & C
C

Chapter 4: Reduced Complexity For Antenna Selection in MIMO System (B&C)

Huge complexity in most of resource allocation schemes.

So, reduce the complexity as much as possible in each step of wireless communication system.

So, try to reduce the complexity in antenna selection for MIMO system.

Figure 1.8: Research works and their relationship in the dissertation.

Table 1.1: Summary

Chapter Contents	
Chapter 1	It introduces the promising technologies of 4G such as OFDM, MIMO, efficient resource allocation in wireless communication system and reduction of complexity in that system, which can be used for the development of next generation wireless communication.
Chapter 2	This chapter presents the resource allocation scheme for Multi-Input Multi-Output Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) broadband mobile wireless communication system for next generation. In this case, users are separated in frequency domain and they can not transmit their data in same frequency with other users at the same time.
Chapter 3	The resource allocation scheme with proportional data rate fairness is proposed. But, this chapter considers to use the radio frequency spectrum more efficiently by using same frequency to transmit for different user's data at the same time in the system. Therefore, we can use scare spectral resources more efficiently in the MIMO-OFDM wireless communication system environments under the consideration of proportional data rate fairness constraint and QoS requirements among users in the system.
Chapter 4	Reduced complexity antenna selection method for practical MIMO communication system is proposed based on Singular value decomposition (SVD) and polarization effect in the antenna system.
Chapter 5	We conclude this dissertation and discusses the further study of research works.

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Chapter 2

Proportional Data Rate Fairness Resource Allocation Scheme for MIMO-OFDMA System

In the conventional subcarrier and power allocation schemes in Multi-Input Multi-Output and Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) systems, only equal fairness among users has been considered, and no scheme for proportional data rate fairness is considered. In this chapter, a subcarrier, bit and power allocation scheme is proposed to maximize the total throughput under the constraints of total power and proportional data rate fairness among users. In the proposed scheme, joint subchannel allocation and adaptive bit loading is firstly performed by using singular value decomposition (SVD) of channel matrix under the constraint of users' data throughput requirements, and then adaptive power loading is applied. Simulation results show that effective performance of the system has been improved as well as each throughput is proportionally distributed among users in MIMO-OFDMA systems.

2.1 Introduction

Spatial Multiplexing offers high channel capacity and transmission rate for the same bandwidth without additional power requirement by employing multiple antennas at the transmitter and receiver. However, high data transmission is limited by Inter-Symbol-Interference (ISI). Orthogonal Frequency Division Multiplexing (OFDM) uses the spectrum efficiently by spacing the channels closer together as well as it gives the ability of reducing ISI. The combination of these two technologies has been researched for the most promising technique for the next generation wireless systems.

Users of multiuser OFDM system observe multipath fading but have independent fading parameters due to their different locations. The probability that a subcarrier in deep fade for one user may also be in deep fade for other users is quite low. Hence, multiuser system creates channel diversity as the number of user increases. Therefore, in multiuser OFDM environment, the system needs to allocate bits as well as subcarriers adaptively to the users. There are two classes of resource allocation schemes; fixed and adaptive resource allocation schemes. Fixed allocation scheme uses time division multiple access TDMA) or frequency division multiple access (FDMA) to allocate each user an independent time slot of subchannel. On the other hand, fixed allocation scheme does not consider the current channel condition for each user to give better performance in the system. Therefore, adaptively assigning resources to each user based on the channel condition can give better performance compared to fixed scheme, which is called multiuser diversity. Adaptive subcarrier and modulation for multiuser OFDM systems with single input single output (SISO) has been studied extensively. [2.1][2.2]. Because of the various channel conditions among different users, the user with higher average channel gains

might use most of the system resources. Therefore, it is necessary to consider the fairness among different users in the system.

In [2.3], Rhee and Cioffi consider the fairness problem by maximizing the worst user's capacity and give the equal fairness among users in the system. However, different data throughput for different users in various services and multimedia applications is required. Thus, it is necessary to develop the resource allocation scheme for different data throughput requirement in multiuser wireless systems. In [2.4] Shen considers an adaptive resource allocation scheme in multiuser OFDM systems with proportional rate constraints. However, this algorithm only considers the multiuser SISO OFDM case. Research of resource allocation for multiuser MIMO OFDM environments with different data throughput requirements for each user is still an open research field, though some researchers studied about rate fairness among users in the MIMO-OFDMA system [2.5]. They consider rate fairness by counting the total number of allocated subcarriers for each user. However they do not consider for the various channel gains of different subcarrier conditions in each user. Some users with equal rate fairness but different channel gains might use equal number of subcarriers in the systems. There has been no consideration for different data rate requirement for different channel gains in different subcarriers. In the conventional allocation schemes, equal power and bits are allocated to the selected subcarriers of the user. These methods cause performance degradation if the gap of channel gain is high in the MIMO system because the bad channel has high error probability. Therefore, most of the system resources might be wasted without using efficiently. If we consider different channel conditions for different users with adaptive bits, power and subcarrier allocation scheme more appropriately, the usage of system resources will be more efficient.

In this chapter, we propose a subcarrier, bit and power allocation scheme for MIMO-OFDMA systems to maximize the total throughput under the constraints of total power and proportional data rate fairness among users in the system. In the proposed scheme, subchannel allocation is performed based on singular value decomposition (SVD) method. We allocate the channel to the user who has the lowest data rate ratio in the system and the largest singular value in the minimum Eigen mode of that channel. We also apply the rate calculation method to control the rate ratio for various kinds of channel conditions among users in the system. To use the adaptive bit loading in different subcarriers with different channel condition, it is necessary to know the channel capacity of each subcarrier in the system. Subcarriers allocation is done under the consideration of different channel capacities in each subcarrier in the system. This is the main idea of our proposed scheme. In the conventional scheme, flat modulation mode and equal power loading for all subcarriers are used in the system although subcarrier allocation is adaptive. If subcarriers with bad channel conditions use equal power and same modulation mode as other good subcarriers, the bit error rate in the system might be increased, because of different channel condition in space and frequency domain. That's why we allocate the subcarriers among users in the system under the consideration of adaptive bit loading in each subcarrier. And then, we apply the adaptive power loading to the predetermined subcarriers for each user in MIMO-OFDMA system. Simulation results show that the system performance is improved as well as throughput is proportionally distributed among users in MIMO-OFDMA systems. This paper is organized as follows. Section 2.2 introduces MIMO-OFDMA system model under consideration. Section 2.3 describes the proposed subcarrier, bits and power allocation scheme. Section 2.4 shows simulation results, and conclusion is shown in section 2.5.
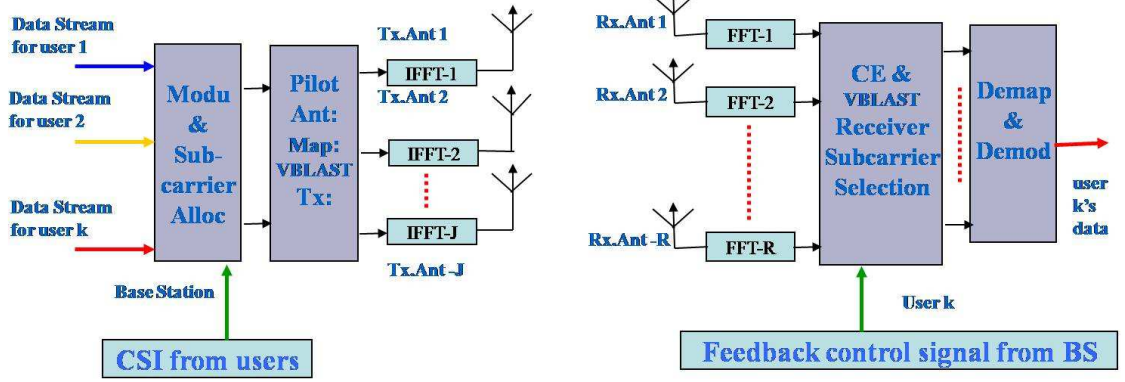
Figure 2.1: MIMO-OFDMA downlink system.

2.2 System Model

Fig. 2.1 shows the block diagram of our system model under consideration. We consider the down link of a MIMO-OFDMA system equipped with M subcarriers and J transmit antennas. There are K users, each of which has R receive antennas. A frequency selective fading channel is characterized by L significant delayed paths. The channel matrix of user k on subcarrier m is $J \times M$ matrix and it is denoted by

$$\mathbf{H}^{k,m} = \begin{bmatrix} h_{1,1}^{k,m} & h_{1,2}^{k,m} & \cdots & h_{1,J}^{k,m} \\ h_{2,1}^{k,m} & h_{2,2}^{k,m} & \cdots & h_{2,J}^{k,m} \\ \vdots & \vdots & \ddots & \cdots \\ h_{R,1}^{k,m} & h_{R,2}^{k,m} & \cdots & h_{R,J}^{k,m} \end{bmatrix}, \tag{2.1}$$

where $h_{r,j}^{k,m}$ is the channel gain from the jth transmit antenna to the rth receive antenna of kth user on m^{th} subcarrier. The received signal $R \times 1$ vector $\mathbf{Y}_{k,m} = [\mathbf{y}_{k,m}^1, \mathbf{y}_{k,m}^2, \cdots, \mathbf{y}_{k,m}^R]^T$ at the mth subcarrier for k^{th} user is then

$$\mathbf{Y}_{k,m} = \sqrt{E_s} \mathbf{H}_{k,m} \mathbf{S}_{k,m} + \mathbf{N}_m \tag{2.2}$$

where $S_{k,m}$ is the $J \times 1$ complex transmitted signal vector $[\mathbf{y}_{k,m}^1, \mathbf{y}_{k,m}^2, \cdots, \mathbf{y}_{k,m}^R]^T$ and

$\sqrt{E_s}$ is the average transmit energy per antenna. N_m is the $R \times 1$ noise vector and its elements are independent identically distributed (i.i.d) circularly symmetric complex Gaussian variables with zero-mean and variance of N_0 .

The system model is developed under the following assumptions: (a) the transmitted signals experience quasi static frequency selective Rayleigh fading which can be modeled as a collection of M parallel flat fading channels due to cyclic prefix (CP) added to each OFDM symbol. As a result, the channel remains unchanged from the time that measurements are made until the data packet is transmitted. (b) the channel state information (CSI) is perfectly known by the receiver, and each user feedbacks a certain form of channel information correctly to the base station (BS). Using the CSI feedback from all K users, the BS allocates a set of subcarriers and transmits power and data bits to each user based on a given criterion. The subcarrier and bit loading information are sent to the K users via separate control channels. The data stream is divided into multiple sub-streams and each antenna transmits independent symbol. We introduce the idea of proportional fairness into the system by adding a set of rate ratio constraints.

The proportional rate fairness is defined as follows:

$$C_1/\rho = \cdots = C_k/\rho_k = \cdots = C_K/\rho_K \text{ for user } k = 1 \text{ to } K, \qquad (2.3)$$

where C_k is actual data rate and ρ_1 is predetermined proportional rate fairness value of user k, respectively. If user 1's predetermined proportional rate fairness value ρ_1 is double compared to all other values of remaining users who have equal proportional rate fairness values

$$\rho_1/2 = \rho_2 = \rho_3 = \cdots = \rho_K, \qquad (2.4)$$

then actual date rate C_1 of user 1 has to be doubled compared to all other remaining users' actual date rate ($C_2 = C_3 = \cdots = C_K$) to satisfy (2.3). Thus, we can control the data rate fairness among users in the system according to their predetermined proportional data rate fairness values ($\rho_1 = \cdots = \rho_k = \cdots = \rho_K$) in the system.

The benefit of introducing proportional fairness into the system is that we can explicitly control the capacity ratios among users, and ensure that each user is able to receive a fair amount of data throughput according to his predetermined rate ratio among users.

2.3   Adaptive Resource Allocation for the System

We use V-BLAST algorithm implementation based on zero forcing (ZF) detection combined with symbol cancellation to improve the performance while maintaining low implemental complexity [2.6]. When symbol cancellation is used, the order in which the sub-streams are detected becomes important for the overall performance of the system. Performance of spatial multiplexing with linear receivers depends on the minimum SNR induced by the particular subset of transmit antennas. The transmitted symbol with the smallest postdetection SNR dominates the error performance of the system [2.7]. That's why we use the minimum SNR as a key factor to choose the best subchannel for each user. The dispread signal $\mathbf{Z}_m$ can be obtained by correlating the received signal $\mathbf{Y}_m$ with pseudo-inverse $\mathbf{U}_m$ of the channel matrix $\mathbf{H}_m$.

$$\mathbf{Z}_m = \mathbf{U}_m\mathbf{Y}_m = \sqrt{E_s}\mathbf{U}_m\mathbf{H}_m\mathbf{S}_m + \mathbf{U}_m\mathbf{N}_m \tag{2.5}$$

For the ZF receiver, the post-processing SNR of the worst m^{th} sub-stream is expressed in [2.8]

$$^{ZF}\Gamma_{m,min} \geq \lambda_{min}^2(\mathbf{H}_m)\frac{E_s}{JN_0} \tag{2.6}$$

where $\lambda_{min}(\mathbf{H}_m)$ represents the minimum singular value of channel matrix $\mathbf{H}_m$. $^{ZF}\Gamma_{m,min}$ is the minimum post-processing SNR of the mth subchannel for zero forcing receiver. The expression in (2.6) confirms the intuition that the performance of linear receivers should be improved as the smallest singular value of the channel increases.

When the transmitted signal reaches the receiver; it is correlated by virtue of the geometry at the receiver. If we assume that there is uniform correlation at the receiver in 2×2 MIMO channel, then the correlated channel matrix $\mathbf{H}$ can be expressed as

$$\mathbf{H} = \left[\begin{array}{cc} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{array} \right] = \vartheta_R^{1/2} \mathbf{H}_\omega \beta, \tag{2.7}$$

where

$$\vartheta_R = \left[\begin{array}{cc} 1 & \alpha \\ \alpha & 1 \end{array} \right] \tag{2.8}$$

is a receive correlation matrix and α is a correlation coefficient whose value is in the range of 0 (no correlation) and 1 (full correlation). $\mathbf{H}_\omega$ is a spatially full rank orthogonal channel matrix and in the case of 2×2 MIMO channel, it is expressed as

$$\mathbf{H}_\omega = \left[\begin{array}{cc} 1 & -1 \\ 1 & 1 \end{array} \right]. \tag{2.9}$$

Average channel gain β is defined as the average value of the absolute channel gain of MIMO channel matrix $\mathbf{H}$ and is calculated by using following equation

$$\beta = \frac{1}{R \times J} \sum_{r=1}^{R} \sum_{j=1}^{J} |h_{r,j}| \tag{2.10}$$

The value of $\lambda_{min}(\mathbf{H}_m)$ can be obtained by using SVD method. SVD method decomposes the channel matrix $\mathbf{H}$ into a diagonal matrix $\mathbf{S}$ of the same dimension with
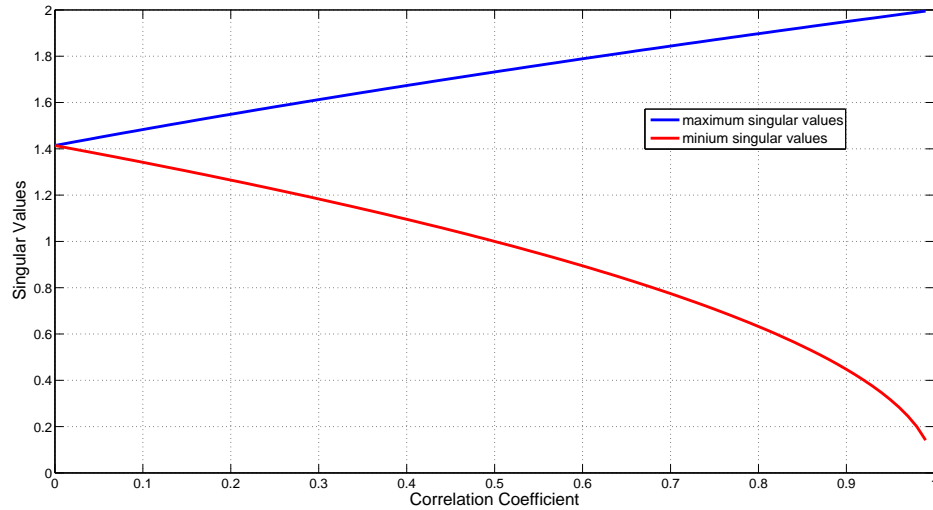
Figure 2.2: Relationship between singular values and correlation coefficient.

non-negative diagonal elements $\lambda(\mathbf{H}_m)$ in decreasing order, and unitary matrices $\mathbf{U}$ and $\mathbf{V}$ so that.

$$\mathbf{H} = \mathbf{U}\mathbf{S}\mathbf{V}^H = \sum_{i=1}^{rank(\mathbf{H})} \mathbf{u}_i\mathbf{s}_i\mathbf{v}_i^H \qquad (2.11)$$

In the above equation, $\mathbf{u}_i$ and $\mathbf{v}_i$ are the left and right singular vectors with $\mathbf{s}_i$ denoting the singular values that are arranged in descending order. The results of singular values obtained by singular value decomposition on channel matrix $\mathbf{H}$ with various channel correlation coefficients and average channel gains are shown in Fig. 2.2 and Fig. 2.3respectively. We draw Fig. 2.2 based on the following conditions:

- 1) The average channel gain β is kept constant to be 1 for all α values to show the relationship between singular values and correlation coefficient.

- 2) The value of correlation coefficient α is changed from 0 to 1 with 0.1 increment in each step.

On the other hand, we draw the Fig. 2.2 based on the following conditions:

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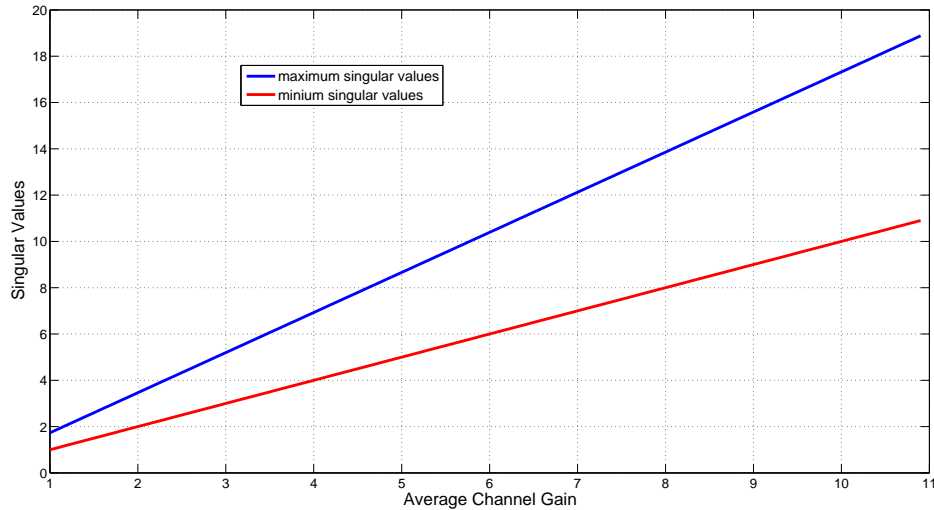
Figure 2.3: Relationship between singular values and average channel gain.

- 1) The spatial fading correlation coefficient α is kept constant to be 0.5 for all β values to get the relationship between singular values and average channel gain.

- 2) The value of average channel gain β is increased from 1 to 11 with 1 increment in each step.

Since we keep one parameter to be constant while the remaining parameter is incremented step by step in these figures, the maximum and minimum singular values become deterministic. Note that in real case, since the channel matrix is random, the values of average channel gain and correlation coefficient are also random. Thus, in our simulation of MIMO-OFDMA system, random variables of α and β are used to obtain the BER performance.

As shown in these figures, the value of $\lambda_{min}(\mathbf{H}_m)$ is effected by two factors. One factor is fading correlation of channel matrix $\mathbf{H}$. As shown in Fig. 2.2, low correlated channel matrix has higher $\lambda_{min}(\mathbf{H}_m)$ value than highly correlated channel matrix. Therefore, fading correlation of channel matrix $\mathbf{H}$ heavily effects on the value of $\lambda_{min}(\mathbf{H}_m)$ for each

subcarrier among users in the system. Fading correlation of the channel matrix $\mathbf{H}$ may also vary from user to user according to their location in the system. The more channel fading is uncorrelated for channel matrix $\mathbf{H}$, the higher value of $\lambda_{min}(\mathbf{H}_m)$ is obtained by singular value decomposition. If the channel matrix $\mathbf{H}$ is an orthogonal channel matrix, then we can get the maximum capacity for the system. On the other hand, highly corre-lated channel matrix has higher $\lambda_{max}(\mathbf{H}_m)$ value than lower correlated channel matrix.

The second factor, which influence on the value of $\lambda_{min}(\mathbf{H}_m)$ is average channel gain of the channel matrix $\mathbf{H}$. Figure. 2.3 shows the relationship between average channel gain and $\lambda_{min}(\mathbf{H}_m)$ value. Channel matrix with higher average gain has higher singular value than channel matrix with lower channel gain under the same fading correlation condition. Because of the various locations of the users in the system, there may be different channel gains among users in the system. Therefore, their channel gains may be varied from user to user. Some users may have better channel gain and higher $\lambda_{min}(\mathbf{H}_m)$ values than other users who have lower channel gains. In Fig. 2.3, we can see that both $\lambda_{max}(\mathbf{H}_m)$ and $\lambda_{min}(\mathbf{H}_m)$ values are increased when channel gains are increased under the same fading correlation condition.

In the MIMO system, good channel condition has low correlated fading channel ma-trix and higher channel gains. We can know the best channel for each user based on these two factors. But sometimes one user may have good channel gain with highly correlated channel matrix and the other user may have low channel gain with low correlated chan-nel matrix. In this condition, it is very difficult to consider the best channel condition by simultaneously comparing the average channel gain and fading correlation. Fortunately, these average channel gain and fading correlation are directly related to $\lambda_{min}(\mathbf{H}_m)$ and we can know the better channel condition by comparing these $\lambda_{min}(\mathbf{H}_m)$ values. Therefore,

$\lambda_{min}(\mathbf{H}_m)$ can be used as an appropriate performance indicator to choose the best m^{th} subchannel for k^{th} user.

Our aim is to maximize the total data throughput under the constraints of total transmit power and proportional data rate fairness among users in the system. The allocation problem is formulated as:

$$max(C_{total}) = max\left(\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{j=1}^{J}b_{k,j,m}\right), \tag{2.12}$$

subject to:

$$\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{j=1}^{J}e_{k,j,m}(b_{k,j,m}) \leq P_{total}, \tag{2.13}$$

$$\frac{C_1}{\rho_1} = \frac{C_2}{\rho_2} = \frac{C_K}{\rho_K}, \tag{2.14}$$

where $\frac{C_k}{\rho_k}$ ($k = 1, 2, \cdots K$) is a predetermined rate ratio of user k in the system. C_{total} and P_{total} are total data rate and total available transmit power in the system, respectively. The convex function $e_{k,j,m}(b_{k,j,m})$ represents the amount of energy necessary to transmit $b_{k,j,m}$ bits from the jth base station transmit antenna to the kth user on the mth subcarrier.

Subcarriers, bits and power should be allocated jointly to achieve the optimal solution in (2.12). However this causes the high computational complexity at the base station in order to reach the optimal allocation. Moreover, base station has to compute optimal subcarrier, bits and power allocation as the wireless channel changes frequently. Hence, we separate the resource allocation scheme into two steps by using joint subcarriers allocation and bit loading algorithm, and power distribution algorithm, to reduce the complexity, while still delivering the proportional data rate fairness among users in the systems.

In the first step, subcarrier allocation to each user and bit loading to the assigned subcarrier are jointly calculated based on the $\lambda_{min}(\mathbf{H}_m)$ value and minimum SNR for each

transmit antennas under the constraint of date rate ratio among users in the system. We will use the value of $\lambda_{min}(\mathbf{H}_m)$ to choose the best subcarrier for each user. After choosing the best subcarrier for each user, it is necessary to calculate the number of bits for that particular subcarrier to know the data rate for each user to give the data rate ratio requirements among users in the system. In the MIMO system, different transmit antennas of different users might have different channel condition. Therefore, it is possible to transmit the different number of bits with different transmit power according to the particular transmit antenna's channel conditions. So, different power loading can be applied to each transmit antenna according to the channel condition of particular transmit antenna's channel condition. Here we transmit the same amount of bits from each transmit antennas for particular subcarrier to reduce the complexity of ZF VBLAST receiver. Therefore, the number of bits to be transmitted is calculated based on the worst transmit antenna's channel gain for predetermined subcarrier assignment. After assigning the subcarrier and number of transmitted bits for each subcarrier among users in the system, power allocation is done for each subcarrier based on the channel condition of each transmit antennas for the user. Section 2.3.1 and 2.3.2 explain the joint subcarrier and bit allocation algorithm with SVD method and adaptive power loading, respectively.

2.3.1   Joint Subcarrier Allocation and Bit Loading Algorithm

In this joint subchannel allocation and adaptive bit loading algorithm, equal power distribution is assumed among all subchannels. At first, the best subcarrier is chosen by each user in the first iteration from user 1 to k according to their $\lambda_{min}(\mathbf{H}_m)$ value. After the first time round robin iteration, it is necessary to know their data rates for the requirement of

proportional data rate ratios among users in the system. Therefore, the number of bits to be transmitted in the chosen subcarrier is estimated as

$$b_{k,j,m}^{est} = \log_2 \left(1 + \frac{SNR_{k,m}^{min}}{GAP} \right), \quad (2.15)$$

where $SNR_{k,m}^{min}$ denotes minimum SNR among the base station transmit antennas to the kth user on m^{th} subcarrier. GAP is SNR gap, which is tuning parameter that characterizes the bit error rate (BER) performance of the system. Different values of GAP yield different SNR threshold levels for adaptive number of bit loading. The meaning and derivation of (2.15) are described in Appendix A.1. The adaptive loading equation in our proposed scheme is a low complexity method to achieve power and rate optimization based on knowledge of the subchannel gains [2.9]. This adaptive bit loading algorithm has five possible square MQAM signal constellations modes, which are no transmission, BPSK, QPSK, 16QAM and 64QAM. We use (2.15) to calculate the suitable bits for each user's predetermined subcarrier allocation. To get the simple decoding at the receiver side, we will use the same number of bits on all of the base station transmit antennas to the kth user on m^{th} subcarrier. Therefore, we omitted the subscript j in $b_{k,j,m}$ the $b_{k,m}$ symbol and used symbol to be simplified. The case $b_{k,m} = 0$ implies no data transmission for the particular carrier. By using (2.15), we get the estimated numbers of bits for k^{th} user on m^{th} subcarrier. The estimated numbers of bits $b_{k,m}^{est}$ is not integer number. So, the integer value $b_{k,m}$ is obtained by rounding the value of $b_{k,m}^{est}$ to the nearest mapped symbol which conveys either 0,1,2,4 or 6. The relationship between bits and required SNR is non-linear, because of the semi-log relationship between bits and SNR values. It means that much more SNR is required to use higher QAMs constellation compared with BPSK and QPSK modes to meet the same BER requirement [2.10]. The data rate for each user is necessary

to update by using (2.15) to get the resultant data rate for each user. The algorithm can be described as follows:

Step 1: Initialization (first time round robin)

a) Set $C_k = 0, \omega_k = \phi$ for $k = 1, 2 \cdots K$

b) Set $A = 1, 2, \cdots M$.

Step 2: For $k = 1$ to K,

a) Find m satisfying $\left|\lambda_{min(k,m)}\right| \geq \left|\lambda_{min(k,i)}\right|$ for all $i \in A$

b) Let, $\omega_k = \omega_k \cup m$, $A = A - m$ and update C_k by using (2.15).

Step 3: While A is not equal ϕ, ,(after first time round robin)

a) Find k satisfying $C_k/\rho_k \leq C_i/\rho_i$, for all $i, 1 \leq i \leq K$,

b) For the found k, find m satisfying $\left|\lambda_{min(k,m)}\right| \geq \left|\lambda_{min(k,i)}\right|$ for all $i \in A$

c) For the found k and m, let $\omega_k = \omega_k \cup m$, $A = A - m$ and update C_k by using (2.15).

Step 4: The step 3 is repeated until all M subchannels have been allocated.

Here, we assume that the total number of available subcarriers is much greater than the total number of users in the MIMO-OFDM system. The principal of the subchannel algorithm is for each user to use the subchannels with the largest value of minimum eigenvalue in channel matrix as much as possible. In the first time round robin, every user has a chance to choose the best subcarrier for him and his data rate is also calculated by using (2.15) and updated according to his subcarrier assignment. After completing the first time round robin, the user with the lowest proportional capacity has the option to pick which subchannel to use and also update his data rate. This process is repeated until all available subchannels are allocated to the users in the MIMO-OFDMA system. This joint subchannel allocation and adaptive bit loading algorithm gives the proportional rate fairness among users in the system.
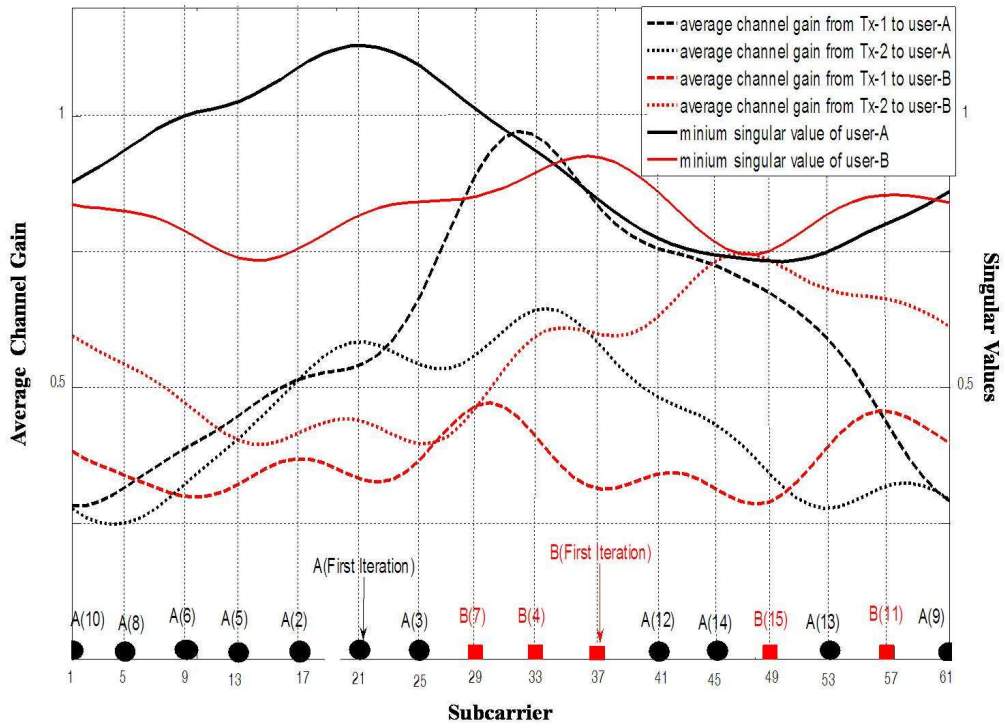
Figure 2.4: Results of subcarrier allocation in the proposed scheme.
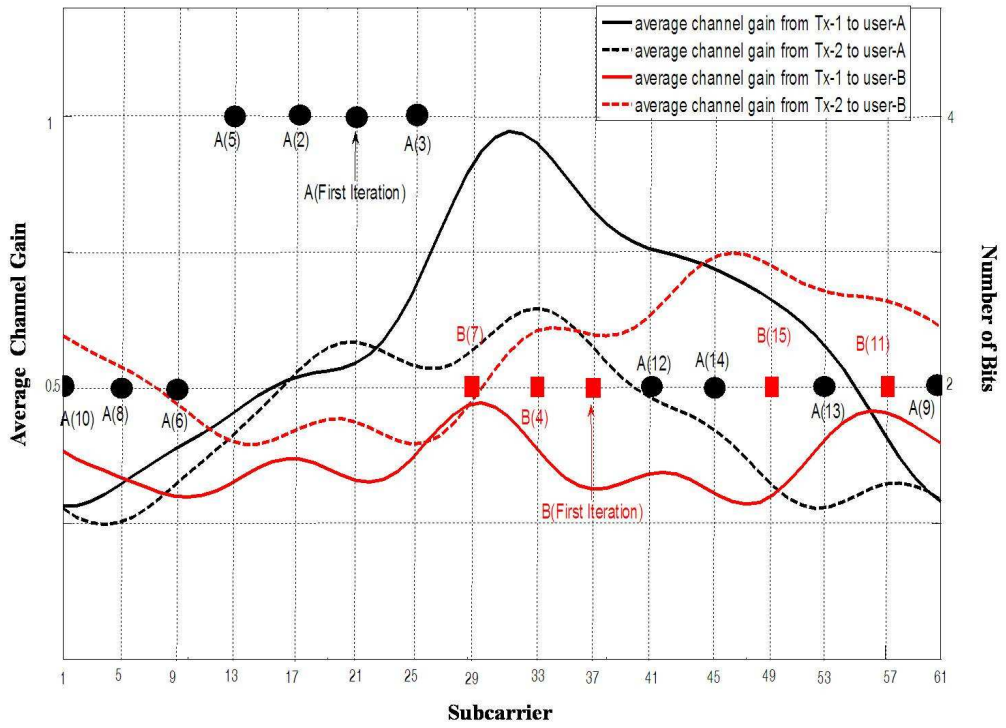
Figure 2.5: Results of adaptive bit loading in the proposed scheme.

The result of joint subcarrier allocation and adaptive bit loading algorithm is also shown in Fig. 2.4 and Fig. 2.5 based on two users (user A and user B) with different channel conditions. In these figures, we consider 2×2 MIMO-OFDMA system with 3:1 proportional data rate ratio between two users in the system. That is, in the joint subcarrier and bit allocation algorithm, it is the required to assign subcarriers and bits to satisfy that the data rate of user A will be three times higher than that of user B's data rate. Note that, in order to show the results of our proposed algorithm clearly, only 16 subcarriers among 64 subcarriers whose extracted subcarrier numbers are $1, 5, 9, \cdots, 61$ are illustrated. At the first time round robin both users will have a chance to choose the best subcarrier for them based on the corresponding minimum singular values. Each user will select the subcarrier which has the largest minimum singular values from the available subcarriers. The selected subcarriers in the first iteration for user A and user B are shown in Fig. 2.5 as A(First Iteration) on subcarrier 21 and B(First Iteration) on subcarrier 37, respectively. Then, the estimated numbers of transmitted bits are calculated based on the equal power distribution and using (2.15). Their estimated numbers of bit are mapped to the nearest constellation mode for the actual transmission as shown in Fig. 2.5. After the first time round robin allocation, we have to check the remaining subcarriers for the next iteration process. In this case, 14 subcarriers are remaining to be allocated in the system. This step is called 'while loop' step, where user with less data rate ratio which is the ratio of allocated data rate and required one. If user A has less data rate ratio than user B, then, in the second iteration, user A will have a chance to choose the best subcarrier among available subcarrier, that is, A(2) on subcarrier 17 as shown in Fig. 2.4. Similarly, if user B will have a chance to choose the best subcarrier for him, this iteration number will be noted as B(iteration No) on the selected subcarrier. After assigning the best subcarrier in each iteration, their data rates are updated by using (2.15) and mapping the result to the

nearest constellation mode for the actual transmission. This 'while loop' step is repeated until all subcarriers are allocated among users in the system.

In the next section, we describe the adaptive power loading algorithm for each user under predetermined subcarrier and bit assignment in the system.

2.3.2 Power Loading Algorithm

In the previous step, we assigned the number of bits on m^{th} subcarrier dependent on the minimum SNR of jth base station transmit antennas to the kth user. At first, we assume the same modulation level on m^{th} subcarrier to transmit the data from all of the base station transmit antennas to the kth user. Then, we use (2.15) to determine the modulation level on m^{th} subcarrier for k^{th} user in the MIMO-OFDMA system. But each mth subcarrier has different level of channel gains for each base station transmit antennas. Therefore, it is necessary to calculate each antenna's transmit energy for the same number of $b_{k,m}$ on m^{th} subcarrier. Thus, after processing this joint subcarrier and bit allocation step, we can distribute the power by using the following equation to calculate the $e_{k,j,m}(b_{k,m})$ transmit energy for $b_{k,m}$ bits from the jth base station transmit antenna to the kth user on m^{th} subcarrier with $SNR_{k,j,m}$ level.

$$e_{k,j,m}(b_{k,m}) = \left(2^{b_{k,m}} - 1\right) \frac{GAP}{SNR_{k,j,m}}, \qquad (2.16)$$

The derivation of (2.16) is described in Appendix A.2. The available total transmit power is distributed to the space and frequency according to the result of $e_{k,j,m}$. The results of power distribution on each transmit antenna and subcarrier between two users in 2×2 MIMO system in the proposed system are also shown in Fig. 2.6. It is shown that in each subcarrier the appropriate transmit power is assigned to each transmit antenna according to the average channel gain.
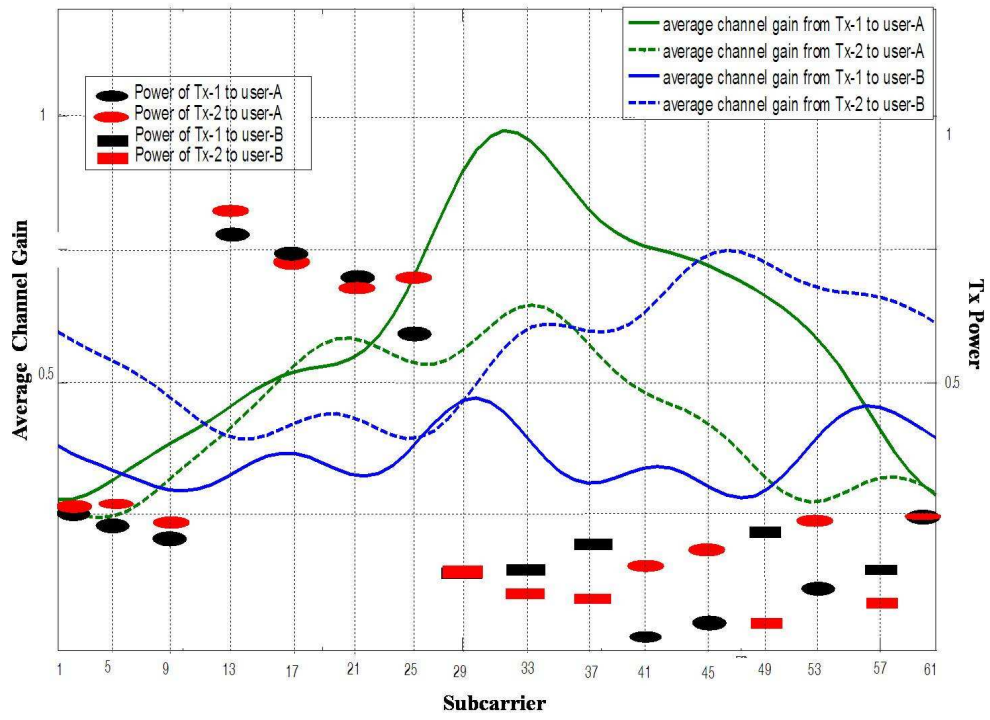
Figure 2.6: Result of power distribution in the proposed scheme.
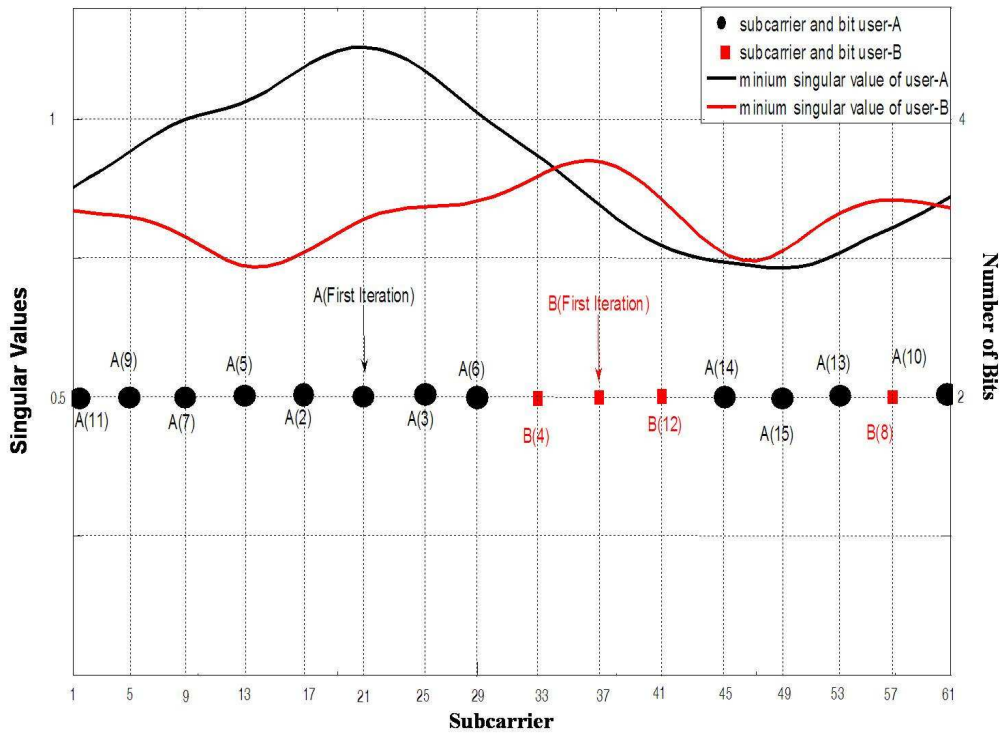
Figure 2.7: Results of subcarrier allocation in the conventional scheme [2.5].

Fig. 2.7 shows the results of subcarrier allocation by using scheme in [2.5] to compare the subcarrier allocation in our proposed scheme. The number of users is 2 and the proportional data rate ratio among users in the system is 3:1. The conventional scheme in [2.5] uses inefficient proportional rate fairness resources allocation methods for the system. That just divides the 16 subcarriers into 12:4 to give the 3:1 proportional rate fairness among users in the system. That does not consider about different channel condition in the space and frequency domains among users in the system. On the other hand, our proposed scheme uses the efficient proportional rate fairness resources allocation method for the system. We assign the subcarriers to the users under the consideration of different channel condition in space and frequency domain. That's why we can use the different numbers of adaptive bit and different amount of power loading in each subcarrier for the efficient usages of system resources in the system to give the better system performance under the constraint of proportional rate fairness among users and total transmit power in the system.

2.4   Simulated Results

In our simulations, we use a channel model with frequency selective Rayleigh fading. We assume that all users have independent fading channel characteristics. Simulation parameters are shown in Table. 2.1. To obtain the frequency selective Rayleigh fading properties of the wireless channel with multipath environment, we used the fading channel model expressed in [2.11]. The channel condition generated by this channel model will vary from one channel instant to another according to the random parameters in the various channel condition among users in the simulation.

To give the fair comparison between our proposed scheme and other bit loading and resource allocation schemes, we have to consider the followings. Our proposed scheme

Table 2.1: Simulation Parameters

Parameter	Value
Modulation levels	0, 1, 2, 4, 6
Number of subcarriers	64
FFT sampling	64 samples
Guard interval	16
Number of users	2, 4, 8
Channel estimation	Pilot symbol aided
Doppler frequency	30Hz
Multipath	6
Number of Tx&Rx antennas	2 & 4
RMS delay spread	50ns
Bandwidth	20 MHz
No of OFDM symbols/ packet	12 OFDM symbols
GAP	0 dB

is the combination of MIMO and OFDM technologies. However, most of them considered only in MIMO or OFDMA systems. Also, equal fairness as well as proportional fairness should be considered for the fair comparison. Therefore, we pick up some papers which consider proportional data rate fairness among users in the MIMO-OFDMA system. Among these MIMO-OFDMA and proportional data rate fairness related papers, we choose [2.5] to compare our proposed scheme, which has some weak points to use the system resources efficiently. It does not consider the various channel condition in the wireless system since it chooses the best carriers for each user and then applies the fixed allocation of power and bits to all of the allocated subcarrier. To use the system resources efficiently, it is necessary to use the adaptive bit and power loading. In that case, it might not give the guarantee for proportional data rate fairness among users in the system, since it assigns the resources without considering various channel condition in frequency and space domain of the system. On the other hand, in our proposed scheme, we can use not
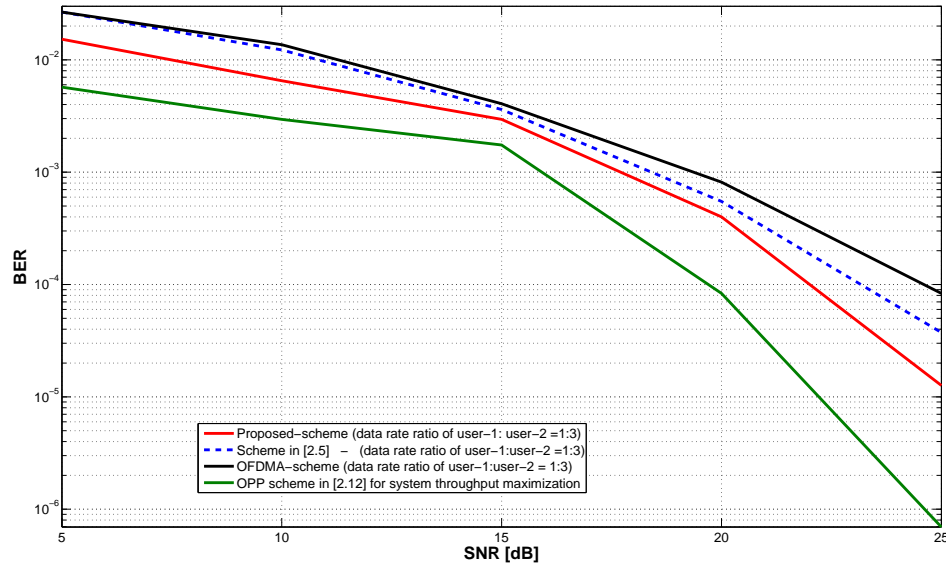
Figure 2.8: BER Performance comparison among the proposed and conventional schemes with 2 users and data rate ratio of 1:3.

only the system resources efficiently but also give the guarantee for proportional data rate fairness among users in the system.

We also use the opportunistic scheduling (OPP) scheme in [2.12] to compare with our proposed scheme. OPP allocates each subcarrier to the user with highest value of minimum singular values without considering proportional data rate fairness among user in the system to achieve maximum total system capacity. After allocating subcarriers among users in the system, adaptive bit and power loading techniques are applied. This maximization of throughput comes at the cost of ignoring proportional data rate fairness in the system.

Fig. 2.8 shows comparison of BER performance of the OFDMA fixed allocation scheme, the scheme in [2.5], OPP scheme in [2.12] and the proposed scheme, where the number of users is 2 and data rate ratio is 1:3. In the OFDMA allocation schemes and scheme in [2.5], the modulation methods are 64QAM and the proposed scheme uses

the adaptive modulation respectively. In the lower SNR level the BER performance of the proposed scheme is better than fixed allocation scheme and the scheme in [2.5] because of robust modulation mode as well as better channel allocation for the users in each subcarrier. OPP scheme gives the best BER performance, since the best user is being selected for every subcarrier allocation step, whereas data rate fairness is not achieved. We can see that at 15 dB SNR there is a turning point in our scheme. This is because of the starting point of the highest modulation mode. This condition depends on the value of GAP in (2.15) and (2.16). When the average SNR is 15 dB, the maximum modulation mode (64QAM) can used, since 15 dB is good enough to use it. When SNR level is much larger than 15 dB, we still have to use 64 QAM due to the limited constellation mode in the system, and thus, we can not increase the modulation level anymore. Of course, due to higher SNR values with the same modulation mode, the BER performance becomes better. In the lower SNR region (less than 15 dB case), the proposed system can use the lower robust modulation mode for the transmitting in the allocated subcarrier (such as BPSK, QPSK or 16QAM). Because of lower modulation mode, the BER performance is better than 15 dB point, whereas the throughput is smaller than that of 15 dB point. That is the trade off between BER and throughput performance.

However, BER performance of the proposed scheme is still better than fixed allocation schemes not only in low SNR region but also in high SNR region with equal modulation mode of 64QAM. That is because not only better subcarrier allocation but also adaptive bit and power distribution on space and frequency of the system are efficiently utilized.

However, BER performance of the proposed scheme is still better than fixed allocation schemes not only in low SNR range but also in high SNR range with equal modulation mode of 64QAM. That is because not only better subcarrier allocation but also adaptive bit and power distribution on space and frequency of the system are efficiently utilized.
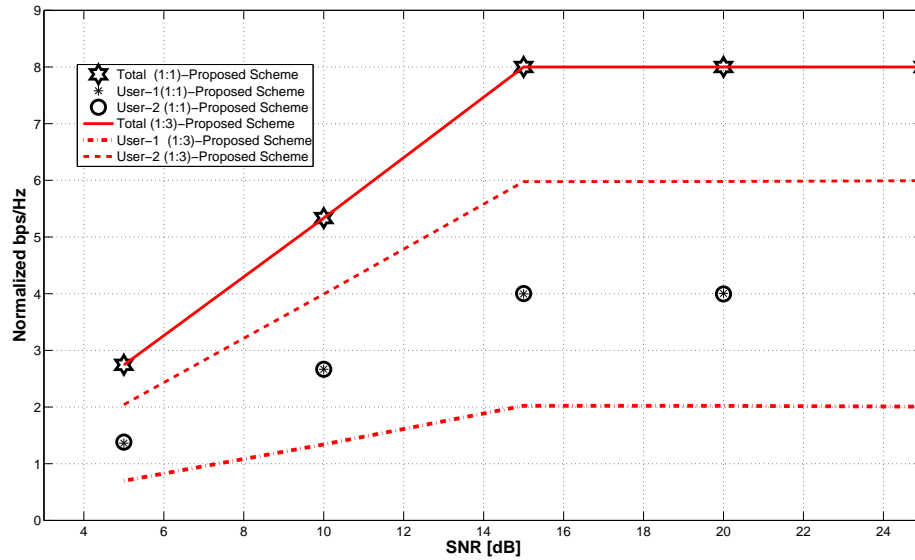
Figure 2.9: Throughput distributions between user-1 and user-2 in adaptive systems with data rate ratio of 1:1 and 1:3, respectively.

The simulated results are shown in Fig. 2.9 for the throughput distribution of user-1 and user-2 in the proposed scheme with proportional data rate ratio of 1:3,and 1:1. System uses robust modulation modes in the low SNR range and high modulation modes in the high SNR range to give the better performance. We can see that the proposed scheme can give the exact proportional data rate fairness among users in the system.

Fig. 2.10 shows comparison of BER performance of the OFDMA scheme, scheme in [2.5] and the proposed scheme with different number of users, where the number of users is 2 and 8, respectively. We also apply the equal fairness among users in the system. We can see that the BER performance of the proposed scheme is better than the scheme in [2.5] for not only fewer users but also larger users in the system. It is also shown that the BER performance is better when the number of users is increased. This is because of the increase in degree of freedom to choose the better subcarriers from each user in the
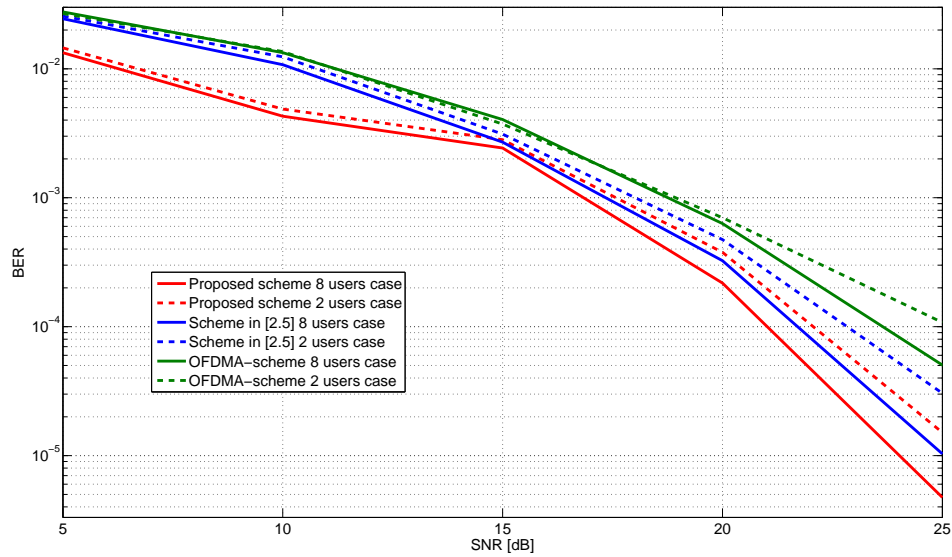
Figure 2.10: Performance comparison between proposed and fixed allocation scheme with 2-users and 8-users case and data rate ratio of 1:1 and 1:1:1:1:1:1:1:1 , respectively.

system. If the number of users is increased, there has more chance to apply the efficient bit and power loading to the best subcarrier in the system.

The throughput distribution of user 1 and user 2 with data rate ratio of 1:3 of our scheme and OPP scheme is shown in Table. 2.2, when the number of transmitted packets is 100 and 10000, respectively. We can see that our proposed scheme can give the exact proportional data rate fairness of 1:3 case not only in the smaller number of transmitted packets but also in the larger number of transmitted packets in the system. Thus, the system performance as well as the proportional data rate fairness among users in the system can be improved whether the number of users in the system is increased or not. On the other hand, in OPP scheme the proportional data rate ratio requirement of 1:3 can not be satisfied. When the number of transmitted packet is small, the average channel condition changes more among users and the user with higher channel condition might use most of the system resource to maximize total system capacity throughput. Therefore, in OPP

Table 2.2: Throughput distributions between user 1and user 2 in the proposed scheme with data rate ratio of 1:3 and OPP scheme in [2.12].

Scheme	No. of Packets	User	SNR=5dB	SNR=10dB	SNR=15dB	SNR=20dB	SNR=25dB
Proposed	10000	Total	2.66765	5.33085	7.95977	8.0	8.0
		User-1	0.67131	1.34400	2.01411	2.02163	2.01982
		User-2	1.99634	3.98685	5.94566	5.97837	5.98018
	100	Total	2.66667	5.33333	7.95917	8.0	8.0
		User-1	0.67	1.35499	2.00542	2.02875	2.02625
		User-2	1.99667	3.97834	5.95375	5.97125	5.97375
OPP [2.12]	10000	Total	2.66775	5.33376	7.95645	8.00	8.00
		User-1	1.33767	2.66074	3.96979	4.052	4.022
		User-2	1.33008	2.67302	3.98666	3.948	3.978
	100	Total	2.73945	5.33456	8.00	8.00	8.00
		User-1	1.33683	2.65231	3.058	4.038	4.00
		User-2	1.40262	2.68225	4.942	3.962	4.00

scheme, there has no guarantee for any proportional data rate fairness. When the number of transmitted packets becomes large, the difference in the average channel condition among users decreases, since the random channel model is used in our simulation, and therefore, the data rate ratio among users in the system will be 1:1 in OPP scheme.

2.5 Conclusion

I have proposed a dynamic resource allocation scheme for MIMO-OFDMA system to improve the BER and throughput performance with considering users' data rate requirement for different condition of data throughput requirement in the system. Computer simulated results show that the proposed scheme achieves better performance than fixed allocation scheme for different data rate ratios and different number of users in the system. Also it is shown that the proposed scheme can give the proportional data rate fairness among users in the system.

In general, we can see that there must be an optimal subcarrier and power allocation scheme that satisfies the proportional fairness among users and total power constraint. This optimal scheme will use power more efficiently than our suboptimal scheme. The

reason is as follows. First, to a certain user, the capacity of the user is maximized if the water filling algorithm is adopted for both frequency and space domains. Second, the capacity function is continuous with respect to the total available power to that user. In other words, C_k is continuous with transmit power of k user. Therefore, if the optimal allocation scheme does not use all available transmit power, there is always a way to redistribute the unused power among users while maintaining the capacity ratio constraints, since C_k is continuous with the transmit power for all k users. Thus, the sum capacity might further increase if the optimal scheme is used with higher computational complexity.

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Chapter 3

Proportional Data Rate Fairness Resource Allocation for Multiuser MIMO-OFDM Uplink System

The performance of multi-user MIMO-OFDM Multiple Access Channel (MIMO-OFDM-MAC) Uplink systems can be significantly increased by using adaptive transmission and efficient resource-allocation scheme in the system. In the MIMO-OFDM-MAC scenario, the base station decides centrally on the optimal bit loading and subcarrier allocation as well as transmit antenna selection from multiple users based on channel state information (CSI) in the system. There have a lot of papers which have done on the resource allocation in MIMO-OFDM system. But most of them consider in MIMO-OFDM downlink and very few papers consider to give the fairness among users. Moreover, there has no paper which considers to give the proportional data rate fairness among user in the uplink MIMO-OFDM-MAC system. In this paper, resource allocation for spatial and spectral dimension and adaptive bit loading scheme is proposed to improve the total system capacity under the constraint of total transmit power and target bit error rate (BER) for each user and proportional data rate fairness among users in the uplink MIMO-OFDM-MAC

system. Simulated results show that the total system capacity is increased under the constraint of each user's total transmit power and predetermined target BER. And at the same time, the proposed scheme also guarantees the proportional data rate fairness requirement among users in the system.

3.1 Introduction

Spatial Multiplexing offers high channel capacity and transmission rate without increasing the transmission bandwidth by employing multiple antennas at the transmitter and receiver sides. But, high data transmission is limited by Inter-Symbol-Interference (ISI) and antenna correlation in the transmitter or receiver sides. However, Orthogonal Frequency Division Multiplexing (OFDM) and space division multiple access (SDMA) technology can be used to reduce the ISI and the transmit antenna correlation in the user sides [3.1].

Users of MIMO-OFDM-MAC system can observe rich scattering multipath fading in non-line of sight (NLOS) or strong Rician fading with (LOS) condition due to their different locations in the system. For the users with NLOS cases, they can have independent fading parameters for their subcarrier and transmit antenna, and thus, correlation in their channel might be quite low [3.2]. Moreover, the probability that a subcarrier in deep fading for one user may also be in deep fading for other users is quite low. In the later case, user with LOS condition, each user's transmit antenna correlation might be quite high but the transmit antenna correlation among users in the system might be quite low because of the different space locations in the system. Hence, multiuser system creates channel diversity as the number of user increases. Therefore, in MIMO-OFDM-MAC environment, the system needs to allocate the system resources efficiently in space and frequency domain to avoid the antenna correlation in the space domain and deep fade in the frequency domain according to each user's channel state information (CSI) in the system.

In most of the resource allocation scheme, it is emphasized to give the maximum system capacity by scarifying the users with worst case channel condition in the system. Because of the various channel conditions among different users, the user with higher average channel gains might use most of the system resources [3.3]. Therefore, it is necessary to consider the fairness among different users in the system. Research of resource allocation for multiuser MIMO OFDM environments with different data throughput requirement for each user is still an open research field, though some researches are done about rate fairness among users in the MIMO-OFDMA system [3.4]. However, they do not consider about MIMO-OFDM-MAC system. Because, they simplified their schemes by multiplexing the users in the frequency domain. Therefore, it is truly necessary to develop the efficient resource allocation scheme for MIMO-OFDM-MAC system with predetermined target BER and proportional data rate fairness among users under the constraint of total transmit power for each user in the system.

In the proposed scheme, subcarrier and transmit antenna allocation is performed based on singular value decomposition (SVD) and channel gain for each user. The user with lowest data rate ratio in the system will choose a subcarrier which channel matrix has the largest minimum SVD. If his transmit antenna elements are highly correlated, then these transmit antennas will be separated in the frequency domain. After selecting the subcarrier, this user will choose the higher channel gain transmit antenna. By using this combining selection method it can choose low correlated transmit antenna as well as higher channel gain for particular user. Simulation results show that the system performance is improved as well as capacity is proportionally distributed among users in the MIMO-OFDM-MAC systems.
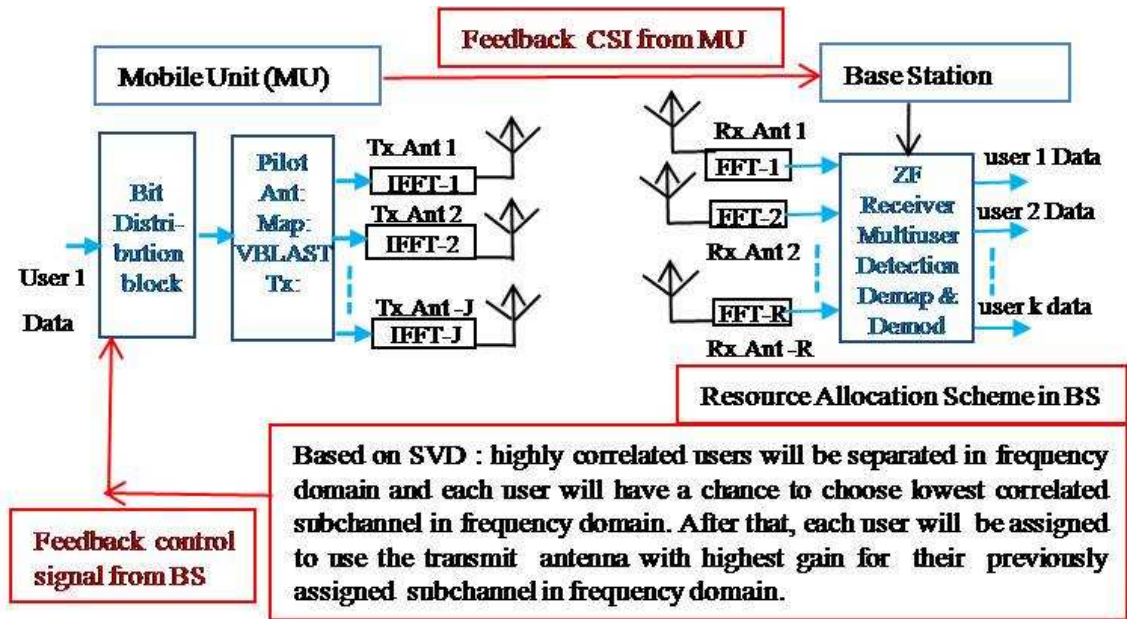
Figure 3.1: System Model.

This chapter is organized as follows. Section 3.2 introduces MIMO-OFDM-MAC system model under consideration. Section 3.3 describes the proposed resource allocation scheme and bit loading for space and frequency domain in the system. Section 3.4 shows simulation results, and conclusion is shown in section 3.5.

3.2 System Model

In the system model the following assumptions are made: (a) the channel is quasi static remains unchanged from the time that measurements are made until the data packet is transmitted; (b) every user has enough data packets to transmit any time; (c) each user feedbacks a certain form of channel information correctly to the base station (BS) and using this CSI the base station decides the uplink transmission parameters for each user based on given criterion. The decision parameters are then feedbacked to each user via the control channel for their uplink transmission. We introduce the idea of proportional

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fairness into the system by adding a set of rate ratio constraints. The benefit of introducing proportional fairness into the system is that we can explicitly control the capacity ratios among users, and ensure that each user is able to receive a fair amount of data throughput according to his predetermined data rate ratio among users.

Fig. 3.1 shows the block diagram of our system model under consideration. We consider the uplink of MIMO-OFDM-MAC system equipped with M subcarriers and R receives antennas at base station. There are K users, each of which has J transmit antennas. For our system, the receive antenna number at base station must be greater than or equal to the sum of the selected transmit antennas from the selected users to obtain acceptable spatial separability of the transmitted data in the system. Several users can share the same subcarrier in frequency domain to make full use of the spatial dimension. Every selected user and its selected transmit antennas can transmit the independent data stream to the base station and these transmitted data streams are jointly detected by using zero forcing (ZF) receiver to cancel the interference and to recover the original transmitted data from each user. The whole frequency bandwidth is divided into M parallel subcarriers and they can be transformed into the flat fading channel condition by using OFDM technology, and thus, the complicated MIMO detection for frequency selective fading channel can be simplified as that in a flat fading channel. In this chapter, vectors and matrices are denoted by boldface letters. Set and empty set are denoted by $\{\}$ and ϕ. The channel matrix of user k on subcarrier m is $R \times J$ matrix and it is denoted by

$$\mathbf{H}^{k,m} = [\mathbf{h}_1^{k,m}, \cdots, \mathbf{h}_j^{k,m}, \cdots, \mathbf{h}_J^{k,m}] = \begin{bmatrix} h_{1,1}^{k,m} & h_{1,2}^{k,m} & \cdots & h_{1,J}^{k,m} \\ h_{2,1}^{k,m} & h_{2,2}^{k,m} & \cdots & h_{2,J}^{k,m} \\ \vdots & \vdots & \ddots & \cdots \\ h_{R,1}^{k,m} & h_{R,2}^{k,m} & \cdots & h_{R,J}^{k,m} \end{bmatrix}, \qquad (3.1)$$

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where $h_{r,j}^{k,m}$ is the channel gain from the jth transmit antenna to the rth receive antenna of kth user on m^{th} subcarrier and $\mathbf{h}_j^{k,m}$ is the jth column vector from $\mathbf{H}^{k,m}$. Based on CSI from all users, the general MIMO channel matrix between the base station and all users on the mth subcarrier can be constrcuted as follows:

$$\mathbf{H}^m = [\mathbf{H}^{1,m}, \cdots, \mathbf{H}^{k,m}, \cdots, \mathbf{H}^{K,m}].$$

To get the maximum sum capacity in the system, we will select not only a user in the system but also a transmit antenna from each selected user. If we assume that the selected user set to transmit on m^{th} subcarrier is $\overline{U}^m \subset \{1, \cdots, k, \cdots, K\}$ and the selected transmit antennas for k^{th} user on m^{th} subcarrier is expressed by $\overline{T}^{k,m}$, then the cardinal number of the elements of set $\overline{T}^{k,m}$ is less than or equal to J. By using these two subsets $\overline{U}^m$ and $\overline{T}^{k,m}$, we can construct the selected subchannel matrix $\overline{\mathbf{H}}^m \subset \mathbf{H}^m$. After deciding the subchannel matrix $\overline{\mathbf{H}}^m$, the post-detection SNR for the signal from the jth transmit antenna of kth user in selected subchannel matrix $\overline{\mathbf{H}}^m$ can be expressed as:

$$SNR_j^{k,m} = \frac{p_j^{k,m}}{N_0 \|\mathbf{g}_j\|^2}, \tag{3.2}$$

where, $p_j^{k,m}$ is the transmit power from the jth transmit antenna, N_0 is the noise power and $\mathbf{g}_i$ is the ZF detection weight vector and can be obtained from the jth row of pseudo-inverse of $\overline{\mathbf{H}}^m$. At m^{th} subcarrier, the selected users will transmit by using their selected transmit antenna set and the total received signal in BS is expressed as:

$$\mathbf{r}^m = \sum_{k \in \overline{U}^m} \sqrt{p^{k,m}} \overline{\mathbf{H}}^{k,m} \mathbf{s}^{k,m} + \mathbf{n}^m, \tag{3.3}$$

where $\mathbf{r}^m$ is a $R \times 1$ receive vector on m^{th} subcarrier, $\mathbf{s}^{k,m}$ is the complex transmitted signal vector and $\mathbf{p}^{k,m}$ is the power allocation vector for k^{th} user. $\mathbf{n}^m$ is the $R \times 1$ noise vector and

its elements are independent identically distributed (i.i.d) circularly symmetric complex Gaussian variables with zero-mean and variance of N_0.

3.3   Adaptive Resource Allocation for the System

Base station uses Vertical-Bell Laboratories-Layered-Space-Time (V-BLAST) algorithm implementation based on ZF detection combined with symbol cancellation to improve the performance while maintaining low implemental complexity [3.5]. When symbol cancellation is used, the order in which the sub-streams are detected becomes important for the overall performance of the system. Performance of spatial multiplexing with linear receivers depends on the minimum SNR induced by the particular subset of transmit antennas. The transmitted symbol with the smallest post detection SNR will dominate the error performance of the system [3.6]. For the ZF receiver, the post-processing SNR of the worst m^{th} sub-stream is expressed in [3.6]

$$^{ZF}\Gamma_{min}^m \geq (\lambda_{min}^m)^2 \frac{p_T^m}{\overline{J}^m N_0} \tag{3.4}$$

where p_T^m is the total transmit power on that subcarrier and $\overline{J}^m$ is the number of selected transmit antenna and λ_{min}^m represents the minimum singular value of subchannel matrix $\overline{\mathbf{H}}^m$. $^{ZF}\Gamma_{min}^m$ is the minimum post-processing SNR of the mth subchannel for zero forcing receiver. Therefore, we will select the best user by using their minimum singular values on each subcarrier. Moreover, it has been shown in [3.4] that, minimum singular value has a strong relationship between the antenna correlation in the channel matrix. If particular user faces the strong LOS effect which causes the high antenna correlation and this will give the result of very low minimum singular value in his channel matrix. By using largest minimum singular value, we can give not only the best SNR for particular user but also

the avoidance of high antenna correlation in the system. After decided the best subcarrier by the selected user, he will select the highest gain transmit antenna for that subcarrier.

Our aim is to maximize the total system capacity under the constraints of target BER and total transmit power for each user and proportional data rate fairness among users in the system. The allocation problem is formulated as:

$$max(C_{Total}) = max \left(\sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{j=1}^{J} b_j^{k,m} \right), \tag{3.5}$$

subject to:

$$\sum_{m=1}^{M} \sum_{j \in \overline{T}^{k,m}} p_j^{k,m} \leq P_{Total}^k, \tag{3.6}$$

$$BER_{actual}^k \leq BER_{target}^k, \tag{3.7}$$

$$\sum_{k \in \overline{U}^m} \sum_{j \in \overline{T}^{k,m}} t_j^{k,m} \leq R, \tag{3.8}$$

$$\frac{C^1}{\rho^1} = \frac{C^2}{\rho^2} = \frac{C^K}{\rho^K}, \tag{3.9}$$

where, C_{Total} and P_{Total}^k are total data rate for the whole system and total available transmit power for each user, respectively. According to (3.6), k^{th} user's transmit power is limited by P_{Total}^k. Equation (3.7) ensures that the actual BER of each user is lower than the predetermined target BER. $t_j^{k,m}=1$ for selected transmit antenna for k^{th} user on m^{th} subcarrier and $t_j^{k,m}=0$ for unselected case. Equation (3.8) ensures that the total number of selected transmit antennas from all of the users in m^{th} subcarrier can not be larger than the avaliable receive antennas in the base station. This limitation will give the acceptable spatial separability of transmitted data from the users. $\frac{C^k}{\rho^k}$ is a predetermined rate ratio of user k in the system and it guarantees to give the proportional data rate fairness among user as stated in (3.9). To achieve the maximum multiuser diversity gain, the greedy scheduling

is optimal and the radio resource should be allocated to the transmit antenna which can give the highest capacity on the particular subcarrier. To find the optimal set, all possible combinations of user and antenna sets are necessary to compute and choose the best combination. At the same time, subcarriers, bits and power should be allocated jointly to achieve the optimal solution in (3.5). This causes the high computational complexity at the base station in order to reach the optimal allocation. So the greedy algorithm will be too complicate to be implemented. Moreover, in the practical case, we should consider to reduce the complexity as well as to give the maximization of total system capacity under the constraint of proportional data rate fairness requirements among users in the system. Hence, we separate the resource allocation scheme into two steps by using subcarriers allocation algorithm and bits loading algorithm to reduce the complexity, while still delivering the proportional data rate fairness requirements among users in the systems.

In this subcarrier allocation algorithm, equal power distribution is assumed across all subcarriers and transmits antennas. We use the following capacity equation to calculate the capacity for each user in a given subcarrier [3.7].

$$C^k = \log_2 \left(1 + \frac{p_j^{k,m}}{N_0} \left(\mathbf{h}_j^{k,m} \right)^H \mathbf{h}_j^{k,m} \right) \tag{3.10}$$

The algorithm can be described as follows:

1. Initialization

   (a) Set $C^k = 0$, $\Theta^m = 0$, $\overline{U}^m = \phi$, $\overline{T}^{k,m} = \phi$, for $k = 1$ to K and $m = 1$ to M

   (b) Set $F = \{1, 2, \cdots, M\}$, $T^{k,m} = \{1, 2, \cdots, J^k\}$
   $p_j^{k,m} = \frac{P_{Total}^k}{MJ^k}$ for $k = 1$ to K and $m = 1$ to M and $j = 1$ to J.
   where C^k and Θ^m represent the capacity for k^{th} user and occupied transmit antenna count for m^{th} subcarrier in the system, respectively. $T^{k,m}$ represents

user k's available transmit antenna set for subcarrier m and $\overline{T}^{k,m}$ represents the selected transmit antennas set for user k in subcarrier m in the system. F represents the available subcarrier set in the system. J^k is k^{th} user's available transmit antenna number.

2. First time round robin

   For $k = 1$ to K, If F is not equal to ϕ,

   (a) Find m and j satisfying $\left|{}^{min}\lambda^{k,m}\right| \geq \left|{}^{min}\lambda^{k,i}\right|$

   and $\left|\mathbf{h}_j^{k,m}\right| \geq \left|\mathbf{h}_t^{k,m}\right|$ and $\Theta^m < R$

   for all $i \in F$, $t \in T^{k,m}$. Update C^k according to (3.10)

   (b) Let, $\overline{T}^{k,m} = \overline{T}^{k,m} \cup \{j\}$, $\overline{U}^m = \overline{U}^m \cup \{k\}$,

   $T^{k,m} = T^{k,m} - \{j\}$, $\Theta^m = \Theta^m + 1$

   If Θ^m is equal to R then, $F = F - \{m\}$,

   where R represent the total number of receive antennas in the system.

3. After first time round robin

   While F is not equal to ϕ,

   (a) Find k satisfying $C^k/\rho^k \leq C^i/\rho^i$, for all $i, 1 \leq i \leq K$

   (b) Find m and j satisfying $\left|{}^{min}\lambda^{k,m}\right| \geq \left|{}^{min}\lambda^{k,i}\right|$

   and $\left|\mathbf{h}_j^{k,m}\right| \geq \left|\mathbf{h}_t^{k,m}\right|$ and $\Theta^m < R$

   for all $i \in F$, $t \in T^{k,m}$. Update C^k according to (3.10)

   (c) Let, $\overline{T}^{k,m} = \overline{T}^{k,m} \cup \{j\}$, $\overline{U}^m = \overline{U}^m \cup \{k\}$,

   $T^{k,m} = T^{k,m} - \{j\}$, $\Theta^m = \Theta^m + 1$

   If Θ^m is equal to R then, $F = F - \{m\}$,

4. Step 4)

   Step (3) is repeated until all $R \times M$ subcarriers have been allocated in space and frequency domain.

In this algorithm, each user tries to use subcarriers with the largest value of minimum Eigen value in their channel matrix as much as possible. In the initialization step 1(a), user's capacity, C^k and occupied transmit antenna counts Θ^m are initialized by zero for all users and subcarriers. And then, selected user set $\overline{U}^m$ and selected transmit antenna sets $\overline{T}^{k,m}$ for each user in each subcarrier are initialized by empty set ϕ. In step 1(b), available subcarrier and transmit antennas for each user are initialized in F and $T^{k,m}$ for all k and m. And then, each user's total transmit power P^k_{Total} is divided and equally distributed in frequency and space domain. In the step 2, for first time round robin, every user has a chance to choose the best subcarrier for him by using minimum singular value and after finding the best subcarrier, he will find the best transmit antenna base on the channel gain. The maximum overlapped selection for m^{th} subcarrier from different users is limited by $\Theta^m < R$. Because, in the VBLAST spatial multiplexing system, the number of total transmit antennas in m^{th} subcarrier Θ^m, must be less than or equal to the number of available antennas R in the receiver side. If we assumed that k^{th} user is selected to use the jth transmit antenna in m^{th} subcarrier in step 2(a), then his data rate is also calculated by using (3.10) and updated. In step 2(b), k^{th} user's selected j^{th} transmit antenna number for m^{th} subcarrier is updated in $\overline{T}^{k,m}$ set and this transmit antenna number is removed from the available transmit antenna set $T^{k,m}$ in m^{th} subcarrier for that user. And Θ^m is also added by 1 for m^{th} subcarrier to check the availability of overlap in that subcarrier for next selection time. If Θ^m is equal to R, then this subcarrier cannot support anymore for spatial multiplexing system and we have to remove this subcarrier number from the

available carrier set F. After completing the first time round robin, the user with the lowest proportional data rate fairness requirement has the option to pick up which subcarrier and transmit antenna to use. His capacity and other related parameters also updated as explained above. This process is repeated until all available subcarriers are allocated to the users in their space and frequency domain. In every selection time, only one transmit antenna can be chosen by the selected user. Therefore, it is not possible to know the completed subchannel matrix $\overline{\mathbf{H}}^m$ at that time and we cannot use the exact SNR equation (3.2) to calculate the capacity for each user without knowing $\overline{\mathbf{H}}^m$. That's why we use the single-input-multi-output (SIMO) equation (3.10) to estimate the capacity for each user at each selection time. Therefore, this subcarrier and space allocation gives the coarse proportional rate fairness among users in the system. And then adaptive bit loading is applied to each selected subcarrier and transmit antenna based on the predetermined *targetBER* and *SNR* threshold for each user. In the context of multiple antenna systems, the constellation size N assigned to the transmit antenna is varied depending on the subchannel *SNR*. The available modulation orders in our scheme are constrained to $N = \{0, 2, 4, 16, 64\}$, where $N = \{0\}$ means no data are transmitted, $N = \{2\}$ is BPSK and $N = \{4, 16, 64\}$ are M-QAM. The relationship of *SNR* and *BER* for coherent detection of constellation size (N) with Gray bit mapping is approximated in [3.2].

$$BER \approx 0.2\exp\left(-1.5\frac{SNR}{N-1}\right) \tag{3.11}$$

With a predefined targetBER, the SNR threshold point γ^N for a specified bit loading can be easily found for given constellation size as in (12).

$$\gamma^N = \frac{N-1}{1.5}\ln\left(\frac{1}{5(\text{BER}_{target})}\right) \tag{3.12}$$

Table 3.1: Simulation Parameters

Parameter	Value
Modulation levels	0, 1, 2, 4, 6
Number of subcarriers	64
FFT sampling	64 samples
Guard interval	16
Number of users	4,2
Receiver Type	ZF
Multipath Channel	LOS and NLOS Conditions
Number of Total-Tx and Rx antennas	(4×4) and (2×2) and (3×3)
RMS delay spread	50ns
Bandwidth	20 MHz
Target BER	1/1000

By using (3.2), (3.11) and (3.12), we can calculate the modulation mode (N) and γ^N based on targetBER and instantaneous SNR for the selected MIMO link.

3.4 Simulated Results

Simulation parameters are shown in Table. 3.1. In the simulation for Fig. 3.2, we use a channel model with NLOS condition for all the users in the system. And all users have independent fading channel characteristics with NLOS channel condition. Fig. 3.2 shows comparison of capacity performance of the proposed scheme, scheme with maximum gain based allocation (Max Gain) and the opportunistic scheduling with round robin based allocation (OPP RR), where OPPRR is short term for conventional resource allocation scheme with opportunistic scheduling with round robin manner for each user in the MIMO wireless communication system. In this scheme, each user will have a chance to choose the best subcarrier from the available subcarrier set based on their channel condition and this chance will assign to each user in round robin manner until all of the available

Figure 3.2: Capacity comparison for proposed and conventional schemes in MAX Gain and OPP-RR with 4-users and 4 antennas in base station and 2 transmit antennas in each user with proportional data rate ratio of 4:2:3:1, while all users faced with NLOS

subcarrier are allocated in multiuser in the wireless communication system. The number of users is 4 and each user has 2 transmit antennas in the user side and base station is setup by 4 receive antennas. Therefore, maximum transmit antenna in each subcarrier cannot be greater than 4. And proportional data rate ratios are 4:2:3:1. As shown in Fig. 3.2, the other two schemes have a little better in total system capacity improvement than the proposed scheme with sacrificing the worst user's data rate requirement. On the other hand, the proposed scheme can give the exact proportional data rate ratio among users in the system while other two schemes cannot give it. In the high SNR region, all of schemes are nearly equal in total system capacity curves, that is because of the highest modulation mode is achieved in all of the selected transmit antennas of selected users in the system.

In the simulation for Fig. 3.3, we use two different types of channel models which are: channel with NLOS condition for two users in the system and LOS condition for other two users in the system. In the simulation, two users are randomly selected to face with LOS
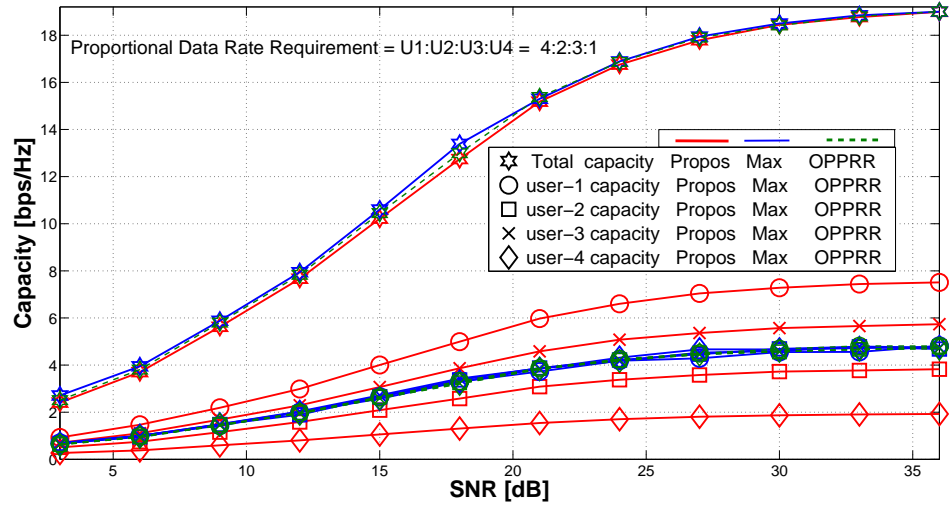
Figure 3.3: Capacity comparison for proposed and conventional schemes in MAX Gain and OPP-RR with 4-users and 2 antennas in base station and 2 transmit antennas in each user with proportional data rate ratio of 4:2:3:1, while 2 users faced with NLOS and other 2 users faced with LOS

condition and the other two users will face the NLOS condition in the system. But the simulation parameters will be different from each user both in LOS and NLOS condition. We use this simulation, to show that the effect of antenna correlation in LOS condition. When some users face the LOS condition, they have high antenna correlation but their channel gain might be quite high because of the strong LOS path. In that case, Max Gain based resource allocation scheme will choose the user with LOS condition because of high gain and mostly this user will have a chance to choose the resources without considering the proportional data rate fairness among users in the system. But in our system, we use the spatial multiplexing scheme with ZF receiver and this system will degrade the performance when there has high antenna correlation in the system. That's why Max Gain base selection scheme has the worst total system capacity curve in the system. On the other hand, OPP-RR scheme will choose each user one after another (round robin) and each user have a chance to choose the best subcarrier and transmit antenna in each
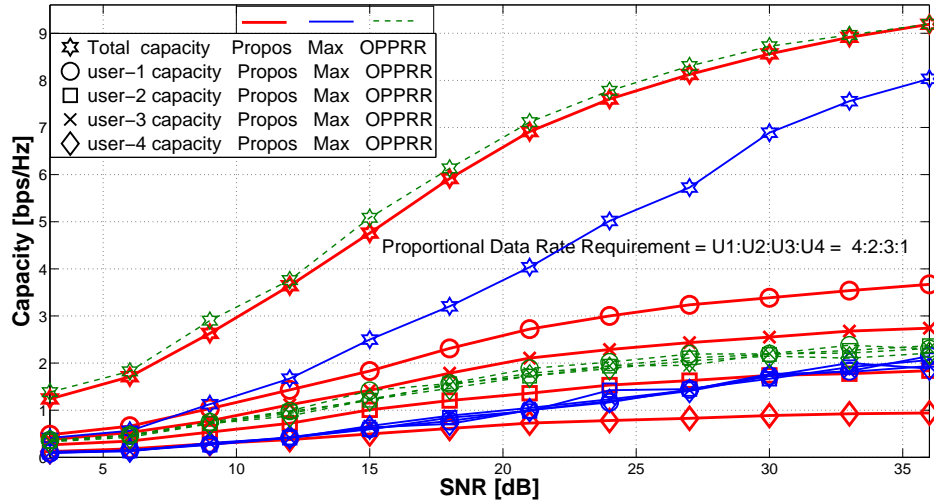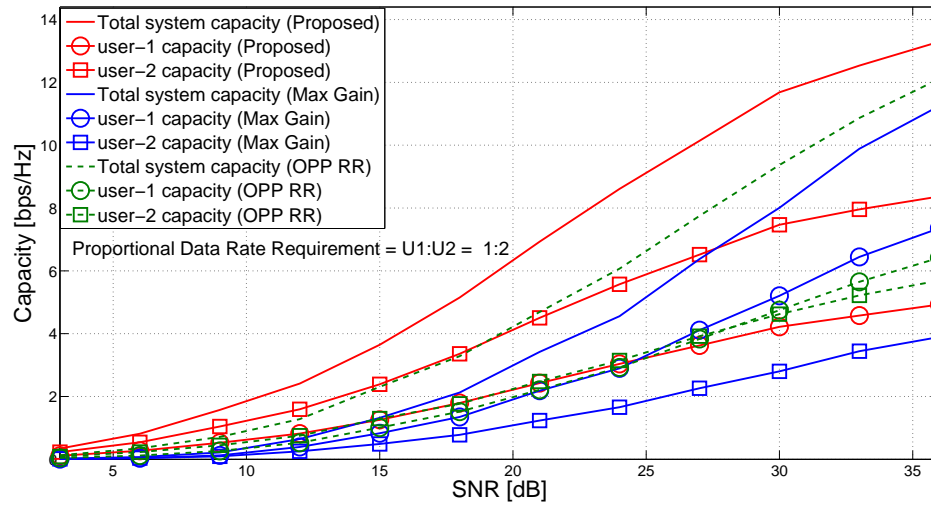
Figure 3.4: Capacity comparison for proposed and conventional schemes in MAX Gain and OPP-RR with 2-users and 3 antennas in base station and 2 transmit antennas in each user with proportional data rate ratio of 1:2.

selection time without considering to give the proportional data rate fairness among users in the system. Even some users, with high data rate requirements, have LOS condition, they cannot choose the resources in every time and they have to give a selection chance to other user in round robin manner. That's why, their highly correlated transmit antenna are separated in the frequency domain and total system capacity performance is better than other two schemes. In the case of the proposed scheme, it cannot select the best user every time because of the consideration of proportional data rate fairness requirements among users in the system. Although certain user with the highest data rate requirement is facing the LOS condition, proposed scheme is necessary to give the chance of selection to that user until his data rate requirement is fulfilled. Because of that condition, total system capacity performance is not as good as OPP-RR scheme. But the proposed scheme can give the exact amount of proportional data rate fairness requirements among users in the system with nearly same capacity as OPP-RR scheme as shown in Fig. 3.3.

In the simulation for Fig. 3.4, there has two users in the system with 2 transmit antennas in each user and 3 receive antennas in the base station. Therefore, maximum transmit antenna in each subcarrier cannot be greater than 3. And proportional data rate ratios is 1:2 for user-1 and user-2 while user-1 has channel with LOS condition and user-2 has channel with NLOS condition in the system with random simulation parameters in LOS and NLOS condition. In this simulation, we can see that the performance of the proposed scheme is better than other two schemes. That's because of the high data rate requirement user-2 has NLOS condition and who will have most of the time to choose the system resources to fulfill his requirements. Therefore, system resources can be used very efficiently with low correlated transmit antenna in user-2 and total system capacity performance is increased as well as fulfillment of proportional data rate fairness requirements between two users in the system. However, Max Gain based will select user-1 with high channel gain to give the resources most of the time. That's why user-1's capacity is much larger than user-2's capacity and it will cause the reciprocal effect of data rate fairness ratio requirements between user-1 and user-2 as shown in this Fig. 3.4. Moreover, total capacity system performance will also reduce because of the high antenna correlation in that user-1. And also, OPP-RR based scheme will also select each user in alternatively and user-1's correlation in transmit antenna effect reflects the decreased in performance of total system capacity although it is not bad as Max Gain based scheme. And we can also see that, the capacity of user-1 is lower than user-2 in lower SNR region and higher than in high SNR region for OPP-RR scheme. That's because of the reason that the influence of high SNR is larger than the influence of antenna correlation in each user. That's why user-1's capacity is higher than user-2 in the high SNR region. In this Fig. 3.4, we can see that the proposed scheme has better performance than other two conventional schemes not only in proportional data rate fairness but also in the total system capacity in the system.

3.5   Conclusion and Future Work

We have proposed the resource allocation scheme for MIMO-OFDM-MAC system to improve the totally system capacity under the constraint of total transmit power and target BER rate with proportional data rate fairness in the system. Computer simulation results show that the proposed scheme can give better system capacity while maintaining the proportional data rate fairness requirements among users in the system. This better system capacity result can be achieved by separating the highly correlated LOS users in frequency domain and assigning the uncorrelated NLOS users in the same frequency with different space domain in the system.

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Chapter 4

Antenna Selection Scheme for Polarized MIMO System with SVD for the Practical MIMO Communication Channel Environment

In the previous chapter 2 and 3, I proposed the resource allocation schemes for MIMO-OFDM wireless communication system under the proportional data rate fairness among users in the system. In the mobile wireless communication system, base station has to compute channel estimation, channel coding, subcarrier, bit and power allocation etc for each user in the system and this will cause the high computational complexity in the base station. Because of the simultaneous resource allocation in frequency and space dimension, the processing time of the base station might be too slow to response the rapidly changing mobile channel environment. Therefore, it is necessary to reduce the complexities in each step of the wireless communication system as much as possible to reduce the over all processing time for the mobile wireless system. So, I emphasized on the research work which is related to the reduction of complexity in the MIMO wireless communication system and I also proposed the reduced complexity scheme for the antenna selection

in the MIMO wireless communication system in this chapter.

In the conventional multi-input multi-output (MIMO) communication systems, most of the antenna selection methods considered are suitable only for spatially separated uni-polarized system under Rayleigh fading channel in non-line of sight (NLOS) condition. There have a few antenna selection schemes for the cross-polarized system in LOS condition and Ricean fading channel, and no antenna selection scheme for the MIMO channel with both LOS and NLOS. In the practical MIMO channel case, influence of LOS and NLOS conditions in the channel can vary from time to time according to the channel parameters and user movement in the system. Based on these influences and channel condition, uni-polarized system may outperform a cross-polarized. Thus, we should consider this kind of practical MIMO channel environment when developing the antenna selection scheme. Moreover, no research work has been done on reducing the complexity of antenna selection for this kind of practical MIMO channel environment. In this research, reduced complexity in antenna selection is proposed to give the higher throughput in the practical MIMO channel environment. In the proposed scheme, suitable polarized antennas are selected based on the calculation of singular value decomposition (SVD) of channel matrix and then adaptive bit loading is applied. Simulation results show that throughput of the system can be improved under the constraint of target BER and total transmit power of the MIMO system.

4.1   Introduction

Spatial multiplexing offers high channel capacity and transmission rate for the same bandwidth by employing multiple antennas at the transmitter and receiver. An adaptive modulation scheme can be applied in the multi-input multi-output (MIMO) system to further improve the system capacity. An adaptive modulation method that enhances the spectral

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efficiency while keeping the bit error rate (BER) under predefined level is proposed in [4.1]. When adaptive modulation is applied in quality of service (QoS) based MIMO system with VBLAST-zero forcing (ZF) receiver, the worst SNR link in the MIMO system will decide the overall modulation mode for that system to realize the predefined target BER level in the system. In that case, system's efficiency might be decreased if the SNR gap between the worst link and other links is large. Therefore, we should consider to improve the worst MIMO link's quality to increase the capacity of the system because all MIMO links have to transmit the same number of bits from each transmit antenna to spatially separate the transmitted symbols in the ZF receiver. The modulation mode will be decided based only on the worst case SNR link although higher SNR links can load the higher modulation mode for the transmission. If we can increase the lowest SNR level without increasing the transmit power to match with higher modulation mode, then overall system efficiency will be improved.

SNR levels of MIMO links can vary depending on the polarization in the system. A lot of papers have been published for the research of uni-polarized spatial MIMO communication systems, where the antennas elements are physically separated in space [4.2]. However, spatial correlation might occur in line-of-sight (LOS) condition. In order to reduce the spatial correlation small enough to be ignored, there will be a strict limit on the spacing distance between the antenna elements especially for mobile station (MS).

In this regard, dual-polarized antennas are inclined to be introduced into the MIMO system since they can reduce the requirement of the spacing between the antennas [4.3]. With dual-polarized antennas, we can place more antenna elements with the same space limit, or obtain better channel performance under poor channel conditions such as highly correlated LOS channel conditions. However, high cross polarization discrimination (XPD) reduces the mean power of the cross coupled component, and thus, the available

diversity benefit due to uncorrelated cross coupling decreases [4.4]. On the other hand, MIMO systems with uni-polarized antennas have better array gain than cross-polarized MIMO systems and thus offer more system throughput in the independent and identically distributed (i.i.d) rayleigh fading channel for NLOS condition [4.5]. Measurement results show that in the environment with rich scattering, there is no benefit to use cross-polarized combination to increase channel capacity. While in the environment without rich scattering, like in space of hall-way, the cross-polarized combination is an efficient way for enhancing channel capacity [4.6]. However in the practical communication system environment, considering the channel condition with only LOS condition or NLOS condition is far from the reality. And it is better to depict the practical channel as the sum of fixed (possibly LOS) component and a variable or scattered (NLOS) component. This real-world channel condition is effected by the average subchannel imbalances, Ricean K-factor and correlation properties [4.7].

Therefore, it is not a good idea to use the fixed-polarized antennas which cannot adapt to match the requirement of the practical channel condition. If a particular MIMO system is employed both uni-polarized and dual-polarized antennas, then we can use both uni-polarized and cross-polarized antennas based on the average subchannel power imbalances, Ricean K-factor and correlation properties to achieve the better MIMO system performances. But this will increase the hardware and signal processing complexity, power consumption, and component size in the transmitter and the receiver [4.8]. One of the main culprits behind this increase in complexity is that each antenna element requires a dedicated radio frequency (RF) chain. Moreover, processing the signals received in spatial multiplexing schemes calls for sophisticated receivers whose complexity increases, sometimes exponentially, with the number of transmit and receive antenna elements. Antenna selection is a solution which can reduce the hardware complexity of transmitters

and receivers by using fewer RF chains, while exploiting the diversity benefits offered by the MIMO architecture. In antenna selection, a subset of the available antenna element is adaptively chosen by a switch, and only signals from the chosen subset are processed further by the available RF chains. This technique has been extensively studied in the context of spatial channels [4.9]. Antenna selection for MIMO systems was first presented in [4.10] based on an argument of capacity increase. The selection criterion proposed therein is based on Shannon capacity and does not readily apply to spatial multiplexing with linear receivers such as ZF or MMSE receivers. Therefore, some researcher considered the antenna selection for spatial multiplexing systems with linear receivers [4.11] to reduce the complexity in MIMO system. The selection scheme uses the post-processing SNRs (signal to noise ratios) of the multiplexed streams and the antenna subset that induces the largest minimum SNR is chosen. However, it is necessary to use the SVD for every subchannel matrices and it takes more time compared with Frobenius norm base selection. Moreover, there has no consideration about effect of adaptive modulation and total transmit power constraint on the selection method.

In [4.8], the reduced complexity with Frobenius norm base antenna selection is expressed for joint transmit/receive selection strategies. This strategies choose a subset of the rows and columns of H to maximize the sum of the squared magnitudes of transmit-receive channel gains. But there has no consideration about transmit and receive antenna correlation and K-factor effect in the system and it cannot work very well in the ill-condition channel matrix of MIMO system. Therefore, efficient (optimal or suboptimal) joint selection of transmit and receive antennas remains an interesting open problem.

In this research work, we propose the SVD based reduced complexity antenna selection method for the practical MIMO communication system with linear receivers. The proposed system and selection method not only consider reducing the complexity but also

the effects of adaptive modulation and total transmit power constraint under the target BER rate in the MIMO system to fulfill the requirements in [4.8] and [4.11]. At first step, the selection algorithm will choose the best subchannel matrix with reduced complexity, based on the second largest minimum singular value and minimum singular values from main MIMO channel matrix and subchannel matrices, respectively. After that, in the second step, adaptive bit loading is applied to the selected subchannel under the constraint of total transmit power, target BER rate and available RF chains in the system. In the first step, there has no consideration about constraint of total transmit power and adaptive bit loading in the transmit side. Therefore, there might be error in the first step channel matrix selection and it might be necessary to recheck the capacity of main MIMO channel matrix and selected subchannel matrix according to the availability of RF chains in the system.

This chapter is organized as follows. Section 4.2 introduces our MIMO system model with uni-polarized and cross-polarized antenna for the practical MIMO communication channel environment. Section 4.3 describes the reduced complexity in antenna selection algorithm which is jointly combined with adaptive bit loading and transmits power distribution. Section 4.4 shows simulation results and conclusion is shown in section 4.5.

4.2   System Model

System model is shown in Fig. 4.1. We consider a MIMO system with two vertical polarized antennas and one horizontal polarized antenna. In the hardware design, one vertical polarized antenna is separated by half of the transmitted wavelength distance d from the cross-polarized antenna as shown in Fig. 4.1. The number of available RF chains in the
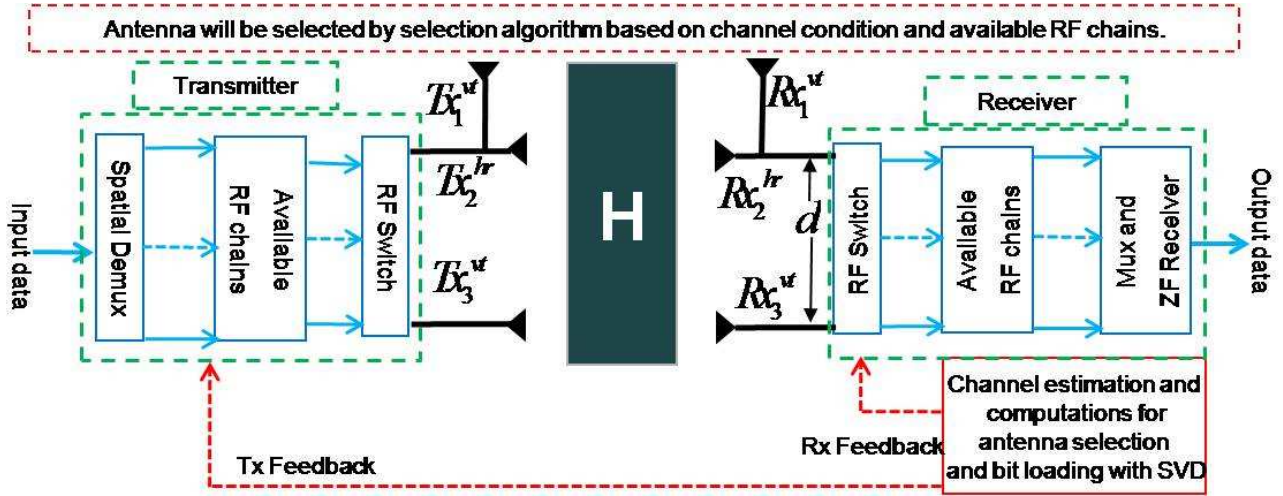
Figure 4.1: MIMO System Model.

transmitter and receiver side will affect the antenna selection method. Therefore, we propose the antenna selection method for three cases according to the available RF chains in the transmitter and receiver sides. In case (1), 3 RF chains are available in each side. In case (2), 2 RF chains and 3 RF chains are available in transmitter side and receiver side, receptively. In case (3), 2 RF chains are available in each side. Based on the available RF chains, we can use 3×3 MIMO system, 3×2 MIMO system or 2×2 MIMO system by choosing the suitable antenna pairs in transmitter and receiver side, receptively. By expanding the results for 2×2 MIMO system shown in [4.12], a practical 3×3 MIMO channel matrix **H** can be modeled as follows:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & h_{1,3} \\ h_{2,1} & h_{2,2} & h_{2,3} \\ h_{3,1} & h_{3,2} & h_{3,3} \end{bmatrix} = \sqrt{\frac{K}{1+K}} \mathbf{H}_{LOS} + \sqrt{\frac{1}{1+K}} \mathbf{H}_{NLOS}, \qquad (4.1)$$

$$\mathbf{H}_{LOS} = \begin{bmatrix} 1 & \sqrt{\beta} & 1 \\ \sqrt{\beta} & 1 & \sqrt{\beta} \\ 1 & \sqrt{\beta} & 1 \end{bmatrix} \qquad (4.2)$$

$$\mathbf{H}_{NLOS} = (R_{RX})^{1/2}(H)_{idd}(R_{TX})^{1/2}, \tag{4.3}$$

$$\mathbf{H}_{idd} = \begin{bmatrix} h_{1,1}^{idd} & \sqrt{\alpha}h_{1,2}^{idd} & h_{1,3}^{idd} \\ \sqrt{\alpha}h_{2,1}^{idd} & h_{2,2}^{idd} & \sqrt{\alpha}h_{2,3}^{idd} \\ h_{3,1}^{idd} & \sqrt{\alpha}h_{3,2}^{idd} & h_{3,3}^{idd} \end{bmatrix} \tag{4.4}$$

where $\sqrt{\frac{K}{1+K}}\mathbf{H}_{LOS}$ is the fixed component of the channel and $\sqrt{\frac{1}{1+K}}\mathbf{H}_{NLOS}$ is the fading component of the channel. K is the Ricean K-factor of the channel and is the ratio of the total power in the fixed component of the channel to the power in the fading component. α and β are the attenuated cross coupling coefficients for the polarization case. $\mathbf{H}_{idd}$ is the flat-fading Rayleigh component of the MIMO channel. The elements of $\mathbf{H}_{idd}$ are complex Gaussian random variables with zero mean and unit variance. $\mathbf{R}_{XX}$ and $\mathbf{R}_{TX}$ are the receive and transmitter side correlation matrices, respectively, and are given by

$$\mathbf{R}_{RX} = \begin{bmatrix} 1 & r_{1,2} & r_{1,3} \\ r_{2,1} & 1 & r_{2,3} \\ r_{3,1} & r_{3,2} & 1 \end{bmatrix}, \tag{4.5}$$

$$\mathbf{R}_{TX} = \begin{bmatrix} 1 & t_{1,2} & t_{1,3} \\ t_{2,1} & 1 & t_{2,3} \\ t_{3,1} & t_{3,2} & 1 \end{bmatrix}, \tag{4.6}$$

$$r_{i,j} = \rho_{i,j}^{spl} \times \rho_{i,j}^{pol},$$

$$t_{i,j} = \rho_{i,j}^{spl} \times \rho_{i,j}^{pol},$$

where $r_{i,j}$ and $t_{i,j}$ are the correlation coefficient between the ith antenna and j^{th} antenna at transmitter and receiver side, respectively. $\rho_{i,j}^{spl}$ and $\rho_{i,j}^{pol}$ denote the real correlation co-

efficient due to the spacing and polarization between antennas i and j, respectively. In order to simplify the MIMO system simulation, we assume that the correlation coefficients between the cross-polarized antennas are equal to zero in the transmitter and receiver side. It is also noted that if selected antennas are of the same polarization, then , α, β and $\rho_{i,j}^{pol}$ are equal to one. By substituting this assumption into (4.5) and (4.6), we can get the simplified receive and transmitter side correlation matrices as follows:

$$\mathbf{R}_{RX} = \begin{bmatrix} 1 & 0 & \rho_{1,3}^{spl} \\ 0 & 1 & 0 \\ \rho_{3,1}^{spl} & 0 & 1 \end{bmatrix}, \tag{4.7}$$

$$\mathbf{R}_{TX} = \begin{bmatrix} 1 & 0 & \rho_{1,3}^{spl} \\ 0 & 1 & 0 \\ \rho_{3,1}^{spl} & 0 & 1 \end{bmatrix}, \tag{4.8}$$

4.3 Reduced Complexity in Antenna Selection Methods Based on the SVD and Adaptive Bit Loading

4.3.1 Minimum Singular Value and its Effect on the Linear Receivers

We use the V-BLAST implementation with ZF receiver to reduce the complexity in our system model. V-BLAST MIMO system improves the system performance based on ZF detection combined with symbol cancellation while maintaining low implemental complexity [4.13]. When symbol cancellation is used, the order in which the sub-streams are detected becomes important for the overall performance of the system. Performance of spatial multiplexing with linear receivers depends on the minimum SNR induced by the

particular subset of transmit antennas. The transmitted symbol with the smallest post-detection SNR dominates the error performance of the system [4.11]. That's why we use the minimum SNR as a key factor to choose the best modulation mode and channel matrix for the system. In our MIMO system, the receive signal vector $\mathbf{y}$ at the receiver side can be represented as

$$\mathbf{y} = \sqrt{E_s}\mathbf{Hx} + \mathbf{n}, \qquad (4.9)$$

where $\mathbf{x}$ is the transmitted symbol vector, $\mathbf{H}$ is the channel matrix, $\sqrt{E_s}$ is the power allocation vector and $\mathbf{n}$ is the noise vector in which it is assumed that noise is zero-mean circularly symmetric complex Gaussian (CSCG) with variance N_0. In the ZF receiver, the dispread signal $\mathbf{z}$ can be obtained by correlating the received signal $\mathbf{y}$ with pseudo-inverse $\mathbf{G}$ of the selected channel matrix $\mathbf{H}$.

$$\mathbf{z} = \mathbf{Gy} = \sqrt{E_s}\mathbf{GHx} + \mathbf{Gn}, \qquad (4.10)$$

For the ZF receiver, the post-processing SNR of the worst sub-stream is expressed in [4.14]

$$\psi_{min}^{ZF} \geq \lambda_{min}^2(\mathbf{H})\frac{E_s}{TN_0}, \qquad (4.11)$$

where $\lambda_{min}(\mathbf{H})$ represents the minimum singular value of channel matrix $\mathbf{H}$. T is the number of selected transmit antenna, and ψ_{min}^{ZF} is the minimum post-processing SNR of the selected channel matrix for ZF receiver, respectively. The expression in (4.11) confirms the intuition that the performance of linear receivers should be improved as the smallest singular value of the channel increases.

4.3.2 Relationship between Minimum Singular Value and Parameters of MIMO Channel Matrix

The value of $\lambda_{min}(\mathbf{H})$ can be obtained by using SVD method. SVD method decomposes the channel matrix into a diagonal matrix $\mathbf{S}$ of the same dimension with non-negative diagonal elements $\lambda(\mathbf{H})$ in decreasing order and unitary matrices $\mathbf{U}$ and $\mathbf{V}$ so that

$$\mathbf{H} = \mathbf{USV}^H = \sum_{i=1}^{rank(H)} \mathbf{u}_i \mathbf{s}_i \mathbf{v}_i^H. \tag{4.12}$$

In the above equation, $\mathbf{u}_i$ and $\mathbf{v}_i$ are the left and right singular vectors with $\mathbf{s}_i$ denoting the singular values that are arranged in descending order. Among these singular values, the value of $\lambda_{min}(\mathbf{H})$ is heavily effected by two factors [4.15]. One factor is fading correlation of channel matrix $\mathbf{H}$. Low correlated channel matrix has higher $\lambda_{min}(\mathbf{H})$ value than highly correlated channel matrix [4.15]. The second factor, which influences on the value of $\lambda_{min}(\mathbf{H})$ is average channel gain of the channel matrix $\mathbf{H}$. Channel matrix with higher average gain has higher singular value than channel matrix with lower channel gain under the same fading correlation condition [4.15]. In the MIMO system, good channel condition has low correlated fading channel matrix and higher channel gains. We can know the best channel condition based on these two factors. However, sometimes one channel instant may have good channel gain with highly correlated channel matrix and the other time instant may have low channel gain with low correlated channel matrix. In this condition, it is very difficult to consider the best channel condition. Fortunately, these average channel gain and fading correlation are directly related to $\lambda_{min}(\mathbf{H})$ and we can know the better channel condition by comparing these $\lambda_{min}(\mathbf{H})$ values. Therefore, $\lambda_{min}(\mathbf{H})$ can be used as an appropriate performance indicator to choose the best channel matrix for the system.
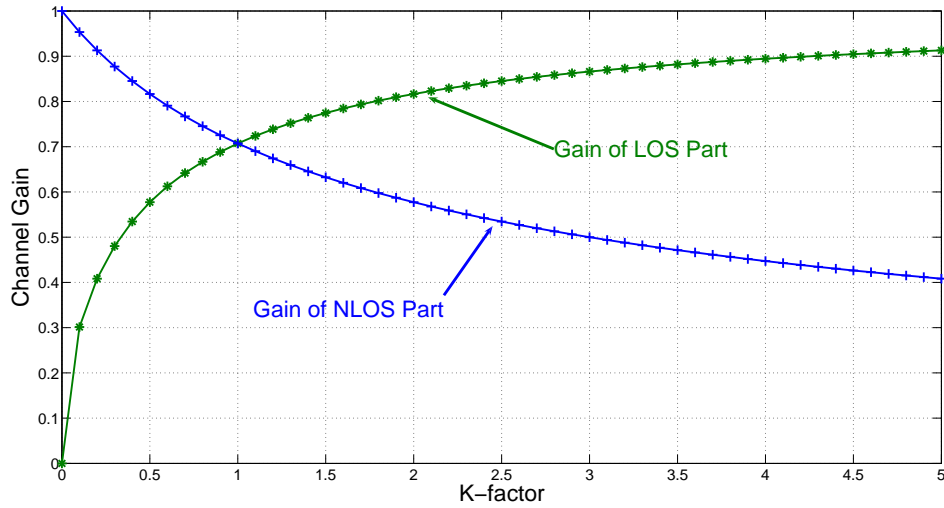
Figure 4.2: Relationship between gains of LOS, NLOS Parts and K-factor.

In the MIMO channel matrix in (4.1), it is a combination of LOS and NLOS and their values are controlled by using K-factor. If K is equal to zero, then MIMO channel is totally influenced by the NLOS part and changed to pure Rayleigh MIMO channel. In this case, the use of cross-polarized antennas will always result in a performance loss and we should use uni-polarized antennas to improve the capacity or diversity in the system [4.3]. On the other hand, if K is equal to infinity, then MIMO channel is totally influenced by the LOS part and the NLOS effect will be removed from the system and approaches to non-fading link. In this case, the use of uni-polarized antennas results in high antenna correlation and it is always better to use cross-polarized antenna. If the antenna correlation is very high, it shown in [4.3] that the use of spatial multiplexing is no longer possible (due to the high error rates), whereas replacing the two antennas by a cross-polarized yields error rates that are acceptable. Therefore, we take these K-factor parts from LOS and NLOS in (4.1) to show the simplified relationship between K-factor and channel gain for MIMO channel matrix. Fig. 4.2 shows the relationship between the channel gains and K-factor values for LOS and NLOS parts in (4.1). According to this figure, we can

know that NLOS part is mainly influenced in the lower K-factor region and we should use uni-polarized MIMO system as explained in above. When LOS part is mainly influenced in the higher K-factor region, we should use cross-polarized MIMO system. On the other hand, around the crossing point of LOS and NLOS curves, both LOS part and NLOS part can influence in the MIMO channel matrix and we should use all MIMO antennas for better system performance if there are available RF chains to support 3×3 MIMO system. However, in the practical channel matrix case, channel cannot be simplified as stated in the above condition. There will be shift in crossing point which is formed by the gain of LOS and NLOS curves in this figure. The actual position of the crossing point will be depend on the various channel parameters in the MIMO system such as transmit and receive antennas correlations, channel gain, multipath fading, line of sight condition and SNR condition. Note that, all these factors have the relationship with $\lambda_{min}(\mathbf{H})$ value as explained in previously. Therefore, we have to compare all available $\lambda_{min}(\mathbf{H})$ values which can be obtained from the available subchannel matrices.

4.3.3   Reduction of Complexity in the Antenna Selection Method

4.3.3.1   First Step: Removal of Unnecessary Subchannel Matrices

Based on the available RF chains in MIMO system, there have 9 possibilities for 2×2 MIMO combinations, three possibilities for 3×2 MIMO combinations and one 3×3 MIMO system can be used in the system and these available channel matrices are shown in Fig. 4.3. In this figure, $_{3\times3}\mathbf{H}^1$ is MIMO main channel matrix and all other channels are its sub-channel matrices which can be obtained by removing row and column of MIMO main channel matrix. Therefore, 13 singular values can be obtained from the MIMO channel matrices of Fig. 4.3. And Fig. 4.4 shows the minimum singular values
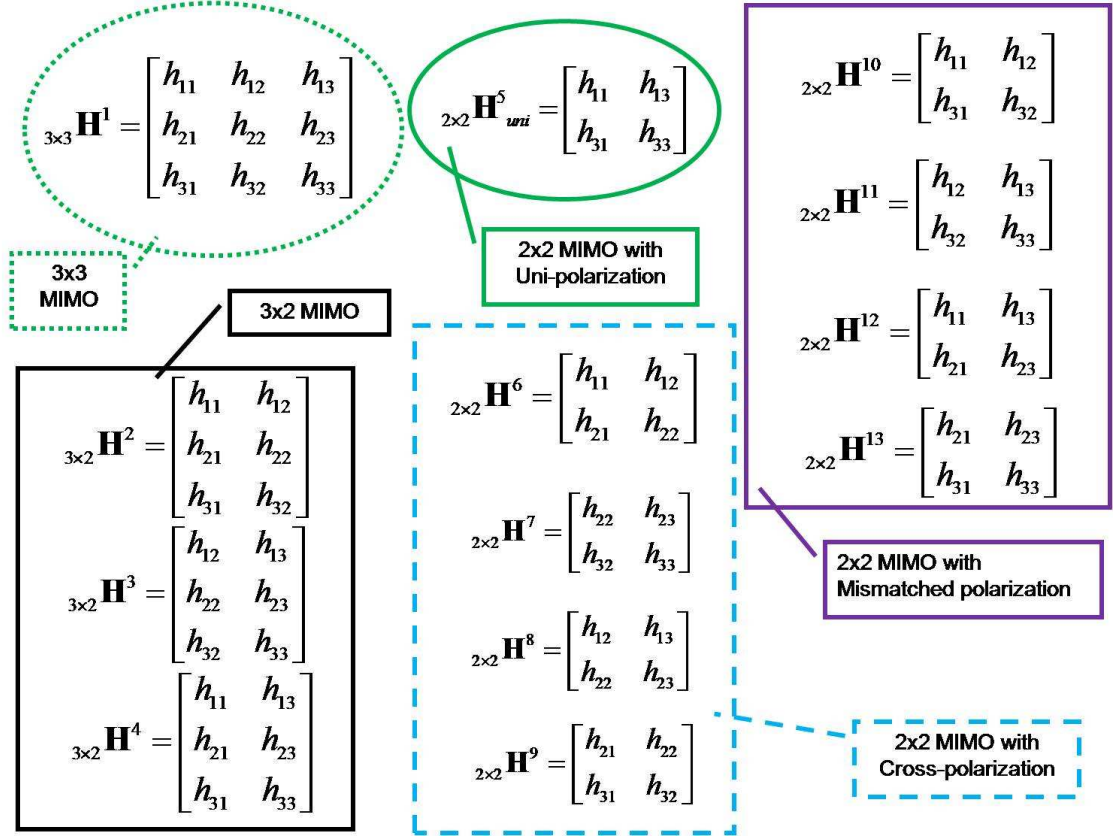
Figure 4.3: Possible subchannel matrices in the proposed MIMO system.

of these available subchannel matrices for various correlation and K-factor values in 3-dimensional graph. This figure is shown for the purpose of statistical descriptions of MIMO subchannel matrices for our system by using 150000 simulation times for each correlation and K-factor value.

We use $K = 1/16$ (low K-factor, mainly influenced by NLOS part), $K = 1$ (medium K-factor) and $K = 16$ (high K-factor, mainly influenced by LOS part) to control the influence of LOS and NLOS parts in the channel matrix, and correlation factors are gradually increased from 0 to 1. In each simulation time for the particular correlation and K-factor value, 3×3 MIMO channel $\mathbf{H}_{idd}$ is randomly generated for equation (4.4). By using this $\mathbf{H}_{idd}$, we can obtain the 3×3 main MIMO channel matrix $\mathbf{H}$ in equation (4.1). After that,

Figure 4.4: Comparison of Minimum Singular Values for subchannel matrices from original 3×3 MIMO system for various correlation and K-factor.

we can obtain 13 channel matrices in Fig. 4.3 and their SVD values are shown in Fig. 4.4 by increasing order in H-axis from right to left direction. I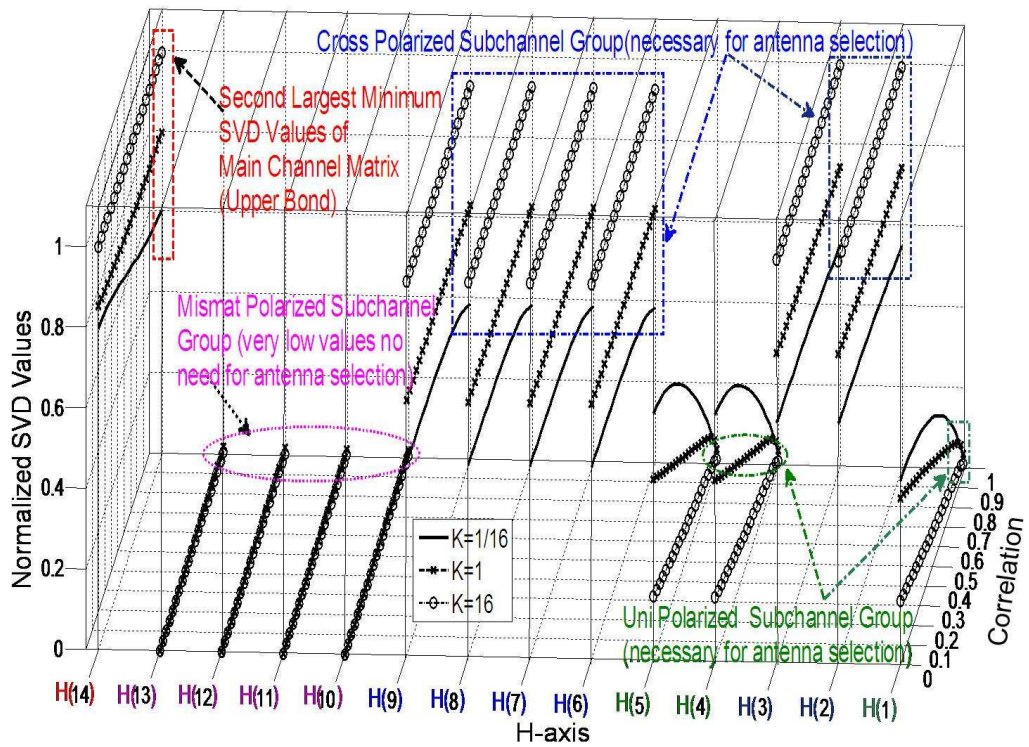n the H-axis of Fig. 4.4, we used H(1), H(2),··· to H(13) to represent the 13 channel matrices in Fig. 4.3. By applying SVD to the original 3×3 main MIMO channel matrix **H**, we can also obtain the second largest minimum SVD value for each simulation time and these SVD values are also shown in the point number 14 in H-axis to be used in next section 4.3.3.2.

For the clear presentation, we will not show the maximum singular values for these channel matrices because we only need minimum singular values to find the best channel matrix for our antenna selection method as already explained in section 4.3.2. In Fig. 4.4, we can see that minimum singular values of uni-polarized subchannel matrices are larger than those of cross-polarized subchannel matrices in low K-factor and low correlation region. That is because of the more influence of NLOS part in the channel for low K-factor condition. On the other hand, minimum singular values of cross-polarized subchannel matrices are larger than those of uni-polarized subchannel matrices in high K-factor and high correlation region. This condition occurs because of the more influence of LOS part in the channel for high K-factor condition and robustness of cross-polarized antenna system to the antenna correlation. However, all of these minimum singular values of uni-polarized and cross-polarized subchannel matrices are always larger than minimum singular values of mismatched polarized subchannel matrices (H(10) to H(13)) in all of the correlation and K-factor values as shown in this figure. According to their polarization mismatches, their channel matrices have very low ranks to show very low minimum SVD values. Therefore, it is not necessary to consider these subchannel matrices to use in the proposed antenna selection scheme. That's why, 13 possible subchannel matrices can be reduced into 9 possible combinations to be considered. That is the first step to reduce the complexity of the proposed antenna selection scheme.

4.3.3.2 Second Step: By Using Upper Bond of Second Largest Minimum Singular Value from Main MIMO Channel Matrix

By applying SVD to the original 3×3 MIMO channel matrix **H**, we can get three singular values with descending order such as $\lambda_{max}, \lambda_2, \lambda_{min}$. And we call λ_2 as a second largest minimum singular value. In the point number (14) of H-axis in Fig. 4.4, we also show the second largest minimum SVD values (λ_2) of original 3×3 main MIMO channel matrix **H**, and we can see that they are upper bonds for all other minimum singular values of subchannel matrices. This condition occurs because all other subchannel matrices are taken out from main 3×3 MIMO channel matrix **H**. Therefore, we do not need to find all of the available subchannel matrices at the same time. At first, we have to find the singular values for 3×3 MIMO channel matrix **H** and after that we have to find the minimum singular value for other subchannel matrices and compare with the second largest minimum singular value of 3×3 MIMO matrix $\mathbf{H}(\lambda_2)$. As soon as they are equal, we can cut off the finding process for the remaining subchannel matrices. That is the second step for the reduction of complexity in the proposed method. In the conventional antenna selection methods in [4.8] and [4.11], they have to compare all singular values or channel gains which are obtained from all possible subchannel matrices and select the maximum one after comparing all these possible values.

4.3.4 Adaptive Bit Loading and Problem Formulation for the MIMO System Model

In our system, we are also applying the adaptive bit loading which dynamically determines the constellation size based on the current channel condition and predefined BER, to improve the capacity under the constraint of QoS requirement. In the context of multiple antenna systems, the constellation size M_i assigned to the ith transmit antenna is

Table 4.1: SNR Threshold and Modulation Modes

SNR Threshold	Γ_2	Γ_4	Γ_{16}	Γ_{64}
Bit Loading	1	2	4	6

varying depending on the subchannel $SNR(\gamma_i)$. The available modulation orders in our work are constrained to $M_i = \{0, 2, 4, 16, 64\}$, where $M_i = \{0\}$ means no data are transmitted, $M_i = \{2\}$ is BPSK and $M_i = \{4, 16, 64\}$ are M-QAM. The relationship of $SNR(\gamma_i)$, BER(P_b) for coherent detection of constellation size (M_i) with Gray bit mapping is approximated in [4.1].

$$P_b \approx 0.2\exp\left(-1.5\frac{\gamma_i}{M_i - 1}\right), \tag{4.13}$$

With a predefined target BER(P_b), the SNR threshold point Γ_{M_i} for a specified bit loading, can be easily found for given constellation size as in (4.13) and shown in Table. 4.1.

$$\Gamma_{M_i} = \frac{M_i - 1}{1.5}\ln\left(\frac{1}{5P_b}\right), \tag{4.14}$$

By using (4.13) and (4.14), we can calculate the modulation mode M_i and Γ_{M_i} based on target BER and instantaneous SNR for the worst MIMO link. Bits, power and antennas should be allocated jointly to achieve the optimal solution. However this causes the high computational complexity at the base station in order to reach the optimal allocation. Hence, we use the equal power distribution and equal number of bit will be loaded on all of the selected transmitted antennas for the simple decoding at the receiver side to reduce the complexity in the system. The proposed method can be started from the following nonlinear constrained optimization problem. Our aim is to maximize the total data throughput under the constraints of total transmit power, available RF chains

and predetermined target BER in the system. The allocation problem is formulated as follows:

$$max(C_{total}) = max\left(\sum_{i=1}^{T_{sel}}\log_2(M_i)\right), \tag{4.15}$$

subject to:

$$T_{sel} \leq R_{sel} \leq \text{Avaliable RF chains}, \tag{4.16}$$

$$e_i\left(\log_2(M_i)\right) = P_{total}/T_{sel}, \tag{4.17}$$

$$BER_i \leq P_b, \tag{4.18}$$

$$\log_2(M_i) \geq 0, e_i \geq 0, \ i = 1, 2, \cdots T \tag{4.19}$$

$$\log_2(M_i) = \log_2(M_k), \ i \neq k \tag{4.20}$$

where C_{total} and P_{total} are total data rate and total available transmit power in the system, respectively. T_{sel} and R_{sel} are the selected number of transmit and receive antennas in the system. The convex function $e_i\left(\log_2(M_i)\right)$ represents the amount of energy necessary to transmit $\left(\log_2(M_i)\right)$ bits from the ith transmit antenna in the system.

4.3.5 Joint Antenna Selection Method with Adaptive Bit Loading under the Constraint of Total Transmit Power, Target BER and RF Chains in the System

In this section, we would like to explain the effect of channel parameters (such as SNR, K-factor and correlation) on the decision of joint antenna selection method. This antenna
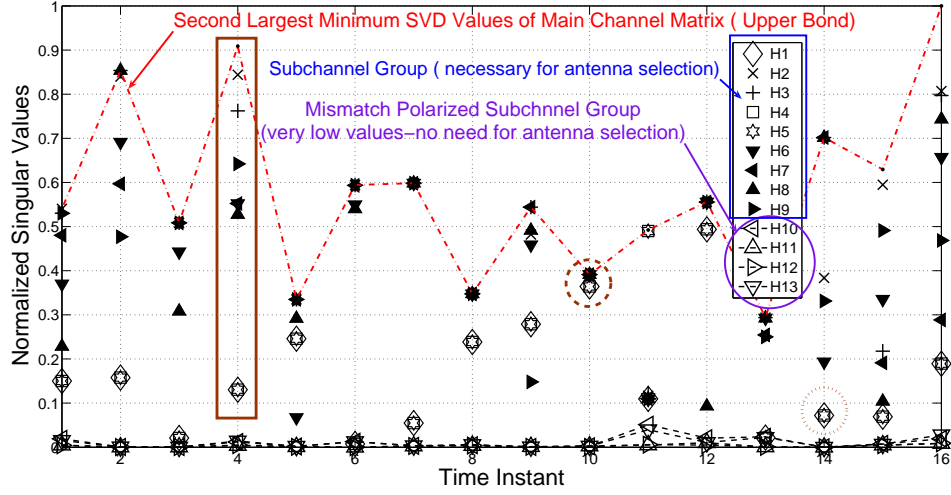
Figure 4.5: Comparison of Singular Values for subchannel matrices from original 3×3 MIMO system for each channel instant.

selection must be performed with adaptive bit loading under the constraint of total transmit power, target BER and available RF chains in the system. To explain the effect of these channel parameters on the decision of joint antenna selection, we show the minimum singular values of 13 subchannel matrices and second largest minimum singular value in Fig. 4.5 for 16 times of channel realizations. To get this figure, 3×3 MIMO channels $\mathbf{H}_{idd}$ are randomly generated by using Matlab simulator for each time instant of channel realization and this $\mathbf{H}_{idd}$ is substituted into (4.1) by using random parameters for K-factors and antenna correlations and average SNR to get each $\mathbf{H}$. The random values which have been used for each time instant are also shown in Table. 4.2. As already mention in the earlier section, minimum singular values of mismatched polarized subchannel matrices are very low and we do not show their values in the following figures for the clear explanation and presentation of our proposed method.

The simulation results for the SNR values of the 3×3 MIMO links and its subchannel matrices from time instant 1 to 16 are shown in Fig. 4.6. When SNR gap between the

Table 4.2: Random Values of K-factor, Correlation and Average SNR for each channel instant which are used in the development
of Figs. 4.5, 4.6 and 4.7.

Time Instant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
K-factor	0.6	9	0.1	0.75	0.3	9	18	0.3	0.7	0.95	0.25	0.35	0.15	0.5	0.6	0.65
Correlation	0.55	0.16	0.11	0.7	0.27	0.99	0.63	0.46	0.14	0.34	0.8	0.67	0.96	0.03	0.3	0.7
SNR(dB)	30	2	8	26	27	4	7	27	10	34	16	6	11	28	4	17
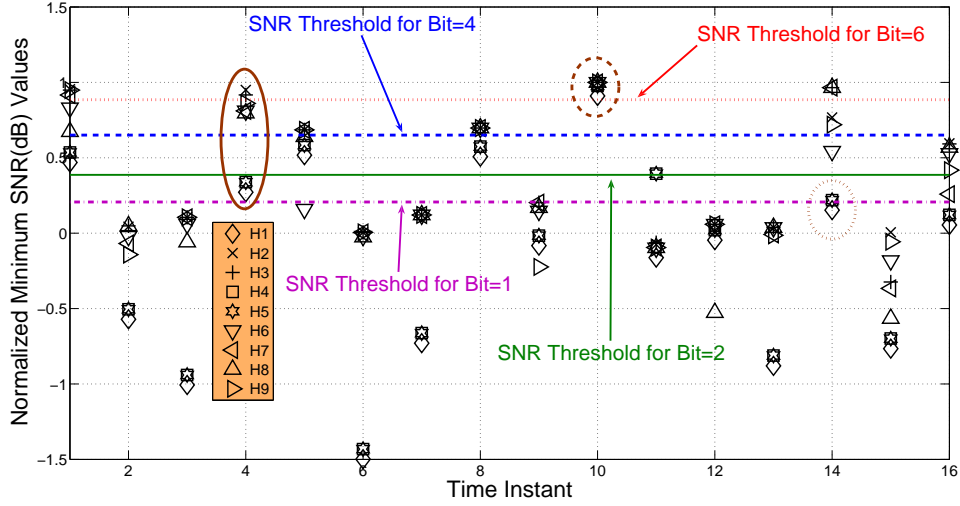
Figure 4.6: Comparison of SNR Values for original 3×3 MIMO channel matrix and its subchannel matrices for 3×2 and 2×2 MIMO systems.

worst link and other link is very large, then efficiency might be reduced for the usage of resources in the system. According to (4.20), the worst MIMO link will limit the lower modulation mode for the whole system although other MIMO link can load higher modulation mode. In the case for time instant 4, we should use only **H2** channel matrix to give the higher throughput because they have the largest minimum singular values. However, we should not always choose the best channel like that. According to (4.16) and (4.17), there are other limitations (which are also degrees of freedom in some conditions) to choose the best channel. In the case for time instant 10, we should use **H1** if limitation of RF chains in (4.16) is allowed to use 3RF chain in both sides. Even the minimum singular values of **H1** is a little smaller than other channel matrices as shown in Fig. 4.5, its SNR region is the same as other subchannel matrices as shown in Fig. 4.6. That means 3RF can transmit higher number of total bit than 2RF chains in the system. When we see at time instant 14 for **H1**, **H4** and **H5**, we can notice that their minimum singular values are equal, but their SNR regions are different and will give the different level of

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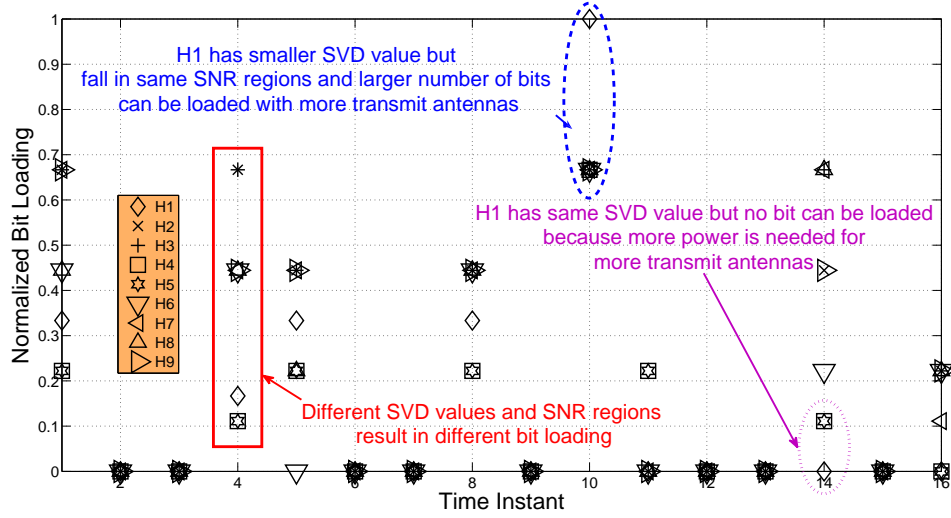
Figure 4.7: Comparison of bit loading for original 3×3 MIMO channel matrix and its subchannel matrices for 3×2 and 2×2 MIMO systems.

bit loading. That is because of the limitation of (4.17) and (4.20). According to (4.17), total transmit power is equally distributed to all selected transmit antennas. Therefore, SNR level of 3RF system is less than SNR level of 2RF system and it will cause the lower modulation modes for 3RF system than 2RF system as shown in Fig. 4.7. That is the weak-points of the selection algorithm in [4.8] and [4.11] and we improve this weak-point in our proposed method. In their papers, they did not consider the effect of (4.16) and (4.17). They just choose the largest minimum singular values or channel gains for their selection algorithm under the predefined RF chains and this might cause the erroneous choosing in sometime as explain in above. That's why we propose the antenna selection method which jointly considers minimum singular values as well as adaptive modulation and available RF chains for efficient usage of system resources.

According to (4.16), there is a limitation in the selection of transmit and receive antenna based on the available RF chains in the system. Therefore, we consider our MIMO system based on the available RF chains. In case 1, we assume that there are 3 RF chains

in both side and thus we can use all available channel matrices. In case 2, we assume that there are 2 RF chains in transmitter side and 3 RF chains in receiver side. Therefore, we can use all subchannel matrices except 3×3 MIMO channel matrices . In case 3, we assume that there are 2 RF chains available in both sides and hence we have to exclude one 3×3 and three 3×2 subchannel matrices in the antenna selection method. These antenna selection algorithms will use adaptive bit loading and antenna selection for the efficient usage of system resources to improve the system throughput under the constraint of total transmit power and predetermined target BER.

4.3.5.1   Case 1: Three RF Chains are Available in Both Sides

In this case, we can use all available subchannel matrices. But, we can see in Fig. 4.4 and Fig. 4.7 that at least one of the minimum singular values of 3×2 subchannel matrices is always greater than or equal to other minimum singular values which are obtained from 2×2 subchannel matrices. That means we do not need to check the minimum singular values of 2×2 subchannel matrices if there has available RF chains which can support to use 3×2 MIMO system. In that case, we can reduce the complexity in case 1 for the antenna selection methods by removing all subchannel matrices with 2×2 systems. Therefore, we will compare the second largest minimum singular value from main 3×3 channel matrix with minimum singular values from 3×2 matrices one by one. As soon as we find it, we can stop the comparison process. However, we still need to compare the capacities of 3×3 MIMO system and the selected 3×2 MIMO system to solve the limitations in (4.16), (4.17) and (4.20).

Step 1: Initialization a) Calculate Γ_{M_i} for each M_i-QAM modulation with predefined target BER by using (4.12).

Step 2: a) Set, $\mathbf{H} = \left\{ \mathbf{H}_1^{3\times3}, \mathbf{H}_2^{3\times2}, \mathbf{H}_3^{3\times2}, \mathbf{H}_4^{3\times2} \right\}$.

b) Get the second minimum and minimum singular values by decomposing the 3×3 MIMO channel matrix with SVD.

Get $\lambda_{2^{nd}min}^{3\times3}$ and $\lambda_{min}^{3\times3}$.

c) After getting these values, compare $\lambda_{2^{nd}min}^{3\times3}$ with $\lambda_{h\ min}^{3\times2}$ as follows:

$\lambda_{sel}^{3\times2} = 0$;

For Loop: $h = 2$ to 4

Get $\lambda_{h\ min}^{3\times2}$;

If $\lambda_{2^{nd}min}^{3\times3} \equiv \lambda_{h\ min}^{3\times2}$, then $\lambda_{sel}^{3\times2} = \lambda_{h\ min}^{3\times2}$ break;

Else if $\lambda_{h\ min}^{3\times2} > \lambda_{sel}^{3\times2}$ then $\lambda_{sel}^{3\times2} = \lambda_{h\ min}^{3\times2}$;

End of For Loop.

Step 3: After getting the selected $\lambda_{sel}^{3\times2}$. Calculate effective throughput for 3×3 and selected 3×2 MIMO system as follows:

$\gamma_{min}^{T_{sel}\times R_{sel}} = \frac{P_t}{N_0 T_{sel}} \lambda_{min}^{T_{sel}\times R_{sel}}$,

If, $\gamma_{min}^{T_{sel}\times R_{sel}} \geq \Gamma_{64}$ then $c^{T_{sel}\times R_{sel}} = 6$;

Else if, $\gamma_{min}^{T_{sel}\times R_{sel}} \geq \Gamma_{16}$ then $c^{T_{sel}\times R_{sel}} = 4$;

Else if, $\gamma_{min}^{T_{sel}\times R_{sel}} \geq \Gamma_4$ then $c^{T_{sel}\times R_{sel}} = 2$;

Else if, $\gamma_{min}^{T_{sel}\times R_{sel}} \geq \Gamma_2$ then $c^{T_{sel}\times R_{sel}} = 1$;

Else, $c^{T_{sel}\times R_{sel}} = 0$;

$C_{total}^{T_{sel}\times R_{sel}} = \left(\sum_{i=1}^{T_{sel}} c_i^{T_{sel}\times R_{sel}} \right)$

Step 4: Compare $C_{total}^{3\times3}$ and $C_{total}^{3\times2}$ and choose the MIMO system which is related to the larger one.

Step 5: Step 2 to 4 is repeated for next channel realization.

4.3.5.2 Case 2: Two RF Chains in Transmit Side and Three RF Chains in Receive Side

This case is similar to **case 1** except that we do not need to compare with 3×3 MIMO system because this system cannot be used by limited RF chains in transmitter side. And the antenna selection algorithm is expressed in following for case 2.

Step 1: Same as step 1 in case 1.

Step 2:

a) Set, $\mathbf{H} = \left\{ \mathbf{H}_2^{3\times2}, \mathbf{H}_3^{3\times2}, \mathbf{H}_4^{3\times2} \right\}$.

b) Get the second minimum and minimum singular values by decomposing the 3×3 MIMO channel matrix with SVD.

Get $\lambda_{2^{nd}min}^{3\times3}$ and $\lambda_{min}^{3\times3}$.

c) After getting these values, compare $\lambda_{2^{nd}min}^{3\times3}$ with $\lambda_{h}^{3\times2}{}_{min}$ as follows:

$\lambda_{sel}^{3\times2} = 0$;

For Loop: $h = 2$ to 4

Get $\lambda_{h}^{3\times2}{}_{min}$;

If $\lambda_{2^{nd}min}^{3\times3} \equiv \lambda_{h}^{3\times2}{}_{min}$, then $\lambda_{sel}^{3\times2} = \lambda_{h}^{3\times2}{}_{min}$ break;

Else if $\lambda_{h}^{3\times2}{}_{min} > \lambda_{sel}^{3\times2}$ then $\lambda_{sel}^{3\times2} = \lambda_{h}^{3\times2}{}_{min}$;

End of For Loop.

Step 3: Step 2 is repeated for next channel realization.

4.3.5.3 Case 3: Two RF Chains are Available in Both Sides

In this case, we don't need consider mismatch polarized MIMO channel because of very lower minimum singular values in these subchannel matrices. And the antenna selection algorithm is expressed in following for case 3.

Step 1: Same as step 1 in case 1.

Step 2: a) Set, $\mathbf{H} = \left\{ \mathbf{H}_5^{2\times2}, \mathbf{H}_6^{2\times2}, \mathbf{H}_7^{2\times2}, \mathbf{H}_8^{2\times2}, \mathbf{H}_9^{2\times2}, \right\}$.

b) Get the second minimum singular values by decomposing the 3×3 MIMO channel matrix with SVD.

Get $\lambda_{2^{nd}min}^{3\times3}$.

c) After getting these values, compare $\lambda_{2^{nd}min}^{3\times3}$ with $\lambda_{h}^{2\times2}{}_{min}$ as follows:

$\lambda_{sel}^{2\times2} = 0$;

For Loop $h = 5$ to 9

Get $\lambda_{h}^{2\times2}{}_{min}$;

If $\lambda_{2^{nd}min}^{3\times3} \equiv \lambda_{h}^{2\times2}{}_{min}$, then $\lambda_{sel}^{2\times2} = \lambda_{h}^{2\times2}{}_{min}$ break;

Else if $\lambda_{h}^{2\times2}{}_{min} > \lambda_{sel}^{2\times2}$ then $\lambda_{sel}^{2\times2} = \lambda_{h}^{2\times2}{}_{min}$;

End of For loop.

Step 3: Step 2 is repeated for next channel realization.

4.4   Simulated Results

We consider the situation of adaptive modulation with $M_i = \{0, 2, 4, 16, 64\}$ to maximize the transmission rate with the target BER of 10^{-3} . The SNR thresholds Γ_{M_i} can be calculated from (4.14). We present the simulation results for capacity and processing time for our propose method, methods in [4.8] and [4.11] for antenna selection in three cases. We also present the results of fixed MIMO system and fixed 2×2 MIMO system for the references in each case. K-factor and antenna correlation and $\mathbf{H}_{idd}$ is randomly generated to develop the 3×3 channel matrix and we use 250000 simulation times for each methods in the system.

In Fig. 4.8, we show the capacity comparison for case 1. In Fig. 4.8, we can see that the capacity of proposed method is always better than conventional antenna selection method and fixed MIMO system. That is because of the consideration for the effect of (4.16),
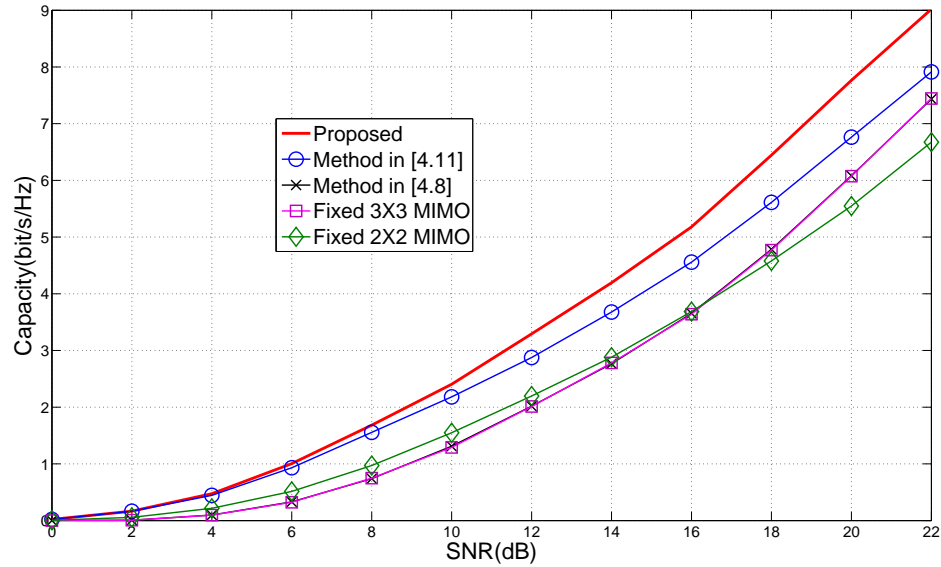
Figure 4.8: Capacity comparison for case 1.

(4.17) and (4.20) in the selection method. The capacity of method [4.8] is always lower than in method [4.11]. Moreover, capacity of method [4.8] is overlapped with that of fixed 3×3 MIMO system and their performances are even lower than fixed 2×2 MIMO system in lower SNR range. Method [4.8] is Frobenius norm based antenna selection method and when they calculate the Frobenius norm for 3×3 MIMO system, its channel gain is always larger than other 3×2 or 2×2 matrices. That's why it will always choose 3×3 channel matrices and its performance will be overlapped with fixed 3×3 MIMO system. Because of the equal power distribution in more transmit antennas and limitation in (4.17) and (4.20) 3×3 MIMO transmit antennas cannot use higher modulation modes in the low SNR range and reduce the capacity. But, when their SNR range is large enough, they can use higher modulation modes with more transmit antennas and will get the higher capacity than 2×2 MIMO system.

We also show the simulation results of case 1 for the processing time for each method in Table. 4.3. In this table, we can see that fixed MIMO systems are the fastest ones

in the system and conventional antenna selection methods in [4.8] and [4.11] are faster than our proposed method. In their methods, they just choose the channel matrix with the largest minimum singular value in [4.11] and highest gain in [4.8]. And there has no more calculation is required to consider the limitation in (4.16), (4.17) and (4.20). On the other hand, the propose method will choose the channel matrix with the largest minimum singular value and after that it is still necessary to compare the total capacity of selected channel matrix with 3×3 MIMO channel matrix to consider the effect of (4.16), (4.17) and (4.20). That's why processing time for propose method is a little longer than methods in [4.8] and [4.11]. In case 1, the proposed scheme takes 107.4% of processing time compared with conventional scheme in [4.11] and 112.1 % of time compared with the conventional scheme in [4.8]. In this case the processing time of the proposed scheme is nearly equal with conventional scheme in [4.11] and a little longer than the conventional scheme in [4.8]. But, we can also see that the capacity of the proposed scheme is also better when compared with methods in [4.11] and [4.8] as shown in Fig. 4.8.

In Fig. 4.9, we show the capacity comparison for case 2. In this figure, we can see that the capacity of proposed method is overlapped with method in [4.11] although they are better than method in [4.8] and fixed MIMO systems. In this case 2, there are only 3×2 MIMO systems available and we do not need to consider the effect of 3×3 MIMO system. That's why our proposed method will choose only the best 3×2 MIMO channel matrix and its performance will be identical to the method in [4.11]. In this figure, we can see that the capacity of method in [4.8] is even lower than fixed 3×2 MIMO system. That is because method in [4.8] will simply choose the highest Frobenius norm from the available channel matrices and they don't consider the effect of channel correlation effect in the system. When channel is heavily correlated, its minimum singular value will be very low although its effective channel gain might be the largest one in the system. And

Table 4.3: Average processing time comparison for antenna selection methods

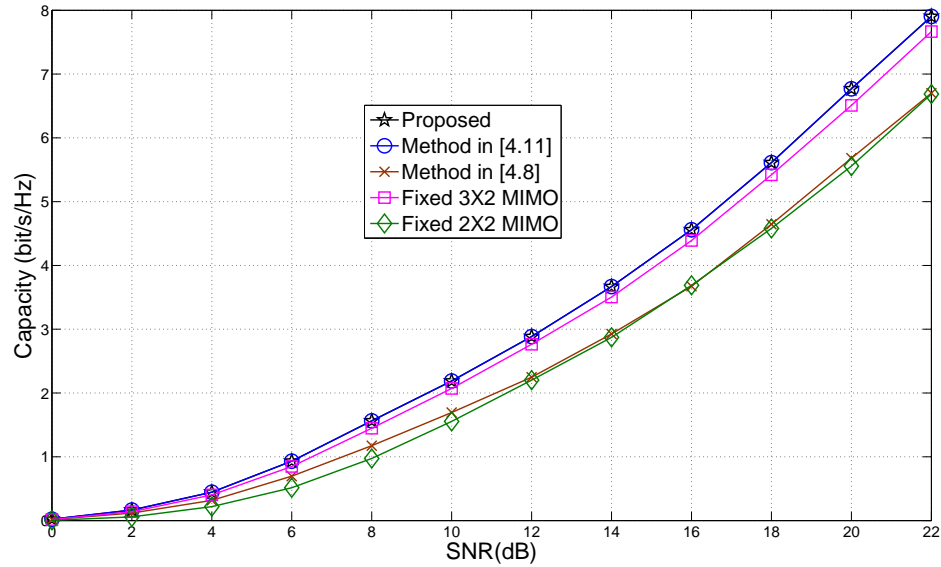|	Proposed	Method in [4.11]	Method in[4.8]	Fixed 3×3 MIMO	Fixed 3×2 MIMO	Fixed 2×2 MIMO
Case 1	0.0001013 sec	0.00009405 sec	0.00009033 sec	0.00002087 sec	-	0.00002511 sec
Case 2	0.00008145 sec	0.00007959 ses	0.0000651 sec	-	0.00002429 sec	0.00002456 sec
Case 3	0.000102 sec	0.0001737 sec	0.000128 sec	-	-	0.00002426 sec

Figure 4.9: Capacity comparison for case 2.

the highest channel matrix will be chosen even though its lowest SNR link cannot carry the higher modulation modes. Therefore, capacity of method in [4.8] is not as good as fixed 3×2 MIMO system.

Their processing times for case 2 are also shown in Table. 4.3. In this table, we can see that fixed MIMO system has the fastest processing time and method in [4.8] has lower processing time than the proposed method and method in [4.11]. That is because of singular value decomposition process in these two methods. SVD processing time is normally longer than Frobenius norm method for the MIMO channel matrix. In case 2, the proposed scheme takes 102.33% of processing time compared with method in [4.11] and 125.1% of time compared with method in [4.8]. In this case the processing time of the proposed scheme is nearly equal with the conventional scheme in [4.11] and a little longer than the conventional scheme in [4.8]. But, we can also see that the capacity of the proposed scheme is equal with the conventional scheme in [4.11] and better than the conventional scheme in [4.8] as shown in Fig. 4.9.
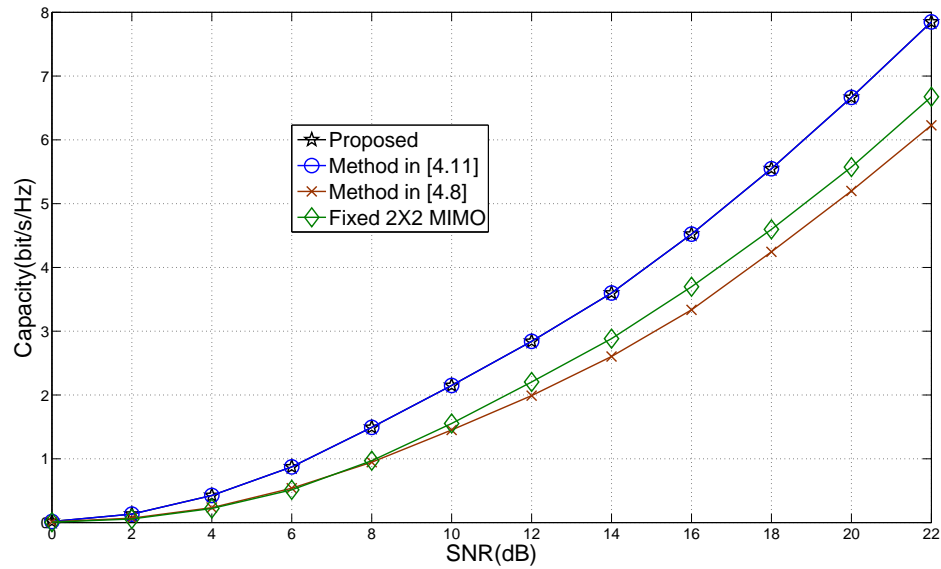
Figure 4.10: Capacity comparison for case 3.

In Fig. 4.10, we show the capacity comparison for case 3. Fig. 4.10, we can see that the capacity of the proposed method is overlapped with method in [4.11] although they are better than method in [4.8] and fixed MIMO systems. In this case 3, there are only 2×2 MIMO systems available and we do not need to consider the effect of (4.16) and (4.17). That's why our proposed method chooses only the best 2×2 MIMO channel matrix and its performance is identical to the method in [4.11]. In this figure, we can see that the capacity of method in [4.8] is also lower than fixed 2×2 MIMO system. That is because of the same reason which is already explained in Fig. 4.9.

In Table. 4.3 for case 3, we can see that fixed MIMO system has the fastest processing time.In the proposed scheme, we have to calculate and choose the best transmit and receive antenna to achieve the best channel condition in the system. And this calculation process will take some amount of time in the system. But, in the fixed scheme, they don't need to select transmit or receive antennas from the system. Therefore, fixed schemes have no calculation delay in their systems and that's why proposed scheme's processing

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time is larger than fixed schemes for all cases.On the other hand, the proposed method has lower processing time than conventional methods in [4.8] and [4.11]. That is because of the effect of reduced complexity in our proposed methods as explained in section 4.3. In case 3, the proposed scheme takes 58.7% of processing time compared with conventional scheme in [4.11] and 79.61% of time compared with conventional scheme in [4.8]. Moreover, we can also see that the capacity of the proposed scheme is equal to that of conventional scheme in [4.11] and much better than the conventional scheme in [4.8] as shown in Fig. 4.10.

4.5   Conclusion

I have proposed the reduced complexity antenna selection method with adaptive bit loading and polarized antennas based on the SVD to improve the throughput performance under the constraint of total transmit power, predetermined target BER and available RF chains in the system. The complexity is reduced by removing unnecessary subchannel matrices which have always very low minimum singular values and by comparing the second largest minimum singular value obtained from original main MIMO matrix. Computer simulated results show that the proposed scheme achieves not only higher throughput but also less processing time than conventional schemes in [4.8] and [4.11].

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Chapter 5

Conclusion

In this dissertation, we presented our research works on promises technologies for next generation broadband wireless mobile communication systems. In chapter 1, the evolution of mobile wireless generation are presented in first and after that, the back ground information and theories of MIMO, OFDM and resource allocation techniques and antenna selection methods are introduced. MIMO technologies can give the high speed internet access under the limited resources of radio frequency without additional transmit power in the wireless system. MIMO technology in spectral multiplexing system will work more efficiently if there has rich scattering multipath channel environment to give the low correlated channel matrix in the system. Therefore, our research works focused on this MIMO technologies in spatial multiplexing system for higher data transfer rate in next generation mobile wireless system. On the other hand, Inter-Symbol-Interferences will be occurred because of the rich scattering multipath channel environment and MIMO system cannot directly applied in the wide band transmission and it is limited to use in the narrow band transmission to avoid the ISI interference in the wireless system. But, we can combine the OFDM technology with MIMO to reduce the ISI interference in the wireless system. So, the combination of OFDM and MIMO technologies is one of the key technologies for next generation mobile wireless communication. So we also discussed about OFDM

technologies in the first chapter to give the better understanding of this dissertation. Users of multiuser OFDM system observe multipath fading but have independent fading parameters due to their different locations. Hence, multiuser system creates channel diversity as the number of user increases and we discussed about the resource allocation techniques for the efficient usages of multiuser diversity in the multiuser MIMO-OFDM system. In the conventional resource allocation schemes, the user with best channel condition will have most of the system resources and it will cause the unfair policies in sharing system resources among users based on their requirements and payments fees. So we focused our research work to give the proportional data rate fairness among users in the system depend on their data rate and QoS requirements in the MIMO-OFDM wireless system. So, the background theories of conventional resource allocation are presented in the later part of chapter 1. In the multiuser MIMO-OFDM wireless communication system; we need huge calculation for channel estimation, resource allocation, channel coding and encoding and other necessary process for the successful data transfer between the base station and mobile unit. Therefore, we should consider how to reduce the complexity in these processes in the wireless communication system. And we also emphasized on the reduction of complexity in the antenna selection method in the MIMO wireless communication system. To give the clear understanding of our proposed method, we introduced the background theories of antenna selection method in MIMO wireless system in the later part of chapter 1.

Chapter 2 focuses on the resource allocation scheme for downlink MIMO-OFDMA system for next generation wireless communication system. In the multiuser mobile wireless communication, some users might have good channel condition and some users might have bad channel condition. In that case, we can give the multiuser diversity into the system, if we apply the adaptive resource allocation in this mobile wireless system by

choosing the best channel user to increase the system performance. On the other hand, it is necessary to consider to support the many different kinds of mobile application and their service requirement among multiple users in the next generation wireless communication system. That means, resource allocation should consider not only to improve the system performance but also to give the proportional data rate requirement among users in the system. Most of the conventional schemes considered to increase the total system capacity in MIMO and OFDM wireless system. So these conventional schemes are not suitable for the next generation wireless communication system. One of the problem in the resource allocation scheme is different channel condition in the space domain and frequency domain among users in the system. So, it is very difficult to know which user has the best channel condition for space and frequency domain if we use the conventional channel gain comparison methods among users in the MIMO-OFDM system. To solve this problem, we use the singular value decomposition method to choose the best sub-carrier for each user based on the assumption of equal power distribution among users in the system. Users are also separated in the frequency domain to reduce the complexity in the MIMO-OFDM wireless system. In each step of the resource allocation process, we consider not only to increase the total system capacity performance but also to give the proportional data rate fairness requirement among user in the system. Therefore, the proposed resource allocation scheme can give exact proportional data rate fairness requirement among users in the MIMO-OFDMA downlink system.

One of the advantages of MIMO system is spatial multiplexing in the system. That means, different users can transmit their different data in the same frequency at that same time without additional transmit power and bandwidth in the wireless system. Therefore

chapter 3 focuses on the resource allocation in the spatial multiplexing multiuser MIMO-OFDM wireless system. That means different user's data can overlap in the same frequency at the same time. Therefore, we can use scare spectral resources more efficiently in the MIMO-OFDM wireless communication system environments. In this chapter, we consider again to give the proportional data rate fairness constraint and QoS requirements among multiple users in uplink MIMO-OFDM wireless system. But this time, wireless users are not separated in the frequency domain and complexity will be increased when compared with previous research work in chapter 2. One of the problem in this kind of system is the antenna correlation in the wireless system. In the conventional resource allocation schemes, they can not handle the antenna correlation properly to increase the total system capacity. Moreover, most of them could not give the proportional data rate fairness among users in the system. In the proposed method, we used the singular value decomposition method to handle the antenna correlation in the spatial multiplexing system. Highly correlated antenna will be separated in the frequency domain and low correlated antenna can be allocated in the same subcarrier to increase the total system capacity based on their minimum singular values. In each resource allocation step, the proposed resource allocation scheme consider not only to increase the total system capacity but also to give the proportional data rate fairness among user in the system under the constraint of total transmit power and target bit error rate for each user.

In the previous research works, we proposed two resource allocation schemes for multiuser MIMO-OFDMA downlink system and MIMO-OFDM uplink system in chapter 2 and 3. In the mobile wireless communication system, base station need to compute channel estimation, coding, subcarrier, bit and power allocation for each user in the system and this will cause the high computational complexity in the base station. Therefore, it is necessary to reduce the complexities in each step of the wireless communication system

as much as possible to reduce the over all processing time for the mobile wireless system. Therefore, we also proposed the reduced complexity scheme for the antenna selection in the MIMO wireless communication system in chapter 4. Chapter 4 describes the reduced complexity antenna selection method with adaptive bit loading and polarized antennas based on the SVD to improve the throughput performance under the constraint of total transmit power, predetermined target BER and available RF chains in the system. In the conventional multi-input multi-output (MIMO) communication systems, most of the antenna selection methods considered are suitable only for spatially separated uni-polarized system under Rayleigh fading channel in non-line of sight (NLOS) condition. In the practical MIMO channel case, influence of LOS and NLOS conditions in the channel can vary from time to time according to the channel parameters and user movement in the system. Based on these influences and channel condition, uni-polarized system may outperform a cross-polarized and vice versa. Thus, we consider how to reduce the complexity in the practical MIMO channel environment when developing the antenna selection scheme. In this research, reduced complexity in antenna selection is proposed to give the higher throughput in the practical MIMO channel environment. The complexity of proposed scheme is reduced by eliminating unnecessary subchannel matrices which have mismatch polarization and by using second largest minimum singular value obtained from original main MIMO matrix as an upper bond for all other minimum singular values in the system.

As an overall conclusion, this dissertation contributes the efficient resource allocation scheme with exact fulfilment of proportional data rate requirement among users for downlink MIMO-OFDMA system and uplink MIMO-OFDM system and reduction of computational complexity in the antenna selection methods in the MIMOM wireless communication systems for next generation mobile communications.

In future extension of our research, we will consider to give the optimal resource allocation with reduce complexity in the subcarrier, bit and power allocation for the downlink and uplink in the multiuser MIMO-OFDM system in chapter 2 and 3. Chapter 4 considers only the limited number of transmit and receive antenna numbers in the transmitter and receiver side in the MIMO wireless communication system. Therefore, it is also necessary to develop the reduce complexity in the antenna selection for MIMO wireless communication system with any transmit and receive antenna numbers in transmitter side and receiver side.

Appendix A

Appdx A

A.1 Derivation of (2.15)

Here, the meaning and derivation of (2.15) are described.

$$b_{k,j,m}^{est} = \log_2 \left(1 + \frac{SNR_{k,m}^{min}}{GAP} \right) \tag{2.15}$$

The general expression of (2.15) can be written as

$$b_{k,j,m}^{est} = \log_2 \left(1 + \frac{p_{k,j,m}\left|h_{k,j,m}\right|^2}{N_0 GAP} \right) = \log_2 \left(1 + \frac{SNR_{k,j,m}}{GAP} \right) \tag{A.1}$$

where

$$SNR_{k,j,m} = \left(\frac{p_{k,j,m}\left|h_{k,j,m}\right|^2}{N_0} \right) \tag{A.2}$$

$p_{k,j,m}$ =transmit power for j^{th} transmit antenna of kth user on m^{th} subcarrier.

$h_{k,j,m}$ =channel gain for j^{th} transmit antenna of kth user on m^{th} subcarrier.

N_0 =average noise power.

$b_{k,j,m}^{est}$ =numbers of estimated bits to be transmitted from j^{th} transmit antenna of kth user on m^{th} subcarrier.

(A.1) is a simplified form of water-pouring energy allocation [2-9]. Although water-pouring energy allocation will yield the optimal solution, it is often difficult to compute, and it tacitly assumes infinite granularity in constellation size, which is not realizable. By using (A.1), we can obtain the estimated number of bits to be transmitted from antenna j of user k on subcarrier m. In the subcarrier allocation step, we assume that equal power distribution $(p_{k,j,m} = 1)$ is carried out for each user's transmitting antenna on the allocated subcarrier. Moreover, the same number of bits are transmitted from all transmit antennas of user k on subcarrier m. (i.e.,$b_{k,1,m}^{est} = \cdots b_{k,j,m}^{est} \cdots = b_{k,J,m}^{est}$) Moreover, we know that minimum SNR dominates the error performance of the system [2-7]. That's why we use the minimum $SNR_{k,j,m}$ to calculate the number estimated bits to be transmitted from all transmit antennas of user k on subcarrier m. For the clear expression, we use the following notation for the minimum SNR among all transmits antennas of user k on subcarrier m. where

$$
\begin{aligned}
SNR_{k,m}^{min} &= \min\left(SNR_{k,1,m}, \cdots SNR_{k,j,m} \cdots SNR_{k,J,m}\right) \\
&= \frac{1}{N_0}\min\left(\left|h_{k,1,m}\right|^2, \cdots \left|h_{k,j,m}\right|^2 \cdots \left|h_{k,J,m}\right|^2\right)
\end{aligned}
\tag{A.3}
$$

Then, (2.15) is obtained by substituting the minimum SNR among all transmits antennas of user k on subcarrier m in (A.2) with $SNR_{k,m}^{min}$ in (A.3). We use (2.15) to give fast processing and simplification for the estimation of number of transmission bits for our proposed scheme.

A.2   Derivation of (2.16)

Here, the derivation of (2.16) is described.

$$
e_{k,j,m}(b_{k,m}) = (2^{b_{k,m}} - 1)\frac{GAP}{SNR_{k,j,m}}
\tag{2.16}
$$

We transmit equal number of bits from all of transmit antennas of user k on subcarrier m. Therefore, we use $SNR_{k,m}^{min}$ value to calculate the estimated number of bits to be transmitted from all transmit antennas of user k on subcarrier m by using (2.15). However, this estimated number of bits might be non-integer value and is not suitable for the available constellation modes (no transmitting, BPSK, QPSK, 16 QAM or 64 QAM). Thus, the integer value $b_{k,m}$ is obtained by rounding the value of $b_{k,m}^{est}$ to the nearest mapped symbol which conveys either 0,1,2,4 or 6. Moreover, the integer value $b_{k,m}$ to obtain the transmit power of antennas j of user k on subcarrier m, should be expressed as.

$$b_{k,m} = \log_2\left(1 + \frac{p_{k,j,m}\left|h_{k,j,m}\right|^2}{N_0 GAP}\right), \tag{A.4}$$

where $b_{k,m} = b_{k,1,m} = \cdots = b_{k,j,m} \cdots = b_{k,J,m}$

In the next step, we have to re-adjust the transmit power according to the rounded number of bits and related channel conditions for user k on subcarrier m of transmit antenna j. Therefore, we take antilog on both side of (A.4) and by shifting the variables from left side and right side, we can obtain the following equation

$$p_{k,j,m} = (2^{b_{k,m}} - 1)\frac{N_0 GAP}{\left|h_{k,j,m}\right|^2} \tag{A.5}$$

(A.5) expresses the required transmit power for antenna j of user k on subcarrier m. By substituting $p_{k,j,m}$ with $e_{k,j,m}(b_{k,m})$, and $\frac{N_0}{\left|h_{k,j,m}\right|^2}$ with $\frac{1}{SNR_{k,j,m}}$, respectively in (A.5), we can obtain (2.16).