國立交通大學

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碩士論文

針對多媒體資訊在正交分頻多工寬頻無線存取系統中排程技術及子載波分配方法之研究

Scheduling and Subcarrier Allocation for OFDMA Based Broadband Wireless Access Systems with Multi-type Traffic

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摘要

在此論文中，我們針對多媒體資訊在正交分頻多工(Orthogonal Frequency Division Multiple Access, OFDMA)寬頻無線存取(Broadband Wireless Access, BWA)系統作排程技術及子載波分配方法之研究。

首先，我們將驗證在正交分頻多工寬頻無線存取此種多載波的系統，使用一種最簡單的最大信號干擾比(Maximum C/I)排程法，即可同時增加系統資料流量(throughput)且維持一定的公平性。最大信號干擾比排程法在單載波分碼多工存取(Code Division Multiple Access, CDMA)系統可有效的增進系統資料流量，但一向被視為一種不公平的排程方法，在此，我們重新評估最大信號干擾比排程法在多載波的正交分頻多工存取系統中的效能。透過分析與模擬，我們發現最大信號干擾比排程法對於正交分頻多工系統的確算是一種公平的排程方法。因此，針對正交分頻多工系統存取，我們發展了一種以最大信號干擾比排程法為基礎的資源分配演算法，模擬結果顯示，最大干擾比排程法並不比比例式公平(proportional fair)排程法差很多，總結，在正交分頻多工存取系統中，最大干擾比排程法，不但可盡量使系統資料流量趨近最大，更可同時維持相當好的公平性。

然而，目前的通訊環境中，多媒體的資訊傳輸已成趨勢，因此如

何對不同服務品質(Quality of Service, QoS)需求的使用者作最好的資源分配亦成一項重要的研究課題。我們在此針對了正交分頻多工存取系統發展了一套滿足服務品質的排程及通道分配的演算法。即時服務(real-time service)的使用者在意的是資料的傳輸延遲，而非即時(non-real-time)服務的使用者則是希望資料流量盡可能的越大越好。而在無線通訊的環境，通道狀況是隨時間改變的，因此，我們針對在正交分頻多工存取系統中，提出了一種考慮通道狀況和服務品質的一套排程演算法。藉著利用多載波環境中的頻率多樣性和通道變化的效應，我們提出的排程演算法可同時滿足即時與非即時使用的的服務品質要求。首先，我們藉著排隊理論中等待時間的分析來分配即時使用者的無線資源，接著使用最大信號干擾比排程法來分配非即時使用者以達最大系統流量。總而言之，我們藉著利用頻率多樣性和實體層的通道效應作跨階層的設計，便同時滿足了不同服務品質需求的使用者。

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Summary

In this thesis, we first demonstrate that the simple maximum carrier to interference ratio (C/I) scheduling can both enhance system throughput and maintain fairness performances for the orthogonal frequency division multiple access (OFDMA) system. The maximum C/I scheduling has long been recognized as an effective method to enhance throughput, but it is viewed as an unfair scheduling policy in the the single carrier code division multiple access (CDMA) system. We reassess the fairness performance of the maximum C/I scheduling in the context of the multi-carrier OFDMA system. Through analysis and simulations, we find that the maximum C/I scheduling is indeed an fair scheduling for OFDMA systems. Thus, with respect to the OFDMA system, we develop a maximum C/I scheduling based resource allocation algorithm. Our results show that the fairness of the maximum C/I scheduling in OFDMA systems is comparable to that of the proportional fair scheduling scheme. To sum up, we conclude that in the OFDMA system, the maximum C/I scheduling not only can maximize system throughput, but simultaneously maintain very good fairness performance.

The orthogonal frequency division multiple access (OFDMA) is becoming an important technique for the future wireless systems. Through parallel multi-carrier transmissions, the inter-symbol interference (ISI) can be easily handled in transmitting high speed data. Furthermore, OFDMA systems bring a new dimension for allocating radio resource - subcarrier. By exploiting frequency diversity in the wide frequency spectrum, a suitable subcarrier allocation technique can further enhance throughput for the OFDMA system. This thesis addresses the issue of allocating subcarriers for providing both real-time and non-real-time traffic in the OFDMA system. We suggest a categorized subcarrier allocation (CSA) technique to improve throughput for non-real-time traffic, while satisfying the quality of service (QoS) requirements for the real-time traffic. In the proposed CSA technique, subcarriers are categorized into two groups based on their quality: good and fair. The real-time traffic will be assigned by the subcarrier with fair condition, while the non-real-time traffic will be assigned with good subcarriers. We find that such a subcarrier allocation method can apply the maximum carrier-to-interference (C/I) scheduling to maximize the throughput in good conditioned subcarriers, while the delay for the real-time traffic can be controlled by allocating enough fair-conditioned subcarriers through a queueing analytical method. Compared to dynamic subcarrier allocation (DSA) and random subcarrier allocation (RSA) methods, the CSA technique outperforms other methods in terms of throughput, blocking probability and fairness performances.

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Chapter 1

Introduction

With the growing demand of high data rate communication, orthogonal frequency division multiple access (OFDMA) is becoming an important technology. OFDMA has been used in many broadband wireless systems, such as the IEEE 802.16a wireless metropolitan area network (WMAN). We investigate the benefits of OFDMA systems from both frequency diversity and multiuser diversity perspectives. Frequency diversity inherently exists in OFDMA systems, while multiuser diversity can be achieved by adopting scheduling algorithms. Although both diversity gains can enhance the system throughput, the challenging issue is how to select a scheduling algorithm that can achieve high system throughput and maintain the fairness among users simultaneously.

In the traditional single carrier systems, many scheduling schemes are developed. Different from single carrier systems, the channel allocation schemes in such multicarrier OFDMA systems have more dimensional consideration to support high-data-rate services. Besides, future wireless communication networks are expected to support multi-type traffic, such as voice, video and data. Therefore, allocating radio resource to different types of services efficiently to meet quality of service (QoS) requirements of multi-types of services is an issue of concern.

1.1 Problems and Solutions

The objective of this thesis is to assess the performances of resource allocation schemes in the OFDMA systems. We investigate the OFDMA system from another resource allocation viewpoint, i.e, scheduling algorithms. Wireless scheduling techniques are developed to exploit the multiuser diversity. In a multiuser wireless system, different users may have different channel responses in a time varying wireless channel. Thus, a channel may be viewed as a bad channel, but may be viewed as a good channel by other users. Consequently, if the system can first pick a user with the best channel quality among a group of users to serve in each channel , the system capacity can be improved significantly. We call this capacity improvement as the multiuser diversity gain. Clearly, for providing delay-tolerant data services, wireless scheduling is an inevitable technique to exploit multiuser diversity which inherently exists in the multiuser system.

1.1.1 Throughput and Fairness Enhancement for OFDMA Broadband Wireless Access Systems Using the Maximum C/I Scheduling

In this thesis, we first assess the fairness performance of the maximum C/I scheduling in the multi-carrier OFDMA system. The maximum C/I scheduling has long been recognized as an effective method to enhance throughput, but it is also viewed as an unfair scheduling policy in the the single carrier CDMA system. Through analysis and simulations, we will find that the maximum C/I scheduling is indeed an fair scheduling for OFDMA systems. Thus, with respect to the OFDMA system, we develop a maximum C/I scheduling based resource allocation algorithm. We show that the fairness of the maximum C/I scheduling in OFDMA systems is comparable to that of the proportional fair scheduling scheme. Hence, we conclude that the simple maximum C/I scheduling can enhance both system throughput and fairness performances for the OFDMA system.

1.1.2 Channel-aware Subcarrier Allocation and QoS Provisioning for OFDMA Systems with Multi-type Traffic

Future wireless communication networks are expected to support multi-type traffic, such as voice, video and data. Therefore, allocating radio resource to different types of services efficiently to meet quality of service (QoS) requirements of each service is an issue of concern. In [1], many conventional subcarrier allocation schemes are listed to try to enhance the system performances of constant data rate services. Nevertheless, in single carrier systems, if the real-time user with higher priority enters the wireless networks, the non-real-time user will delay the transmission due to lower priority. However, in multicarrier systems, the real-time users can be served by the enough good subcarriers without delay and the non-real-time users use other good subcarriers to achieve the throughput requirements at the same time.

Good scheduling algorithms should have the following characteristics: (1) channel aware, (2) high throughput, (3) fair resource allocation and (4) achieving quality of service. There exist some scheduling algorithms discussed to assure QoS requirements of different types of traffic in single carrier code division multiple access (CDMA) systems [2–6]. To provide both minimum service rate guarantees and dynamic channel bandwidth allocation to all users , generalized processor sharing (GPS) [7] [8] discipline is a scheduler candidate. In [2], the author employs fair queueing algorithm to minimize queueing delays in wireless networks. In [3] and [4], the author proposes a GPS based dynamic fair scheduling scheme, called code division GPS (CDGPS) for wideband direct sequence code division multiple access (DS-CDMA) networks to support multi-type traffic. Furthermore, in [3], the author develops a credit-based CDGPS (C-CDGPS) to improve capacity by trading off short-term fairness. The CARR (channel-aware round robin) scheduler [5] utilizes channel information to increase system capacity and guarantees to allocate certain amount of time slots in an assignment round period in code division multiple access 2000 high data rate (CDMA2000 HDR) [9] or wideband code division multiple access high speed downlink packet access (WCDMA HSDPA) [10] systems. In [6], the idea of the FPLS (fair packet loss sharing) scheduling algorithm is to schedule the session of multimedia packets in the way that all the users share the packet loss fairly depending on their QoS requirements and to maximize the system capacity under the QoS constraints. However, in multicarrier systems, such as OFDM, if radio resource management makes use of the frequency diversity, the system performance can be improved. In [11], the author discusses the adaptive modulation and proposes dynamic GPS (DGPS) scheduling for OFDM wireless communication systems, which exploits both multiuser diversity and frequency diversity. Yet, in [12], the proposed proportional rate adaptive optimization considers subcarrier and power allocation in the multiuser orthogonal frequency division multiplexing (MU-OFDM) system. Therefore, we develop a channel-aware and quality of service (QoS) provisioning subcarrier allocation algorithm for the OFDMA systems.

1.2 Thesis Outline

The research of this thesis investigates how to exploit frequency diversity and multiuser diversity by scheduling and subcarrier allocation in the multicarrier systems. We first demonstrate that the simple maximum carrier to interference ratio (C/I) scheduling can both enhance system throughput and maintain fairness performances for the orthogonal frequency division multiple access (OFDMA) system. Furthermore, we develop a new quality of service (QoS) provisioning subcarrier allocation algorithm used in the orthogonal frequency division multiple access (OFDMA) system.

The remaining chapters of this thesis are organized as follows. Chapter 2 introduces the background of the IEEE 802.16a wireless metropolitan area network (WMAN) and some scheduling techniques in the single carrier systems. Furthermore, we discuss the subcarrier allocation approaches in the multicarrier systems and quantitative measure of fairness. Chapter 3 demonstrates that the simple maximum carrier to interference ratio (C/I) scheduling can both enhance system throughput and maintain fairness performances by exploiting frequency diversity and multiuser diversity in the OFDMA system. Chapter 4 develops a subcarrier allocation scheme that supports quality of service (QoS) requirements of multiple types of services with considering characteristics of channel. At last, Chapter 5 gives the concluding remarks and suggestions for future work.

Chapter 2

Background

In this chapter, we introduce the background of the IEEE 802.16 WMAN and some existed resource allocation schemes.

2.1 IEEE 802.16 WMAN

In [13], an OFDMA based wireless metropolitan area network (WMAN) is specified in the IEEE 802.16a standard. In a none line of sight (NLOS) environment, WMAN in the IEEE 802.16a specification is recommended to operate in a multicarrier modulation mode. Each OFDMA symbol consists of various types of subcarriers, including data, pilot and null. The number of the total subcarriers is 2048, which is equal to the fast Fourier transform (FFT) size.

As shown in Fig 2.1, the carriers are grouped into subsets of carriers, which is called a subchannel. Each carrier of a subchannel is not adjacent, which can mitigate the effect of deep fading by exploiting frequency diversity.

IEEE 802.16 provides two frequency bands. One is IEEE 802.16 and the other is IEEE 802.16a [13]. The former is applied in a line of sight (LOS) The latter is operated in the frequency band of 2 to 11 GHz. In none line of sight (NLOS) channel, Table 2.1 describes the difference between IEEE 802.16 and 802.16a.

The carrier allocation condition of the uplink and the downlink in IEEE 802.16a are showed in Table 2.2 and Table 2.3. Considering downlink case, there are 173 left and 172 right guard carriers, respectively. One dc carrier and 166 pilots. Actually, only 1536 carriers are used for data transmiision. On the other hand, in

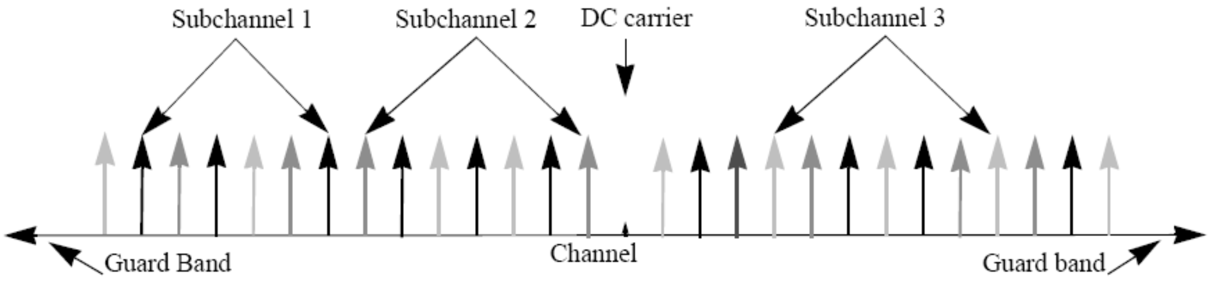

Fig. 2.1: OFDMA carrier allocation diagram

Tab. 2.1: Air Interface Nomenclature

Destination	**Applicability**	**PHY**	**MAC**	**Duplexing**
WirelessMAN-SC	10-66GHz	SC	Basic	TDD,FDD,HFDD
WirelessMAN-SCa	2-11GHz	SCa	Basic,ARQ,STC,AAS	TDD,FDD,HFDD
WirelessMAN-OFDM	2-11GHz	OFDM	Basic,AAS,ARQ,Mesh,STC	TDD,FDD,HFDD
WirelessMAN-OFDMA	2-11GHz	OFDMA	Basic,ARQ,STC,AAS	TDD,FDD,HFDD

uplink case, there are 176 left and 175 right guard carriers and one dc carriers. The remaining carriers are divided into 32 subchannels. Each subchannel has 53 carriers, including 48 data carriers and 5 pilots. Table 2.4 shows frequency spacing in different definition of guard time T_g in Multichannel Multipoint Distributed Service (MMDS) band (from 2.1 to 2.7 GHz). We will adopt this to model our channel and describe the corresponding channel delay profile.

The way of allocating subcarriers is based on the following formula.

$$carrier(n,s) = N_{subchannels} \cdot n + \{p_s[n_{mod(N_{subchannels})}] + ID_{cell} \cdot ceil[(n+1)/N_{subchannels}]\}_{mod(N_{subchannels})} \quad (2.1)$$

where

$carrier(n, s)$ = carrier index of carrier n in subchannel s.

s = index number of a subchannel from the set [0,1,...,$N_{subchannels}$-1].

n = carrier-in-subchannel index from the set [0,1,...,$N_{subcarriers}$-1].

$N_{subchannels}$= number of subchannels.

$p_s[j]$ = the series obtained by rotating $\{PermutationBase_0\}$ cyclically to the left s times.

$ceil[\ ]$ = function which rounds its argument up to the next integer.

ID_{cell} = a positive integer assigned by the MAC to identify this particular BS sector.

$X_{mod(k)}$ = the remainder of the quotient X/k (which is at most k-1).

We take an uplink example to illustrate the use of this formula. The subcarriers for subchannel $s = 1$ in cell $ID_{cell} = 2$ are computed. The number of subchannels $N_{subchannels} = 32$, while the number of carriers in each subchannel $N_{subcarriers} = 53$, and the number of data carriers in each subchannel is 48.

$PermutationBase_0$ = {3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30}.

Using equation (2.1),

1. The basic series of 32 numbers is {3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30}

2. In order to get 32 different permutation the series is rotated to the left (from no rotation at all up to 31 rotations). Since we have assumed s=1, ($permutationbase_{s=1}$) is: {18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30, 3}

3. We repeat the permuted series 2 times and take the first 53 numbers only: {18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0,

13, 12, 19, 14, 30, 3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30, 3}.

4. The concatenation depends on the ID_{cell} (which characterizes the working cell and can range from 0 to 31). Since we have assumed $s = 1$ and $ID_{cell} = 2$, the last term in the equation becomes
$p_s[n_{mod(32)}] + 2 \cdot ceil[(n+1)/32]_{mod(32)}$ with n = 0,1, ..., 52

   = {20, 4, 10, 18, 12, 13, 17, 28, 24, 8, 11, 29, 22, 27, 3, 31, 9, 23, 7, 30, 1, 25, 19, 6, 26, 2, 15, 14, 21, 16, 0, 5, 22, 6, 12, 20, 14, 15, 19, 30, 26, 10, 13, 31, 24, 29, 5, 1, 11, 25, 9, 0, 3}

5. Finally adding in the first term, the set of carriers is found: $carrier(n,1)$ = {20, 36, 74, 114, 140, 173, 209, 252, 280, 296, 331, 381, 406, 443, 451, 511, 521, 567, 583, 638, 641, 697, 723, 742, 794, 802, 847, 878, 917, 944, 960, 997, 1046, 1062, 1100, 1140, 1166, 1199, 1235, 1278, 1306, 1322, 1357, 1407, 1432, 1469, 1477, 1505, 1547, 1593, 1609, 1632, 1667}

2.2 Scheduling Techniques

Many scheduling algorithms have been developed for the single carrier code division multiple access (CDMA) system [14–18]. First, the maximum C/I scheduling scheme allocates the channel to the user J that has the best current channel condition.

$$J = arg\{\max_i \ r_i(t)\} \ , \tag{2.2}$$

where J is the scheduled user, i is the user index and r_i is the channel response of the user i, while t indicates time. This scheduling algorithm can exploit multiuser diversity at the expense of the fairness performance to some other users. Second, the round-robin scheduling approach allocates resource to each user periodically, which can provide the best fairness performance, but has poor throughput because it does not take the channel information into account. We express this algorithm mathematically as follow.

$$J = arg\{\max_i \ d_i(t)\} \ , \tag{2.3}$$

where d_i is the delay of user i. Third, the proportional fair scheduling algorithm [15] was proposed to use the ratio of the short-term channel response to the long-term channel condition of each user as a criterion to allocate the resource. We describe the principle of the proportional fair scheduling by (2.4).

$$J = arg\{\max_i \ (\frac{r_i(t)}{\overline{r_i(t)}})\} \ , \tag{2.4}$$

where $\overline{r_i(t)}$ is the long-term channel response of user i while $r_i(t)$ is the short-term channel response of user i. Last, the exponential rule scheduling policy [16–18] further considers the service delay of each user. If the user has waited for a long time, this user will be allocated a channel with a higher priority depending on (2.5).

$$J = arg\{\max_i \ [\frac{r_i(t)}{\overline{r_i(t)}} \ \exp \ (\frac{d_i(t) - \overline{d(t)}}{1 + \sqrt{\overline{d(t)}}})]\} \ , \tag{2.5}$$

where $\overline{d(t)}$ is the average delay of all users. By (2.5), we can see the exponential term dominates that means the delay of each user can determine the priority of each user. These wireless scheduling algorithms were only evaluated in the single carrier wireless system. To our knowledge, how these scheduling algorithms perform in the multi-carrier OFDMA system is an open issue.

2.3 Subcarrier Allocation Strategies

In this section, we introduce three conventional multicarrier allocation (MCA) [1] schemes as follows.

2.3.1 Fixed Subcarrier Allocation (FSA)

Fixed subcarrier allocation means that we allocate the fixed sets of subcarriers to certain users whether the subcarriers is good or bad for these users. In other words, users use a certain set of subcarriers all the time. This scheme does not exploit multiuser diversity and frequency diversity at all. Therefore, FSA scheme is regarded as a simple but inefficient subcarrier allocation scheme.

2.3.2 Random Subcarrier Allocation (RSA)

In each time slot, users randomly select sets of subcarriers for transmission when using random subcarrier allocation (RSA) scheme. This scheme makes use of frequency diversity to avoid some unfavorable condition. If a user select a set of bad subcarriers in a time slot, he may select another better set of subcarriers for communication and does not suffer from bad communication environments all the time. In short, the RSA scheme exploit the frequency diversity to provide fairer resource allocation and this scheme do not know any channel state information.

2.3.3 Dynamic Subcarrier Allocation (DSA)

In order to enhance the system throughput performance, we prefer that each subcarrier is allocated to the user that the subcarrier channel response is the best to the user among all users in each time slot. Nevertheless, it will cause unfair resource allocation. Therefore, we allocate the resource from the viewpoint of users.

Furthermore, the wireless communication environments are time-varying. Hence, dynamically allocating subcarriers according to channel condition can improve the throughput performance while this resource allocation approach is called dynamic subcarrier allocation (DSA) scheme. The DSA scheme is similar to the maximum C/I (carrier-to-interference-plus-noise ratio) scheduling used in single carrier CDMA system [14] [18]. This scheme exploits both frequency diversity and multiuser diversity. We describe the subcarrier allocation policy as follows.

First, we define a channel matrix H in the OFDMA environment. Assume that there are N users and M subcarriers in the system.

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & & & \\ \vdots & & \ddots & \\ h_{N,1} & h_{N,2} & \cdots & h_{N,M} \end{bmatrix} \tag{2.6}$$

where $h_{n,m}$ represents the $m-th$ subcarrier condition to the $n-th$ user. For example, $h_{3,2}$ means the response of subcarrier 2 observed by user 3. The DSA scheme operates as the following procedure.

1. Give each user a priority number.
2. According to the priority of each user, the user n selects his own favorite subcarriers for any user in order.
3. Users with lower priority do not select the selected subcarriers of the users with higher priority and they can only select the rest subcarriers.

Due to the multiuser environments, if the channel responses are independent of users, which makes the multiuser diversity exist to improve system throughput.

2.4 Quantitative Measure of Fairness

Fairness consideration is very important in the field of radio resource management. We should show the how fair resource allocation is among all users numerically. However, there are many fairness measures proposed to indicate the fairness level of resource allocation. We describe those fairness indices as follows. Define x_i the resource quantity allocated to user i, and n the number of total users.

Variance

$$Variance = \frac{1}{n-1}\sum_{i=1}^{n}(x_i-\mu)^2 \quad where\ mean\ \mu = \frac{1}{n}\sum_{i=1}^{n}x_i \tag{2.7}$$

Coefficient of Variation

$$Coefficient\ of\ Variation\ (COV) = \frac{Variance}{Mean} \tag{2.8}$$

Min-max Ratio

$$Min - max = \frac{\min\limits_{i}\{x_i\}}{\max\limits_{j}\{x_j\}} = \min_{i,j}\frac{x_i}{x_j} \tag{2.9}$$

Jain's Fairness Index

$$F = \frac{(\sum\limits_{i=1}^{N}x_i)^2}{N\sum\limits_{i=1}^{N}{x_i}^2} \tag{2.10}$$

As above, all the indices can represent the degree of fairness of resource allocation among users. Nevertheless, in [19], we desire that the fairness index has the following properties.

(a) Population size independence: The index should be suitable for infinite or finite users. The above four indices all satisfy the requirement.

(b) Scale and metric independence: We expect that the indices are independent of scale. In other words, if users are allocated ten times quantity of resource simultaneously, the indices should be the same values. However, the variance index does not meet the goal.

(c) Boundedness: In addition to population size independence and scale independence, the indices are desired to be bounded between 0 and 1. Therefore, we can judge the policy of resource allocation fair according whether the fairness index approaches 1 or not. The COV (coefficient of variation) is not bounded. Its value distributes from 0 to infinity.

(d) Continuity: The continuous index can respond the little change in allocation way. The min-max ratio index only take the users with best resource and with worst resource into account. Therefore, if the allocation changes among medium users, the min-max ratio index does not change.

To sum up, we observe the behaviors of the indices. We find that Jain's fairness index satisfies all the desired properties. Consequently, we adopt the index as one of our simulation performance metric.

Tab. 2.2: OFDMA downlink subcarriers allocation

Parameters	**Value**
Number of DC carriers	1
Number of Guard Carriers: Left, Right	173,172
Number of Used Carriers	1702
N_used	1702
Total Number of Carriers	2048
$N_varLocPilots$	142
Number of Fixed-location Pilots	32
Number of Variable-Location Pilots which coincide with Fixed-Location Pilots	8
Total Number of Pilots	166
Number of data carriers	1536
$N_subchannels$	32
$N_subcarriers$	48
Number of data carriers per subchannel	48
BasicFixedLocationPilots	{0,39,261,330,342,351,522,636,645,651,708,726,756,792,849,855,918,1017,1143,1155,1158,1185,1206,1260,1407,1419,1428,1461,1530,1545,1572,1701}
$\{PermutationBase_0\}$	{3,18,2,8,16,10,11,15,26,22,6,9,27,20,25,1,29 7,21,5,28,31,23,17,4,24,0,13,12,19,14,30}

Tab. 2.3: OFDMA uplink subcarriers allocation

Parameters	**Value**
Number of DC carriers	1
N_used	1696
Number of Guard Carriers: Left, Right	176,175
$N_subchannels$	32
$N_subcarriers$	53
Number of data carriers per subchannel	48
$\{PermutationBase_0\}$	{3,18,2,8,16,10,11,15,26,22,6,9,27,20,25,1, 29,7,21,5,28,31,23,17,4,24,0,13,12,19,14, 30}

Tab. 2.4: MMDS band frequency spacing ($f_s/BW = 8/7$) OFDMA($N_{FFT} = 2048$)

			$T_g(\mu_s)$			
BW(MHz)	Δf(kHz)	$T_b(\mu_s)$	$T_b/32$	$T_b/16$	$T_b/8$	$T_b/4$
1.5	$\frac{36}{43}$	$1194\frac{2}{3}$	$37\frac{1}{3}$	$74\frac{2}{3}$	$149\frac{1}{3}$	$298\frac{2}{3}$
3.0	$1\frac{60}{89}$	$597\frac{1}{3}$	$18\frac{2}{3}$	$37\frac{1}{3}$	$74\frac{2}{3}$	$149\frac{1}{3}$
6.0	$3\frac{8}{23}$	$298\frac{2}{3}$	$9\frac{1}{3}$	$18\frac{2}{3}$	$37\frac{1}{3}$	$74\frac{2}{3}$
12.0	$6\frac{39}{56}$	$149\frac{1}{3}$	$4\frac{2}{3}$	$9\frac{1}{3}$	$18\frac{2}{3}$	$37\frac{1}{3}$
24.0	$13\frac{11}{28}$	$74\frac{2}{3}$	$2\frac{1}{3}$	$4\frac{2}{3}$	$9\frac{1}{3}$	$18\frac{2}{3}$

Chapter 3

Throughput and Fairness Enhancement for OFDMA Broadband Wireless Access Systems Using the Maximum C/I Scheduling

In this chapter, we demonstrate that the simple maximum carrier to interference ratio (C/I) scheduling can both enhance system throughput and maintain fairness performances for the orthogonal frequency division multiple access (OFDMA) system. The maximum C/I scheduling has long been recognized as an effective method to enhance throughput, but it is viewed as an unfair scheduling policy in the the single carrier code division multiple access (CDMA) system. We reassess the fairness performance of the maximum C/I scheduling in the context of the multi-carrier OFDMA system. Through analysis and simulations, we find that the maximum C/I scheduling is indeed an fair scheduling for OFDMA systems. Thus, with respect to the OFDMA system, we develop a maximum C/I scheduling based resource allocation algorithm. Our results show that the fairness of the maximum C/I scheduling in OFDMA systems is comparable to that of the proportional fair scheduling scheme. In short, we conclude that in the OFDMA system, the maximum C/I scheduling not only can maximize system throughput, but simultaneously maintain very good fairness performance.

3.1 Introduction

With the growing demand for high data rate communication, orthogonal frequency division multiple access (OFDMA) is becoming an important technology. OFDMA has been used in many broadband wireless systems, such as the IEEE 802.16a wireless metropolitan area network (WMAN) [13] [20]. This chapter investigates the benefits of OFDMA systems from both frequency diversity and multiuser diversity perspectives. Frequency diversity inherently exists in OFDMA systems, while multiuser diversity can be achieved by adopting scheduling algorithms. Although both diversity gains can enhance the system throughput, the challenging issue here is how to select a scheduling algorithm that can achieve high system throughput and maintain the fairness among users simultaneously.

OFDMA is not only a modulation scheme but also a multiple access technology. In an OFDMA system, each user is allocated a set of orthogonal subcarriers. In addition to overcoming the inter-symbol interference (ISI), an OFDMA system can also mitigate the multiple access interference (MAI) due to the orthogonality among subcarriers. Moreover, it can result in frequency diversity benefit with interleaving and channel coding. To further take advantage of frequency diversity [21–25], many adaptive resource allocation techniques were suggested from a view point of subcarrier power allocation [12] [26].

The goal of this chapter is to investigate the OFDMA system from another resource allocation viewpoint, i.e, scheduling algorithms. Wireless scheduling techniques are developed to exploit the multiuser diversity. In a multiuser wireless system, different users may have different channel responses in a time varying wireless channel. Thus, a channel may be viewed as a bad channel, but may be viewed as a good channel by other users. Consequently, if the system can first pick a user with the best channel quality among a group of users to serve in each channel , the system capacity can be improved significantly. We call this capacity improvement as the multiuser diversity gain. Clearly, for providing delay-tolerant data services, wireless scheduling is an inevitable technique to exploit multiuser diversity which inherently exists in the multiuser system.

Many scheduling algorithms have been developed for the single carrier time division multiple access (TDMA) or code division multiple access (CDMA) systems [14–18]. First, the maximum C/I scheduling scheme allocates the channel to the user that has the best channel condition [14]. This scheduling algorithm can fully exploit multiuser diversity at the expense of sacrificing the fairness performance for other users. Second, the round-robin scheduling approach allocates resource to each user periodically, which can provide the best fairness performance, but has lowest throughput because it does not take the channel information into account. Third, the proportional fair scheduling algorithm [15] was proposed to use the ratio of the short-term channel response to the long-term channel condition of each user to allocate the resource. Last, the exponential rule scheduling method [16–18] further considers the service delay of each user. If the user has waited for a long period of time, this user will be allocated a channel with a higher priority. These wireless scheduling algorithms were only evaluated in the single carrier wireless system. To our knowledge, how these resource management algorithms perform in the multi-carrier OFDMA system is an open issue.

There were a lot of dynamic radio resource management technologies in OFDM based multicarrier systems discussed in the literature. In traditional wired discrete multitone asymmetric digital subscriber lines (ADSL), a resource management method named water-filling power allocation [27] is popularly used. Therefore, a lot of papers [21] [23] [24] adopted this rule to solve the optimization problem that to maximize the system capacity under the total power constraint.

In this chapter, we first assess the fairness performance of the maximum C/I scheduling in the multi-carrier OFDMA system. The maximum C/I scheduling has long been recognized as an effective method to enhance throughput, but it is also viewed as an unfair scheduling policy in the the single carrier CDMA system. Through analysis and simulations, we will find that the maximum C/I scheduling is indeed an fair scheduling for OFDMA systems. Thus, with respect to the OFDMA system, we develop a maximum C/I scheduling based resource allocation algorithm. We will show that the fairness of the maximum C/I scheduling in OFDMA systems is comparable to that of the proportional fair scheduling scheme. Hence, we conclude that the simple maximum C/I scheduling can enhance both system throughput and fairness performances for the OFDMA system.

The rest of this chapter is organized as follows. Section 3.2 introduces the channel models for an OFDMA based IEEE 802.16a system. Section 3.3 formulates this problem. In Section 3.4, we analyze the system throughput performance with the maximum C/I scheduling algorithm in the multicarrier systems. Section 3.5 introduces the current two resource allocation strategies. Simulation results are given in Section 3.6. We give our concluding remarks in Section 3.7.

3.2 Channel Models for the IEEE 802.16a System

We will introduce more complicated but practical channel models specified in the IEEE 802.16a WMAN standard [28]. There are six typical Stanford University Interim (SUI) channel models for three types of terrains. These SUI channels are used for the fixed broadband wireless applications (BWA) in the multichannel multipoint distributed service (MMDS) band. We will use the two SUI channel models, SUI-1 and SUI-5, in our simulations. Parameters in the two SUI channels are summarized in Tables 3.1 and 3.2.

SUI-1 channel model is for low mobility with small delay spread, which is close

Tab. 3.1: SUI-1 Channel

	Tap 1	Tap 2	Tap 3	Units
Delay	0	0.4	0.8	μs
power (omni. ant)	0	-15	-20	dB
power (30° antenna)	0	-21	-32	dB
K Factor	18	0	0	
Maximum Doppler frequency	0.4	0.4	0.4	Hz

Tab. 3.2: SUI-5 Channel

	Tap 1	Tap 2	Tap 3	Units
Delay	0	5	10	μs
power (omni. ant)	0	-5	-10	dB
power (30° antenna)	0	-11	-22	dB
K Factor	0	0	0	
Maximum Doppler frequency	2	2	2	Hz

to Rician fading. On the other hand, SUI-5 is close to Rayleigh fading channel and it is exposed severe multipath fading effect. Moreover, the channel response value “1” is defined to be the state that received signal-to-noise ratio (SNR) can be satisfied. If the value is above 1, the channel is in good condition. In our simulation, we evaluate the system capacity by using the QPSK with coding rate 1/2 case [13]. The channel response “1” corresponds to the received SNR 9.4 dB. The receiver with SNR values in Table 3.3 can achieve BER less than 10^{-6}.

Tab. 3.3: Receiver SNR and E_b/N_0 assumptions

Modulation	coding rate	Receiver SNR
QPSK	1/2	9.4
QPSK	3/4	11.2
16QAM	1/2	16.4
16QAM	3/4	18.2
64QAM	2/3	22.7
64QAM	3/4	24.4

3.3 Problem Description

3.3.1 Two-state Random Channel Matrix

A simple channel model is adopted to describe the impact of the number of subchannels when using the maximum C/I scheduling algorithm. We assume that there are N users requiring the same data rate. Each subchannel has two states: good and bad [29]. Good state means that the channel could bear $1 + \delta$ times of the required rate rate, while the bad state means that the channel only could transmit $1 - \delta$ times of the normal data rate. We also assume that the channel condition on which each user observed is independent. In other words, the same channel may be viewed as a good channel for a user, but a bad one for others.

As described above, an arbitrary subchannel may have different states for different users. Consequently, we can form a channel matrix H :

$$H = \text{user index} \left\{ \overbrace{\begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & & & \\ \vdots & & \ddots & \\ h_{N,1} & h_{N,2} & \cdots & h_{N,M} \end{bmatrix}}^{\text{subcarrier index}} \right. \tag{3.1}$$

where $h_{n,m}$ represents the $m-th$ subchannel condition to the $n-th$ user. For example, $h_{3,2}$ means the response of subchannel 2 observed by user 3. Each element can be in two states, good or bad with equal probability $\frac{1}{2}$. This model will be used for only analysis.

3.3.2 Problem Formulation

For simplicity, we adopt the two-state channel model to analyze both the throughput and fairness performance of multicarrier systems. We first assume that each user uses just one subchannel. Next, we will calculate the probability that all users are allocated with good subchannels. This is an issue of permutation and combination in mathematics. As the numbers of users and subchannels increase, the process of permutation and combination calculation becomes very complicated. Therefore, we propose a systematic analytical approach. Owing to too many possibilities in permutation and combination as the numbers of users and subchannels increase, we will apply the Inclusion-Exclusion Principle to analyze system performance.

We define a permutation matrix P, which contains all permutations of 1,2,3,...,N. Take N=3 as an example.

$$P = \begin{bmatrix} 1 & 1 & 2 & 2 & 3 & 3 \\ 2 & 3 & 1 & 3 & 1 & 2 \\ 3 & 2 & 3 & 1 & 2 & 1 \end{bmatrix} \tag{3.2}$$

where P is an $N \times N!$ matrix. This matrix will be used to permutate all conditions that all users have observed good channel conditions. The value x of each entry in the $i-th$ row of the permutation matrix P represents the entry located at the $i-th$ row and the $x-th$ column of the channel matrix H in a good condition. In other words, the $x-th$ subchannel is in a good condition for the $i-th$ user. For example, if the second column vector of P, $[1, 3, 2]^T$, this means that h_{11}, h_{23} and h_{32} are in the good state. Then the channel matrix becomes

$$H = \begin{bmatrix} \vee & free & free \\ free & free & \vee \\ free & \vee & free \end{bmatrix}, \tag{3.3}$$

where the elements labelled "$\vee$" in the $i-th$ row and the $j-th$ column in channel matrix H mean that the $j-th$ subchannel is in a good state for the $i-th$ user. The elements labelled "$free$" mean that the subchannel conditions responding to some users can be either good or bad. Thus, all users can use good subchannel without conflicts. Consider both the second and fourth columns of P in (3.2), i.e. $[1, 3, 2]^T$ and $[2, 3, 1]^T$, simultaneously. Then the channel matrix becomes

$$H = \begin{bmatrix} \vee & \vee & free \\ free & free & \vee \\ \vee & \vee & free \end{bmatrix}. \tag{3.4}$$

Since there are at least N good subchannels in different rows and different columns, each user can have a good subchannel for transmissions. In the following, we introduce a systematic approach to analyze the impact of the maximum C/I scheduling algorithm in the multicarrier systems by applying the Inclusion-exclusion principle [30].

3.4 Analysis

3.4.1 Inclusion-Exclusion Principle

Our goal is to calculate all conditions that all users can use good subchannels. Consider N users and N subchannels. We count the number of cases that the good subchannels can distribute in N different rows and different columns in the channel matrix $H_{N \times N}$. First, we will use the parameter, permutation matrix P. Any combinations of the columns in matrix P corresponds to a channel matrix H. It is possible that different combinations of columns in P map to the same channel matrices H. Our objective is to calculate the number of matrices H in which all users can find a good subchannel without conflicts. For example,

$$H = \begin{bmatrix} \vee & bad & bad \\ bad & \vee & bad \\ bad & bad & \vee \end{bmatrix} \tag{3.5}$$

represents a case that all users can have good subchannels without conflicts. By contrast,

$$H = \begin{bmatrix} \vee & bad & bad \\ \vee & bad & bad \\ bad & \vee & bad \end{bmatrix} \tag{3.6}$$

represents a case that users 1 and 2 compete for subchannel 1. Next, we apply the Inclusion-Exclusion Principle to calculate the number of all users having good channels.

Lemma To calculate the size of $A_1 \bigcup A_2 \bigcup \ldots \bigcup A_n$, calculate the sizes of all possible intersections of sets from $\{A_1, A_2, \ldots, A_n\}$, and then add the results obtained by intersecting an odd number of the sets and then subtract the results obtained by intersecting an even number of the sets [30].

For example, if we will calculate the number of multiples of 2 and 3 from 1 to 100, we will first count the number of multiples of 2, then we add the number of multiples of 3; and finally we subtract the number of multiples of 6.

We define $F(k)$ as the number of matrices H for selecting k columns from the permutation matrix P. For an even number of k, $F(k)$ is denoted as $F^e(k)$, whereas for an odd number of k, $F(k)$ is represented by $F^o(k)$. Note that k is ranged from 1 to N! and P is an $N \times N!$ matrix. By applying the Inclusion-Exclusion Principle, we can calculate the number of the non-conflict conditions as

$$\sum_{k=1,3,...,N!-1} F^o(k) - \sum_{k=2,4,..,N!} F^e(k) \tag{3.7}$$

For example, if N = 3, then the permutation matrix P

$$P = \begin{bmatrix} 1 & 1 & 2 & 2 & 3 & 3 \\ 2 & 3 & 1 & 3 & 1 & 2 \\ 3 & 2 & 3 & 1 & 2 & 1 \end{bmatrix} \tag{3.8}$$

For $F^o(1)$, there are six ($C_1^{3!}$) selections, which corresponds to the case that {1}, {2}, {3}, {4}, {5} and {6} columns in permutation matrix P are selected individually. In this case, each $F^o(1)$ corresponds to 2^6 channel matrices H because there are six free elements in H. (see (3.3) as an example). For $F^e(2)$, there are $C_2^{3!}$ combinations, which means that we choose {1,2}, {1,3},{1,4},...{4,5},{4,6} and {5,6} columns from the permutation matrix P. $F^e(2)$ may be either 2^3 (e.g. {1,4}) or 2^4 (e.g. {2,4}). When N increases, the permutation and combination conditions becomes huge. The systematic approach based on (3.7) can solve the complex permutation and combination problems.

3.4.2 Fairness Index

According to [31] [19], we define a fairness index F in the multiuser systems as follows:

$$F = \frac{(\sum_{i=1}^{N} r_i)^2}{N \sum_{i=1}^{N} {r_i}^2} \ , \tag{3.9}$$

where r_i is the transmission data rate of the $i-th$ user, and N is the number of total users. For $F = 1$, it is the fairest condition between users, and it is not fair as $F < 1$. For example, if there are two users transmitting data, one is transmit at 1.2 times of the required data rate, and the other transmit at 0.8 times of the required data rate. Then the fairness index F is about 0.96. If the transmission data rate of one user is 1.5, and the other is 0.5, the fairness index is 0.8. Thus the former example is fairer than the latter.

We will illustrate that a random assignment method cannot easily achieve high value of the fairness index. We illustrate this point as follows. We generate a set of random variables. Each random variable represents the resource allocated to each user. We assume the random variables are uniformly distributed in the interval (0,1). Fig. 3.1 shows the cumulative distribution function (CDF) of the value of the fairness index. From Fig. 3.1, we find that the more the users, the harder the fairness is achieved. When there are 8 users, the probability that the fairness index is larger than 0.8 is 38%. However, if 32 users exist in the system, the probability that the fairness index is greater than 0.8 is smaller than 20%. From this example, we know that a random assignment approach can not easily achieve the fairness index higher than 0.8 or 0.9. Thus, it is not trivial to design a resource allocation scheme achieving the fairness index higher than 0.9.

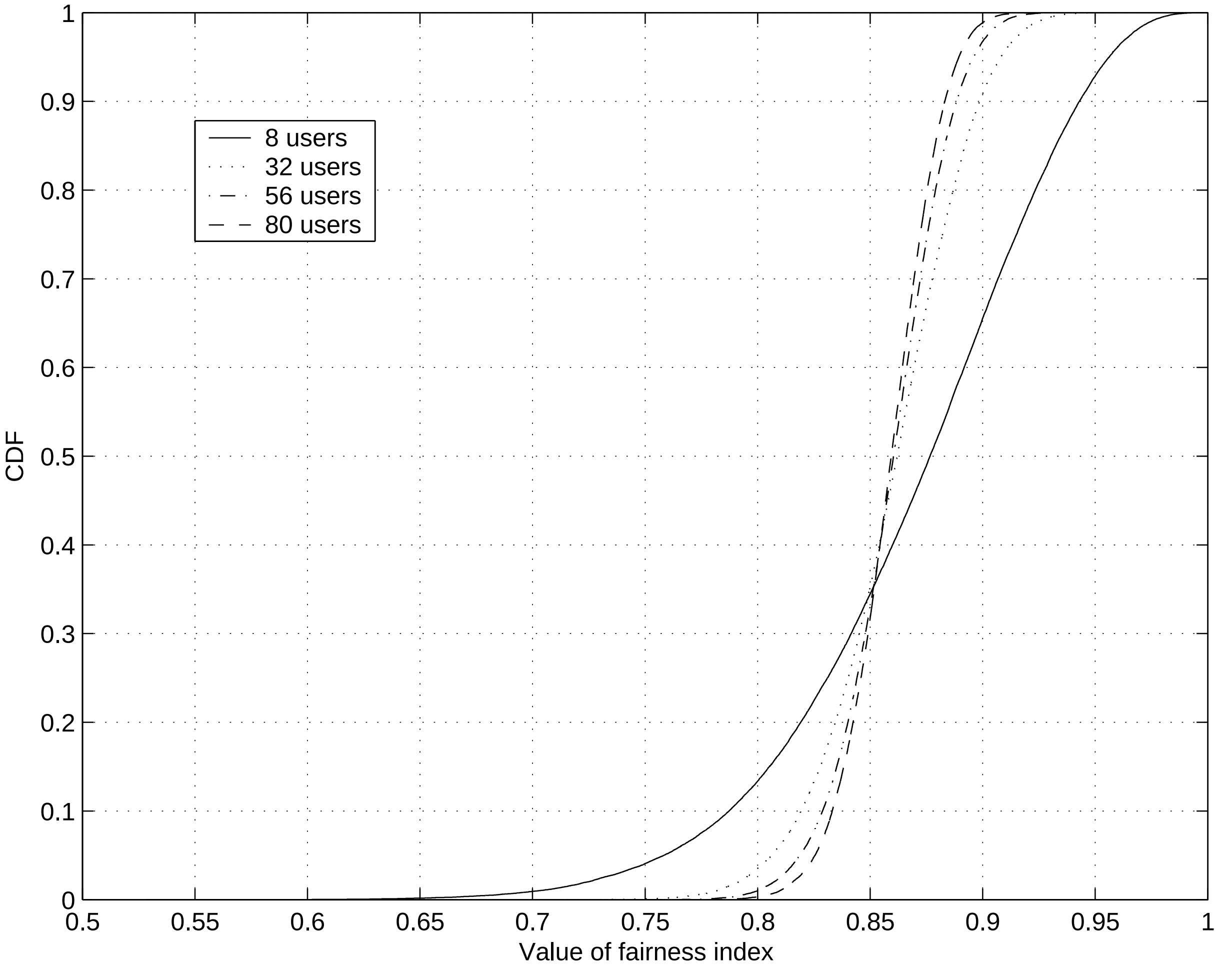

Fig. 3.1: Distribution of fairness index value for a random assignment

3.4.3 Observation

By applying the Inclusion-Exclusion Principle, we can systematically calculate probability that all users can use good subchannels when N is not too large. We list the results in Table 3.4.

Tab. 3.4: Analytical results of non-conflict condition

Number of users (subchannels)	**Probability**
2	$7/16 = 0.4375$
3	$247/512 = 0.4824$
4	$37823/65536 = 0.5771$

From Table 3.4, we observe that the probability of the non-conflict condition (i.e., all users can use good subchannels.) increases with the number of users (subchannels) increasing apparently. By increasing the number of subchannels and users, we find that system throughput performance can be improved even without other complicated scheduling algorithms, such as proportional fairness scheduling or even exponential rule scheduling algorithms.

Furthermore, we observe the effect of the number of subcarriers on the fairness when the maximum carrier-to-interference scheduling algorithm is used in the multicarrier systems.

Due to the complexity, we obtain the numerical results by programming when N is larger than 5. We find that we can further achieve good fairness performance between users by efficiently exploiting both multiuser diversity and frequency diversity. For the case of N = 7 in Fig. 3.2, one can find that with 90% probability, all

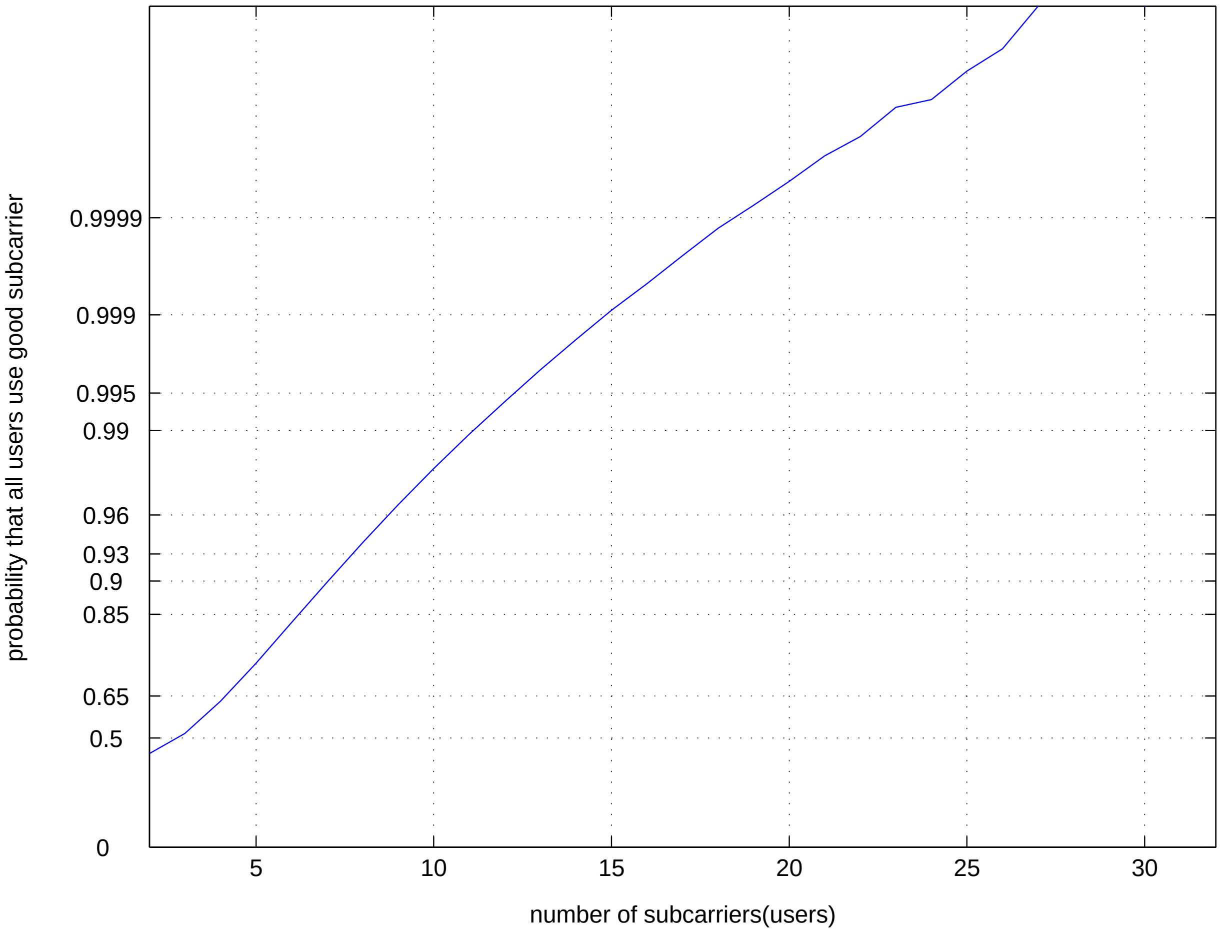

Fig. 3.2: Probability of the non-conflict condition with the varying number of users and subchannels.

the seven users can have the good subchannels and the fairness index $F = 1$.

Figure 3.3 shows the effect of increasing number of the subcarriers on fairness performance with different numbers of users in a two-state random channel model. We can easily see that the more the number of subcarriers, the better the system fairness performance. However, as the number of users increases, the required number of subcarriers to provide satisfying fairness performance increases. Observing Fig. 3.3, if we require the system fairness index has to be larger than 0.9 when there are

24 users in the system, we should divide available total bandwidth into at least 22 subcarriers.

3.5 Resource Allocation Strategies

Besides some scheduling algorithms mentioned in Section 2.2, we will describe some other resource allocation approaches mathematically in the multicarrier OFDMA system.

3.5.1 Dynamic Power Allocation

The dynamic power allocation is commonly used in traditional wired discrete multitone (DMT) [27] systems, such as ADSL. We allocate power in different tones with different channel condition. The goal is to maximize the system capacity. Consequently, this issue becomes an optimization problem under total power constraint. We describe this problem by the following equations.

$$\max_{P_{n,m}} \sum_{n=1}^{N} \sum_{m=1}^{M} \frac{\rho_{n,m}}{M} \log_2\{1 + \frac{P_{n,m} h_{n,m}^2}{N_0 \frac{B}{M}}\} \tag{3.10}$$

subject to

$$\sum_{n=1}^{N} \sum_{m=1}^{M} P_{n,m} \leq P_{total} \tag{3.11}$$

$$P_{n,m} \geq 0 \ \forall n, m \tag{3.12}$$

$$\rho_{n,m} = \{0, 1\} \ \forall n, m \tag{3.13}$$

$$\sum_{n=1}^{N} \rho_{n,m} = 1 \ \forall m \tag{3.14}$$

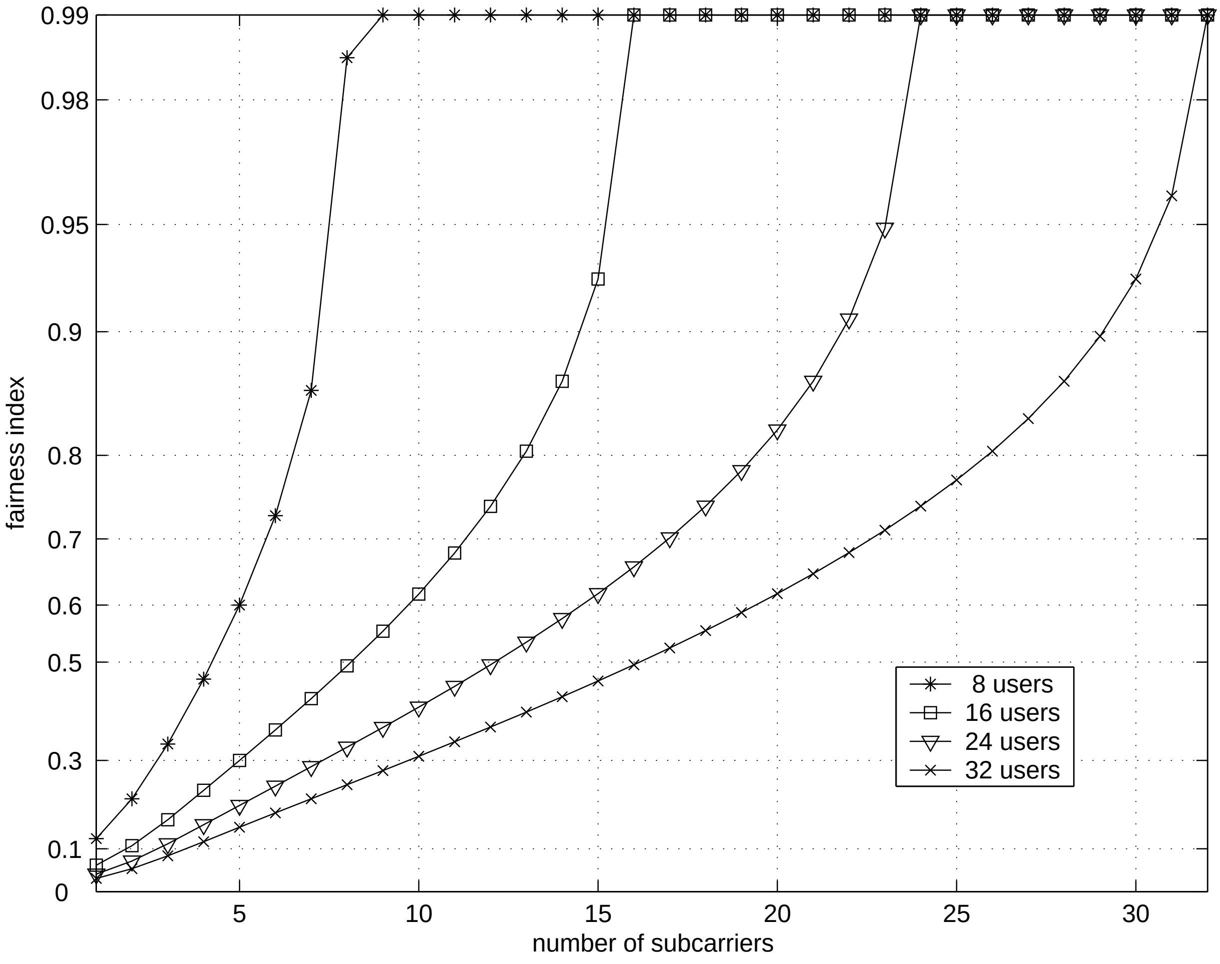

Fig. 3.3: Fairness index with the number of subchannels varying in different numbers of users.

where $\rho_{n,m} = 1$ means that the m-th subchannel is assigned to the n-th user, n is the user index while m is the subcarrier index, and B denotes the total bandwidth. In this case, $\rho_{n,m}$ is fixed with time. The dynamic power allocation algorithm can solve such optimization problem under several constraints.

3.5.2 Maximum C/I Channel Allocation

We see this problem from another scheduling viewpoint. Instead of power allocation, we schedule users with best channel response for each subcarrier. In order to maximize the system capacity, we can regard the maximum C/I channel allocation as to apply water-pouring principle to the dimension of multiple users. The following equations describe the principle of maximum C/I channel allocation to maximize system throughput.

$$\max_{\rho_{n,m}} \sum_{n=1}^{N} \sum_{m=1}^{M} \frac{\rho_{n,m}}{M} \log_2\{1 + \frac{h_{n,m}^2}{N_0 \frac{B}{M}}\} \tag{3.15}$$

subject to

$$\rho_{n,m} = \{0, 1\} \ \forall n, m \tag{3.16}$$

$$\sum_{n=1}^{N} \rho_{n,m} = 1 \ \forall m \tag{3.17}$$

$$\sum_{m=1}^{M} \rho_{n,m} = \frac{M}{N} \ \forall n \tag{3.18}$$

where (4.2) and (4.3) mean that each subchannel is allocated to only one user, and (4.4) means that each user can use a certain number of subcarriers, respectively.

3.6 Simulation Results

Besides numerical results described in Section 3.4, we will show some simulation results to illustrate the benefits of multicarrier system when using the maximum C/I scheduling scheme. Furthermore, we will compare both system throughput and fairness performances of different resource management approaches in the multicarrier systems.

3.6.1 Simulation Methodology

Then, we apply the two practical IEEE 802.16 channel models, SUI-1 and SUI-5, to our simulation. In [28], six SUI channel delay profiles are specified. For the multicarrier OFDMA system, we first take the appropriate 2048 samples of the channel delay profiles where the sample time

$$T_s = \frac{1}{B} \ , \tag{3.19}$$

where B is total bandwidth and 2048 is FFT size corresponding to the number of subcarriers. And then we use the fast Fourier transform (FFT) technique [32] to transform from time domain to frequency domain. Hence, we can observe the multipath fading effect in the frequency domain, (see Fig. 3.4). Finally, observing a long time period of this frequency domain channel models, we pick different time points to represent the channel response of different users. Therefore, we can form a practical channel matrix for simulation to evaluate the system performance. The simulation parameters are listed in Table 3.5.

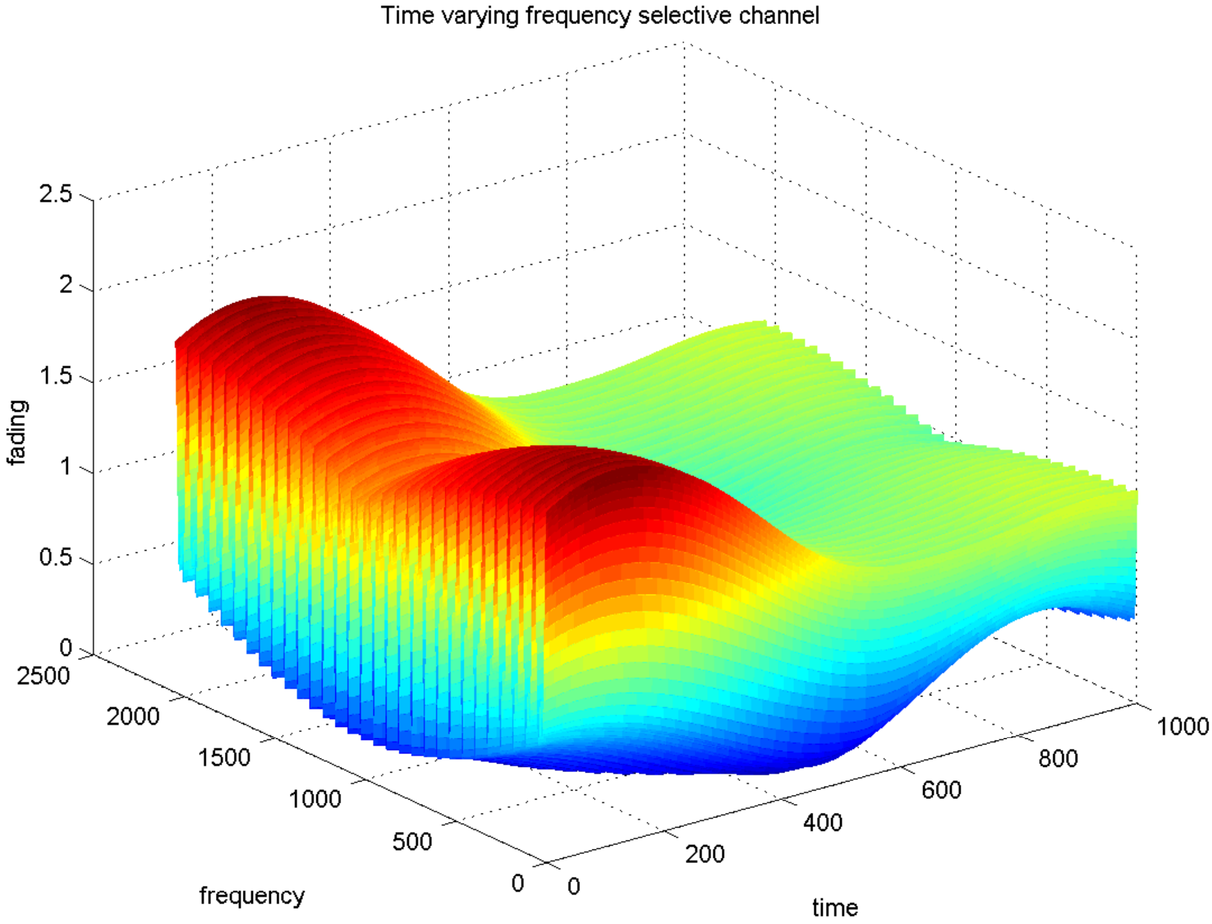

Fig. 3.4: Time varying with multipath fading model

Tab. 3.5: Simulation Parameters

No. of user	32
FFT size	2048
Total bandwidth	6 MHz
Channel model	SUI-1 and SUI-5

3.6.2 Effect of Multiuser Scheduling on the Fairness of Multi-carrier System

Figure 3.5 shows the fairness by using the IEEE 802.16a SUI-5 channel models in simulation. For the sake of fitting in with IEEE 802.16a OFDMA physical layer standard, 2048 FFT size used, we divide the total bandwidth into 2,4,8,16 and 32 subchannels. We still observe that when the number of subcarriers increases, the system fairness performance becomes better even in the SUI-5 channel model.

3.6.3 System Performances Comparison of Different Resource Allocation Techniques

Figures 3.6 and 3.7 compares the fairness and throughput performances of different resource management algorithms in SUI-1 and SUI-5 channel models, respectively. In SUI-1 channel model, the fairness performance can be maintained easily. However, SUI-5 channel suffer from more severe fading.

Figure 3.6 shows that dynamic power allocation and maximum C/I scheduling policies do not have obvious difference in fairness performance in SUI-1 channel models. Because frequency and multiuser diversity exist in the multiuser multi-carrier environment, fairness performance is very good. However, the fairness performance of the maximum C/I scheduling is worse than that of the power allocation scheme about 3.5%. Nevertheless, the value about 0.96 of the fairness index of the maximum C/I scheduling algorithm still means it is a fair resource allocation.

At the same time, we observe Fig. 3.7. We find that the throughput performances of the maximum C/I scheduling policy always better than that of the power allocation scheme whether in the SUI-1 channel model or in the SUI-5 channel model. In the SUI-1 channel model, the difference of the throughput performances of the maximum C/I scheduling algorithm and the power allocation scheme is very small. The maximum C/I performs better than the dynamic power allocation about 5%. On the other hand, the throughput performance of the maximum C/I scheduling policy is better than that of the power allocation algorithm about 13%. In short, we observe that the system performances of the maximum C/I scheduling algorithm and the power allocation policy are similar in the SUI-1 channel model. However, in the SUI-5 channel model, the maximum C/I scheduling enhance the system throughput about 13% more than the power allocation at the expense sacrificing 3.5% of the fairness performance. Therefore, we concludes that good fairness performance is easily achieved in the multiuser multi-carrier system even when the maximum C/I scheduling adopted.

3.6.4 System Performances Comparison of Different Scheduling Techniques

In addition to comparing the system performance of the power allocation and the maximum scheduling schemes, we compare the system performances of the maximum C/I and proportional scheduling algorithms in this subsection.

Figure 3.8 compares the fairness performance of the maximum C/I scheduling and the proportional fair scheduling in the IEEE 802.16 SUI-1 and SUI-5 channel models. In the IEEE 802.16 SUI-1 channel model, the fairness performance can be easily maintained. However, because of more severe fading, it is more difficult to maintain the short-term fairness performance in the IEEE 802.16 SUI-5 channel than that in the IEEE 802.16 SUI 1 channel. The proportional fair scheduling takes the great part of frequency diversity and multiuser diversity when the channel variation is not severe, so it also performs well. Furthermore, from the figure, we see that in the IEEE 802.16 SUI-1 channel model, the difference of fairness performance between the maximum C/I and the proportional fair scheduling is insignificant. Even in the IEEE 802.16 SUI-5 channel model, although the fairness of the proportional fair scheduling scheme is still better than the maximum C/I scheduling scheme, the difference of the fairness index between the two scheduling algorithms is less than 3.5%.

Figure 3.9 shows that main advantage of using maximum C/I in a multiuser multi-carrier system. In Fig. 3.9, we compare the throughput performance of both scheduling schemes. In the SUI-1 channel, the throughput performances of the two algorithms are about the same. Interestingly, when consider the SUI-5 channel model with more severe fading, Fig. 3.9 indicates that maximum C/I can take advantage of severer fading and maximize the system throughput. Summarizing from Figs. 3.8 and 3.9, we find that the maximum C/I scheduling can improve the throughput performance by 20% over the proportional fair scheduling at the cost of degrading the fairness index by only 3.5%.

Consequently, the maximum C/I is sufficiently used in the OFDMA system. We do not need other complicated resource allocation algorithms, such as proportional fair scheduling or power allocation method, to achieve good fairness performance at the expense of throughput. By adopting this simple maximum C/I scheduling schemes, we can obtain good fairness performance and the best throughput performance simultaneously. In SUI-5 channel model, the maximum C/I improves total system throughput about 13% compared to the power allocation without dynamic subcarrier allocation. Moreover, the maximum C/I scheduling algorithm even increase more than 20% of system throughput than that using the proportional fair scheduling policy.

3.6.5 Discussions

In the scenario described above, we should decide to whom all subcarriers belong every transmission time interval (TTI). It is impractical to do this in such a short time. In fact, because IEEE 802.16a is a fixed wireless application, the channel does not change frequently. Hence, we do not need to schedule users every TTI. Considering the coherence time of the system, the maximum Doppler frequency is 20Hz (SUI-5 channel), and then we will calculate the coherence time based on (3.20) [33]. Coherence time is the time duration over which two received signals have a strong potential for amplitude correlation. The Doppler spread and coherence time are inversely proportional to one another. The equation (3.20) is defined as the time over which the time correlation function is above 0.5. For example, when the maximum Doppler shift $f_d = 2Hz$, and the coherence time T_c is about 90 ms. Therefore, the maximum C/I scheduling approach is practical in the system.

$$T_c = \frac{9}{16\pi f_d} \tag{3.20}$$

3.7 Conclusions

In this chapter, we have demonstrated that the simple maximum carrier-to-interference scheduling scheme can be a fair scheduler in the OFDMA system, although it is viewed as an unfair scheduling scheme in the single carrier TDMA/CDMA systems. Using this simple maximum C/I scheduling algorithm in the OFDMA system can exploit multiuser diversity and frequency diversity thoroughly, thereby achieving both high throughput and good fairness performances. Moreover, using this simple maximum C/I scheduling algorithm can combat the worse channel effect and observe the good fairness performance in a multiuser OFDM system.

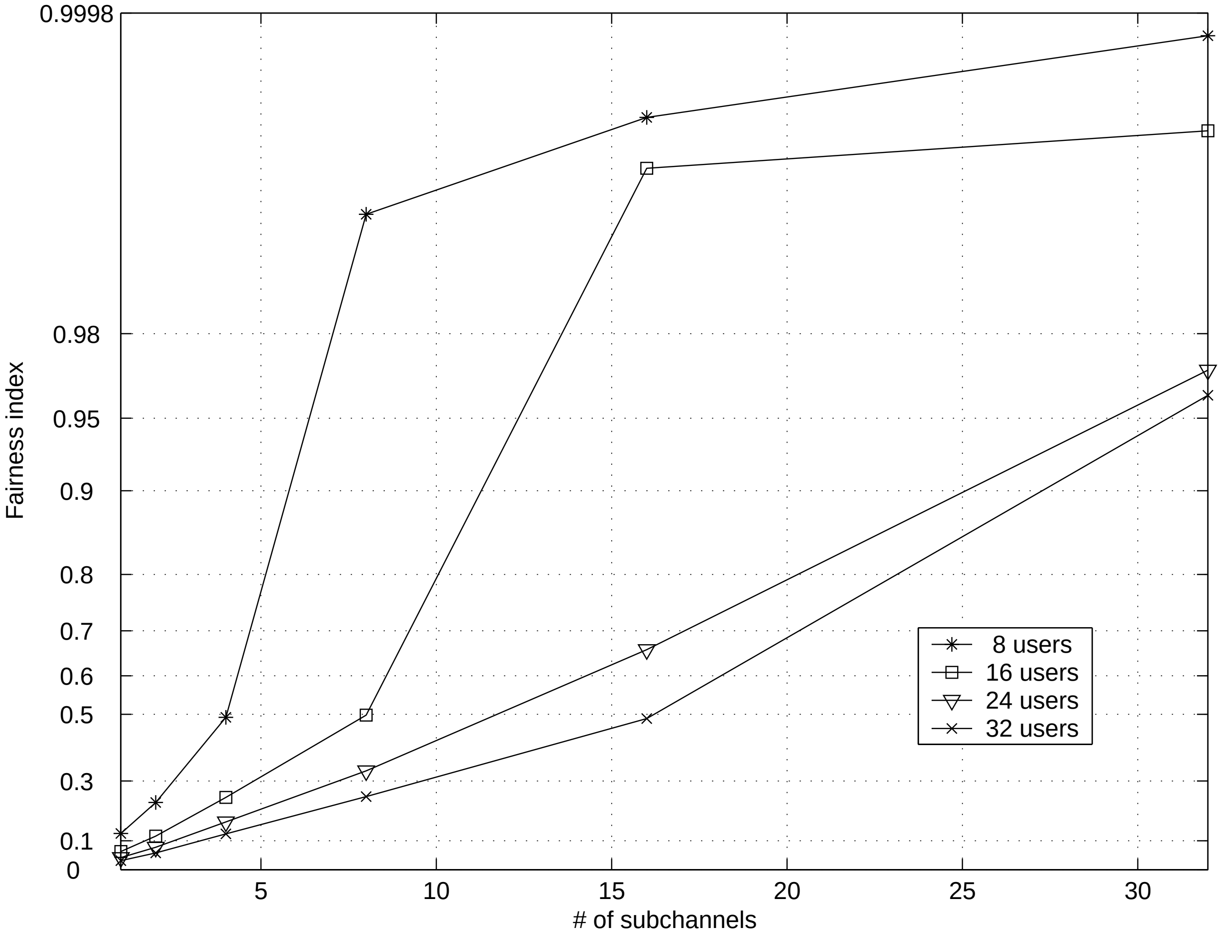

Fig. 3.5: Fairness index with the number of subchannels varying in different numbers of users when the IEEE 802.16 channel models are used.

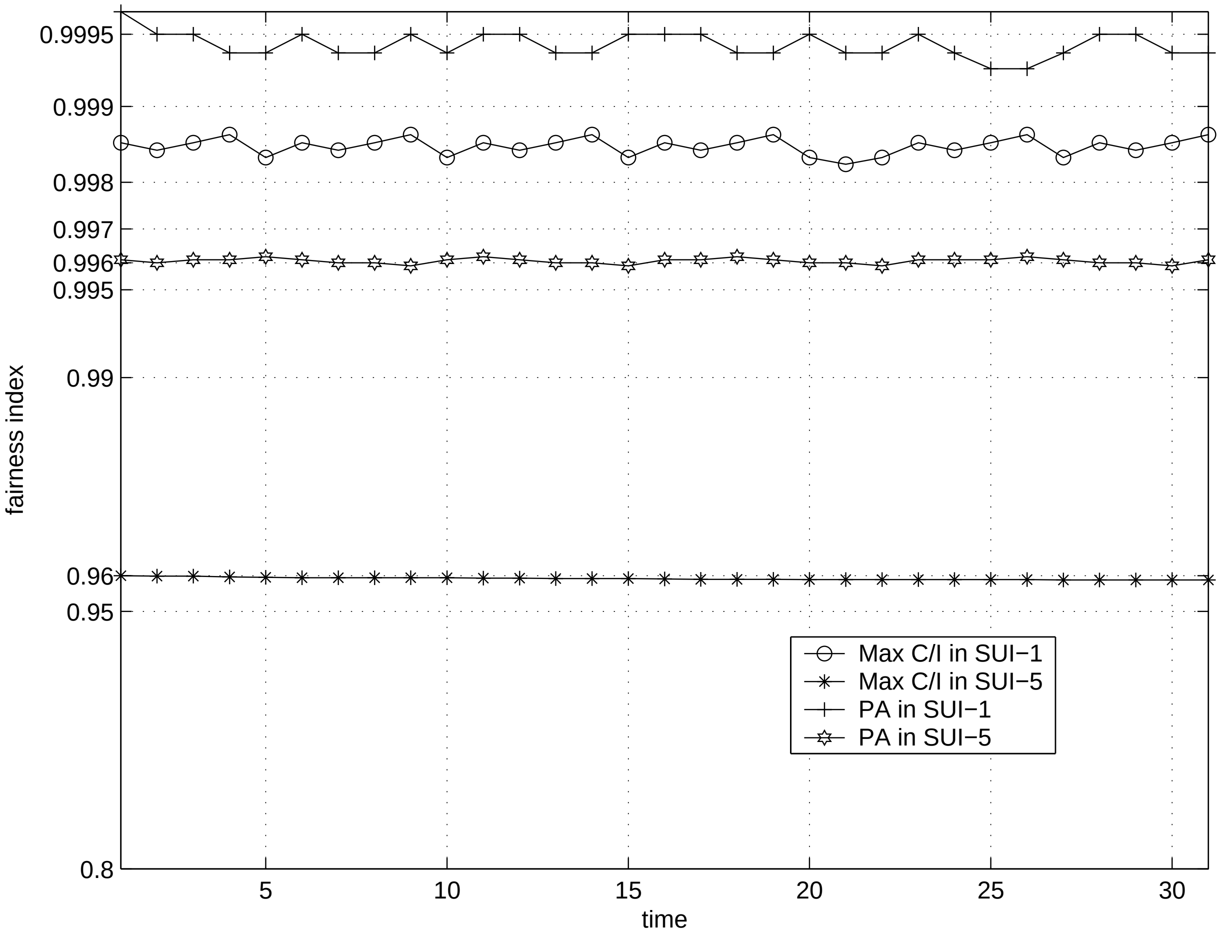

Fig. 3.6: Comparison of fairness performance of dynamic sbucarrier allocation and power allocation ($1TTI = 2048/6MHz = 341\mu s$)

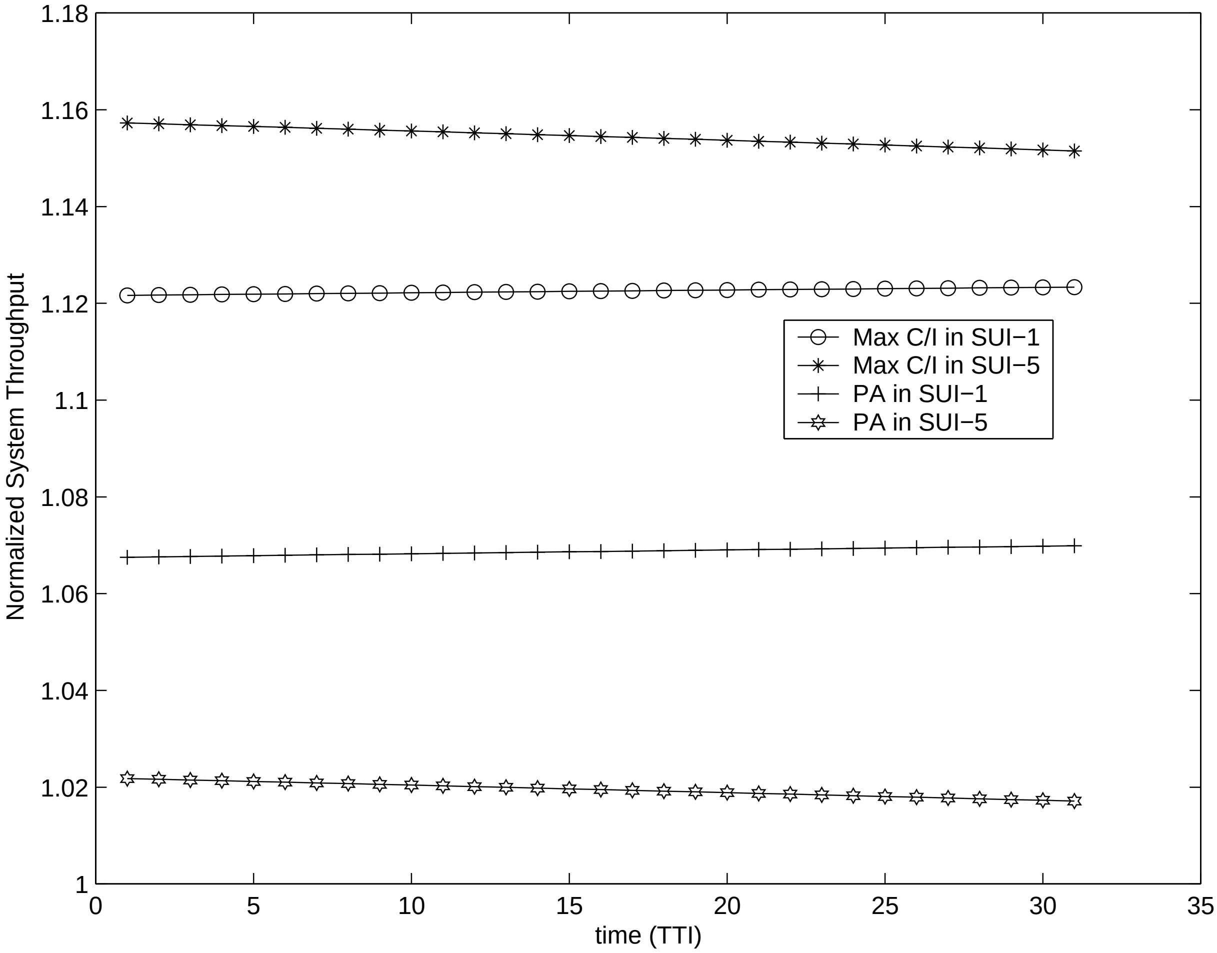

Fig. 3.7: Comparison of throughput performance of dynamic sbucarrier allocation and power allocation ($1TTI = 2048/6MHz = 341\mu s$)

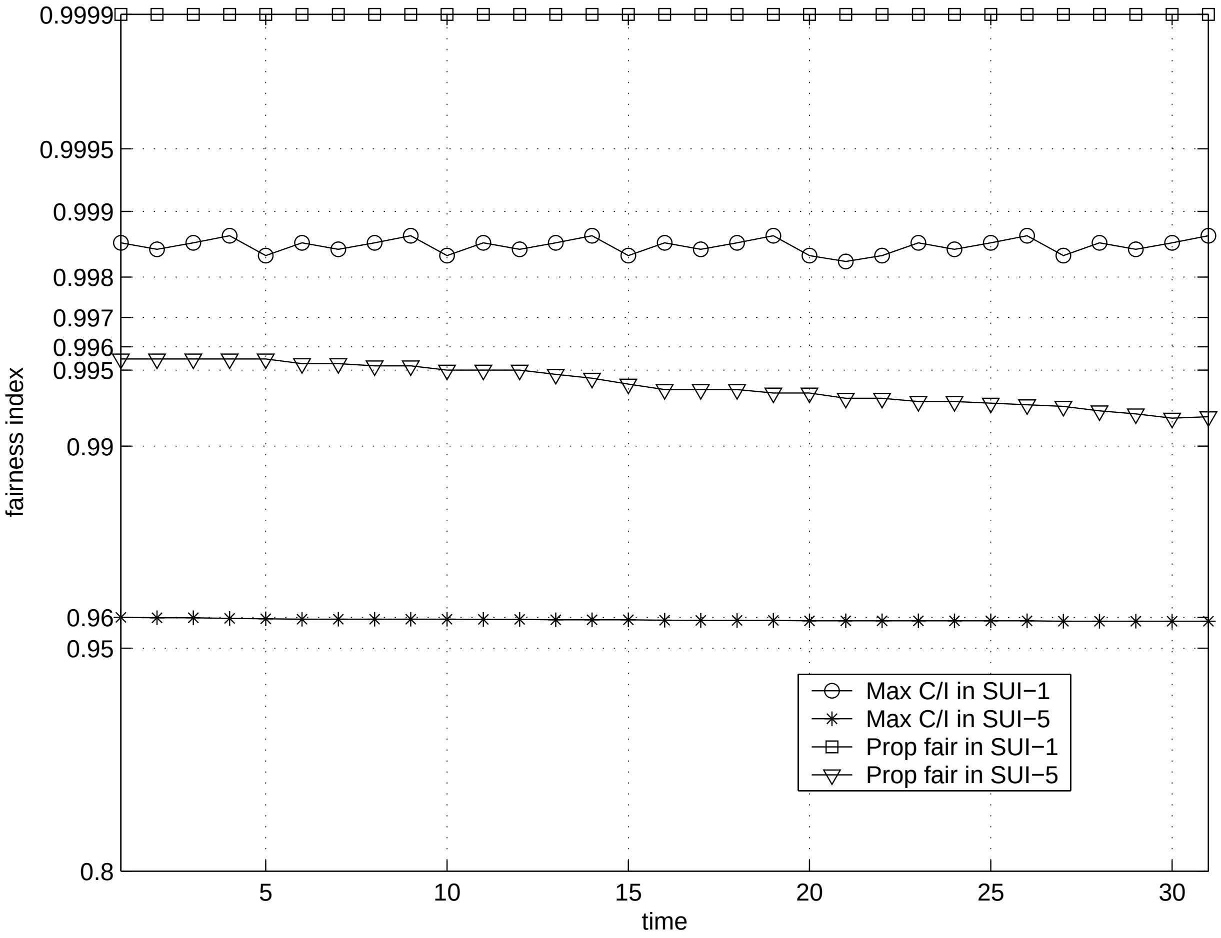

Fig. 3.8: Comparison of fairness performance of max C/I and proportional scheduling $(1TTI = 2048/6MHz = 341\mu s)$

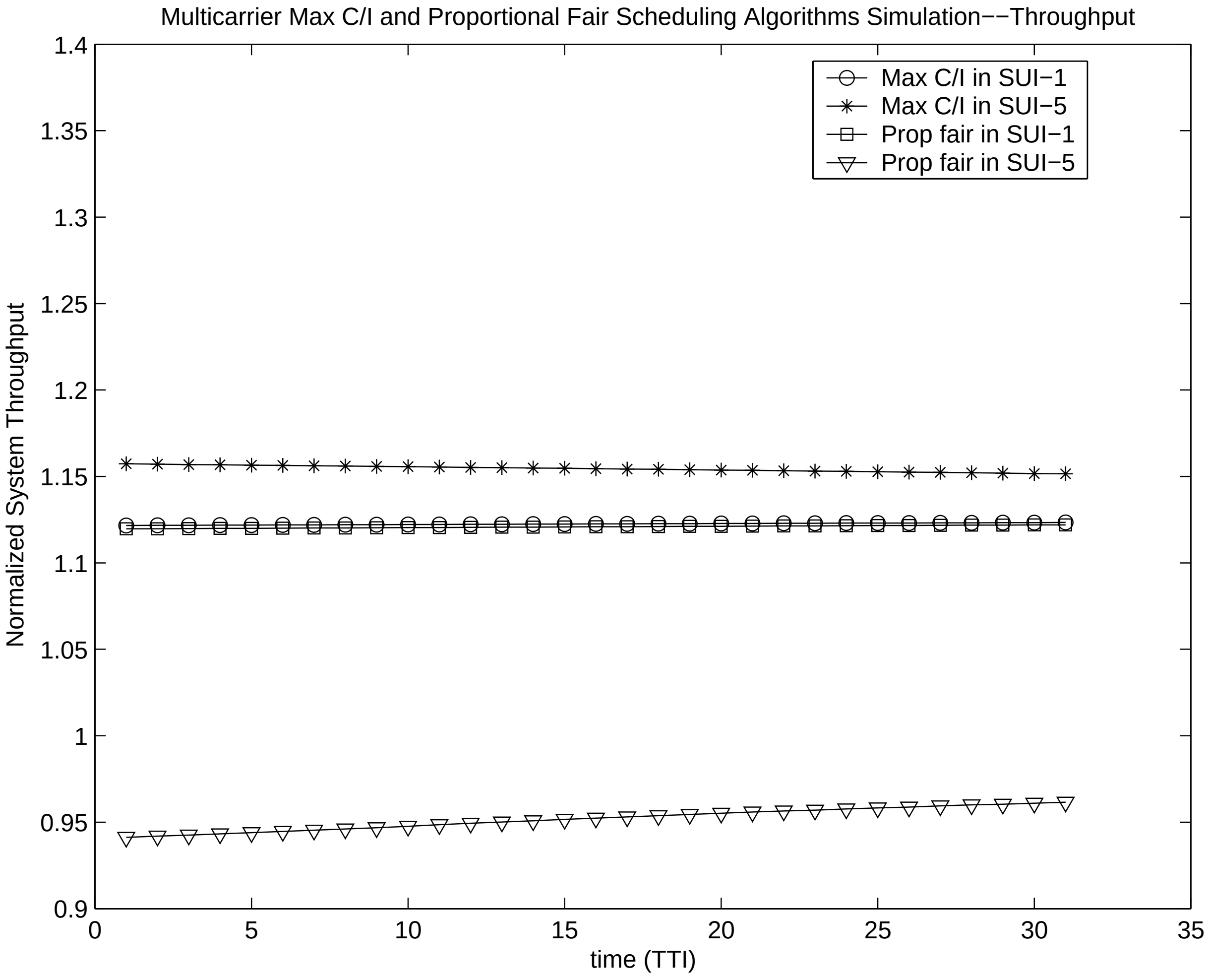

Fig. 3.9: Comparison of throughput performance of max C/I and proportional scheduling ($1TTI = 2048/6MHz = 341\mu s$)

Chapter 4

Channel-aware Subcarrier Allocation and QoS Provisioning for OFDMA Systems with Multi-type Traffic

The orthogonal frequency division multiple access (OFDMA) is becoming an important technique for the future wireless systems. Through parallel multi-carrier transmissions, the inter-symbol interference (ISI) can be easily handled in transmitting high speed data. Furthermore, OFDMA systems bring a new dimension for allocating radio resource - subcarrier. By exploiting frequency diversity in the wide frequency spectrum, a suitable subcarrier allocation technique can further enhance throughput for the OFDMA system. This chapter addresses the issue of allocating subcarriers for providing both real-time and non-real-time traffic in the OFDMA system. We suggest a categorized subcarrier allocation (CSA) technique to improve throughput for non-real-time traffic, while satisfying the quality of service (QoS) requirement for the real-time method. In the proposed CSA technique, subcarriers are categorized into two groups based on their quality: good and fair. The real-time traffic will be assigned by the subcarrier with fair condition, while the non-real-time traffic will be assigned with good subcarriers. We find that such a subcarrier allocation method can apply the maximum carrier-to-interference (C/I) scheduling to maximize the throughput in good conditioned subcarriers, while the delay for the real-time traffic can be controlled by allocating enough fair-conditioned subcarrier through a queueing analytical method. Compared to other methods, such as dynamic subcarrier allocation (DSA) and random subcarrier allocation (RSA), our results show that the CSA technique outperforms other methods in terms of throughput dropping probability and fairness performances.

4.1 Introduction

With the growing demand of high data rate communication, orthogonal frequency division multiple access (OFDMA) is becoming an important technology. OFDMA has been used in some broadband wireless systems, such as the IEEE 802.16a wireless metropolitan area network (WMAN) [13] [20]. In single carrier systems, many scheduling schemes are discussed in [14–18, 23]. Different from single carrier systems, the channel allocation in such multicarrier OFDMA systems has more dimensional consideration to support high-data-rate services. Besides, future wireless communication networks are expected to support multi-type traffic, such as voice, video and data. Therefore, allocating radio resource to different types of services efficiently to meet quality of service (QoS) requirements of each service is an issue of concern. In [1], many conventional subcarrier allocation schemes, fixed subcarrier allocation (FSA), dynamic subcarrier allocation (DSA) and random subcarrier allocation (RSA), are listed to try to enhance the system performances of constant data rate services. Nevertheless, in single carrier systems, if the real-time user with higher priority enters the wireless networks, the non-real-time user will delay the transmission due to lower priority. However, in multicarrier systems, the real-time users can be served by the enough good subcarriers without delay and the non-real-time users use other good subcarriers to achieve the throughput requirements at the same time.

Good scheduling algorithms should have the following characteristics: (1) channel aware, (2) high throughput, (3) fair resource allocation and (4) achieving quality of service. There exist some scheduling algorithms discussed to assure QoS requirements of different types of traffic in single carrier code division multiple access (CDMA) systems [2–6]. To provide both minimum service rate guarantees and dynamic channel bandwidth allocation to all users , generalized processor sharing (GPS) [7] [8] discipline is a scheduler candidate. In [2], the author employs fair queueing algorithm to minimize queueing delays in wireless networks. In [3] and [4], the author proposes a GPS based dynamic fair scheduling scheme, called code division GPS (CDGPS) for wideband direct sequence code division multiple access (DS-CDMA) networks to support multi-type traffic. Furthermore, in [3], the author develops a credit-based CDGPS (C-CDGPS) to improve capacity by trading off short-term fairness. The CARR (channel-aware round robin) scheduler [5] utilizes channel information to increase system capacity and guarantees to allocate certain amount of time slots in an assignment round period in code division multiple access 2000 high data rate (CDMA2000 HDR) [9] or wideband code division multiple access high speed downlink packet access (WCDMA HSDPA) [10] systems. In [6], the idea of the FPLS (fair packet loss sharing) scheduling algorithm is to schedule the session of multimedia packets in the way that all the users share the packet loss fairly depending on their QoS requirements and to maximize the system capacity under the QoS constraints. However, in multicarrier systems, such as OFDM, if radio resource management makes use of the frequency diversity, the system performance can be improved. In [11], the author discusses the adaptive modulation and proposes dynamic GPS (DGPS) scheduling for OFDM wireless communication systems, which exploits both multiuser diversity and frequency diversity. Yet, in [12], the proposed proportional rate adaptive optimization considers subcarrier and power allocation in the multiuser orthogonal frequency division multiplexing (MU-OFDM) system.

In this chapter, we develop a channel-aware and quality of service (QoS) provisioning scheduling subcarrier allocation algorithm, categorized subcarrier allocation (CSA), for the OFDMA systems. Frequency diversity inherently exists in OFDMA systems, while multiuser diversity can be achieved by adopting scheduling algorithms. Our proposed algorithm makes use of both diversity gains to support non-real-time service flows to achieve high throughput and considers the queueing analysis to allocate the suitable amount of resource to the real-time service flows. Taking advantage of the specific characteristics of channels in OFDMA multicarrier environments, the proposed categorized subcarrier allocation (CSA) scheme can satisfy QoS delay constraint of real-time services and higher throughput requirements of non-real-time services at the same time. Moreover, the proposed subcarrier allocation algorithm can maintain good fairness performance in the multicarrier systems. As described above, we dynamically allocate subcarriers for of different types of service flows. This is a cross-layer design of radio resource management. Furthermore, it can be regarded as another form of water-pouring. We name it *Service-oriented Water-pouring*, which satisfy the QoS requirements of multi-type services, respectively. In addition, we manage the radio resource allocation from the viewpoint of users. In other words, it is the users that select the subcarriers that can assure their service-oriented QoS requirements.

In a multiuser wireless system, different users may have different channel responses with respect to a time varying wireless channel. Thus, one user may view a channel as a bad channel, whereas the others may view it as a good channel. Consequently, for each channel, if the system can first pick a user with the best channel quality among a group of users and then deliver the service to this target user, the system capacity can be significantly improved. We call this capacity improvement as the multiuser diversity gain. However, in addition to multiuser diversity, we also make use of the correlation of subcarriers to efficiently allocate radio resource to real-time and non-real-time services, respectively.

The rest of this chapter is organized as follows. Section 4.2 introduces the quality of service (QoS) scheduling service specified in the IEEE 802.16 standard.

Section 4.3 describes the motivation. Section 4.4 formulates the problem. In Section 4.5, we explain our proposed a QoS provisioning subcarrier allocation method and describe the merit. Numerical results are given in Section 4.6. In Section 4.7, we give our concluding remarks.

4.2 IEEE 802.16 Scheduling Service

In the IEEE 802.16 specification for fixed broadband wireless access (BWA) systems [34], scheduling services are designed to improve the efficiency of the poll/grant process. Owing to different quality of service (QoS) requirements of various service flows, the IEEE 802.16 standard defines four types of services, unsolicited grant service (UGS), real-time polling serivce (rtPS), non-real-time polling Service (nrtPS) and best effort (BE) service [34, 35]. We will illustrate each type of service later.

First, the UGS supports real-time service flows with fixed size data packets periodically, such as T1/E1 and Voice over IP (VoIP). The UGS type of service eliminates the delay of subscriber stations (SS) and assures that grants are available to meet the requirements of the service flows. In a word, UGS has the highest priority to access the network resource among the four types of services.

Second, the rtPS supports real-time service flows with variable size data packets on periodic basis, such as MPEG video. This type of service requires more request overhead than UGS, but supports variable grant sizes to optimize the efficiency of data transmission.

Third, the nrtPS is designed to support non-real-time service flows which require variable size Data Grant Burst Types regularly, such as high bandwidth FTP. This service offers unicast polls on a regular basis which assures that the flow receivers request opportunities even during network congestion.

Finally, the BE service provides efficient service to best effort traffic. This type of service has the lowest priority to access network but needs higher quality transmission. In other words, it is not tolerant of higher bit error rate.

4.3 Motivation - Channel Characteristics of OFDMA Systems

To develop an efficient subcarrier allocation scheduling algorithm, we have to comprehend the characteristic of the communication channel. At first, we assume that in the multicarrier environments, each subcarrier channel response to each user is independent. Therefore, we can exploit the multiuser diversity and frequency diversity to enhance the system throughput and maintain good fairness performance. Nevertheless, in the practical OFDMA multicarrier environments, we observe that the subcarrier channel responses have some relationship among different users. We describe the characteristic by Fig. 4.1. In Fig. 4.1, each subcarrier is judged for 12000 times. Each user gives the good mark to the first 682 best subcarriers, medium mark to the following 682 subcarriers and bad mark to the first worst 684 subcarriers among the total 2048 subcarriers. Fig. 4.1 (A) shows that for each subcarrier, how many users think it is good for himself. Fig. 4.1 (B) points how many users think the subcarriers medium while Fig. 4.1 (C) represents the number of users who think subcarriers bad.

Here, we illustrates the subcarrier correlation for users by Fig. 4.2. We only care the medium subcarriers and good subcarriers because the bad subcarriers are scheduled lastly. In Fig. 4.2, we observe that the ratio of the number of good users to the number of medium plus good uers for each subcarrierfar far away 0.5 is in the majority, which means that for the same subcarrier, the most part of users regard it as the same rank, good, medium or bad. Of course there are exceptions. But the exceptions is minor. From Fig. 4.2, we can find that the number of subcarriers whose ratio is less than 0.2 or greater than 0.8 is 82.6% of all subcarriers. The fact shows that the subcarriers are correlated among users. We will make use of the characteristic of the OFDMA channel to design our subcarrier allocation scheduling algorithm.

In the following, we see Fig. 4.3 and Fig. 4.4. The two figures show that the distribution different opinions to each subcarrier. Figure 4.3 is the summation of Fig. 4.1 (A), (B) and (C). We can find that for the most part of subcarriers, opinion of users on them are almost the same. We take some examples from Fig. 4.4 which is selected a section of 4.3 for the sake of clear observation. For the 2001st subcarrier, there are 68 users regarding it as a good subcarrier, while there are 11100 and 832 users seeing it as a medium and bad subcarrier, respectively. Taking another example, for the 2018th subcarrier, 11618 users regarding it as a good subcarrier, while 382 and 0 users seeing it as a medium and bad subcarrier. These two subcarriers have common consensus of users. However, there are still subcarriers with different opinions. For instance, 6296 users regard the 2008th subcarrier as a good subcarrier while 5699 users see it as a medium subcarrier and 5 users think it good. Nevertheless, this kind of subcarriers is minor that the fact can be observed by Fig. 4.2. Based on the characteristics of the channel, we will design a useful subcarrier allocation algorithm for OFDMA systems.

4.4 Problem Formulation

In the third-generation and beyond or the future communication systems, there will be a mixture of different traffic classes. Therefore, what is the suitable ratio of real-time service and non-real-time service resource allocation is a research topic. How to utilize the limited radio resource for various types of service flows with different QoS requirements is a very important issue.

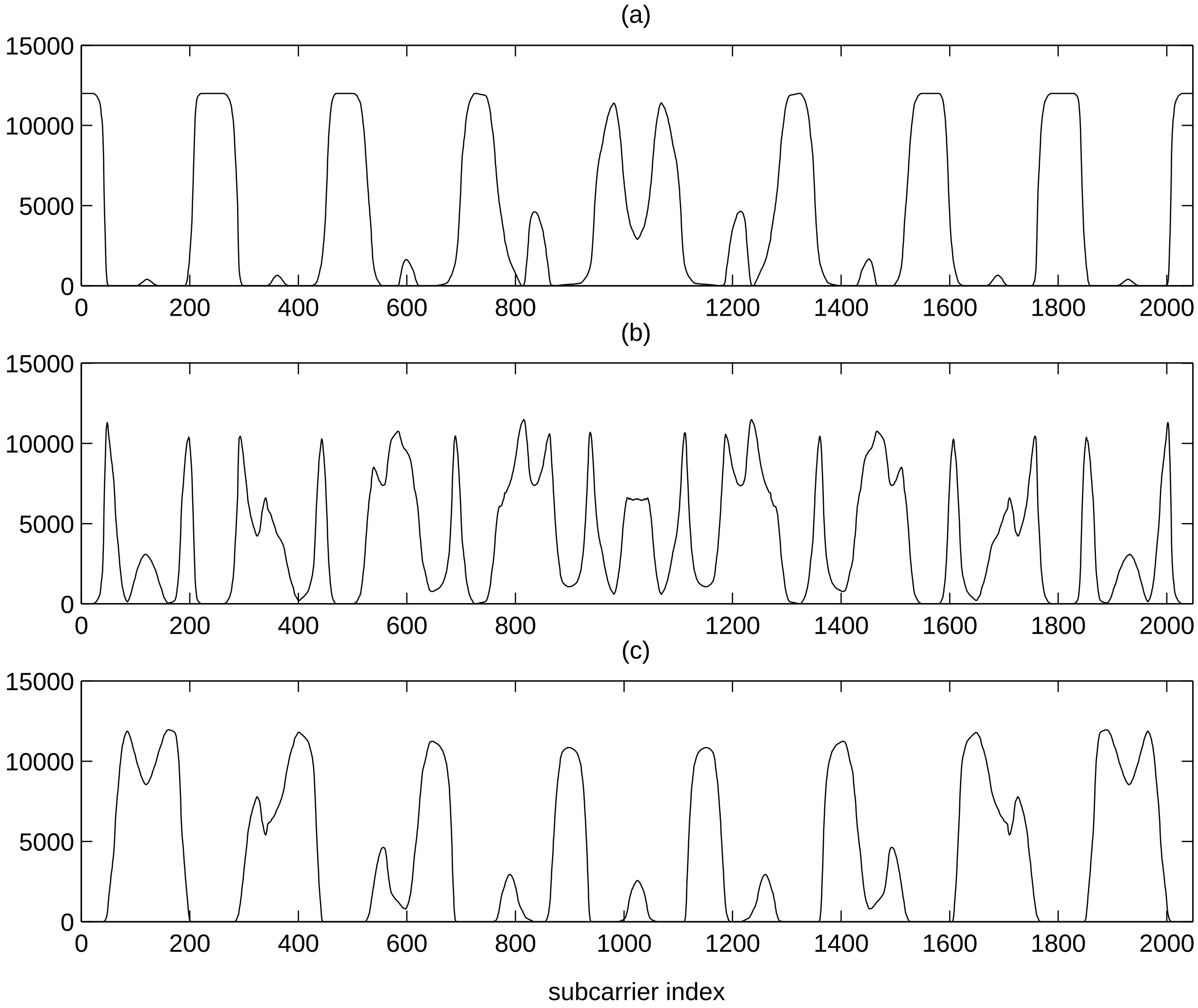

Fig. 4.1: (a) The number of users that judge the subcarrier is good for each subcarrier; (b) The number of users that judge the subcarrier is medium for each subcarrier; (c) The number of users that judge the subcarrier is bad for each subcarrier.

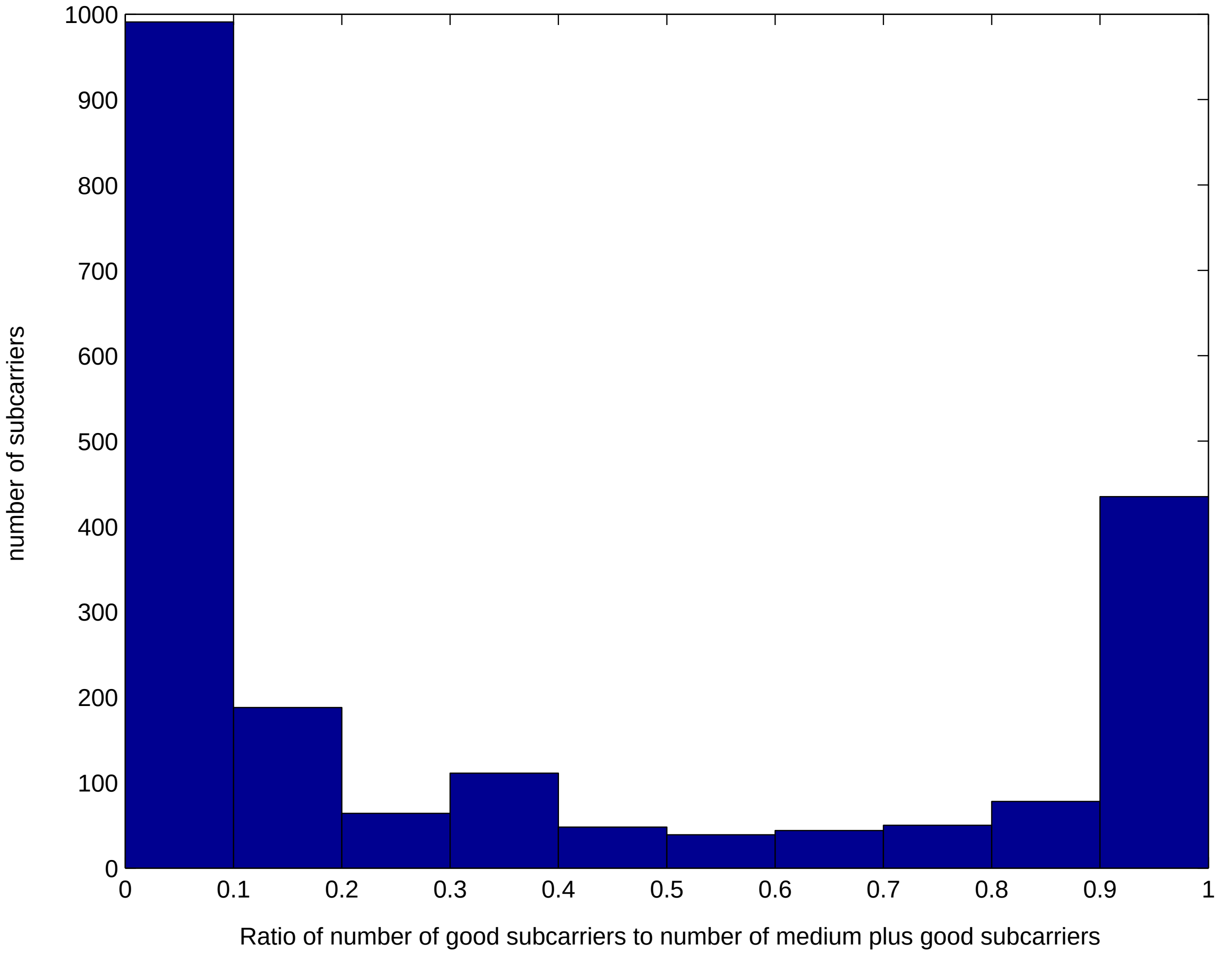

Fig. 4.2: The cumulative number of subcarriers of different ratios, which is the number of good users to number of medium plus good uers for each subcarrier.

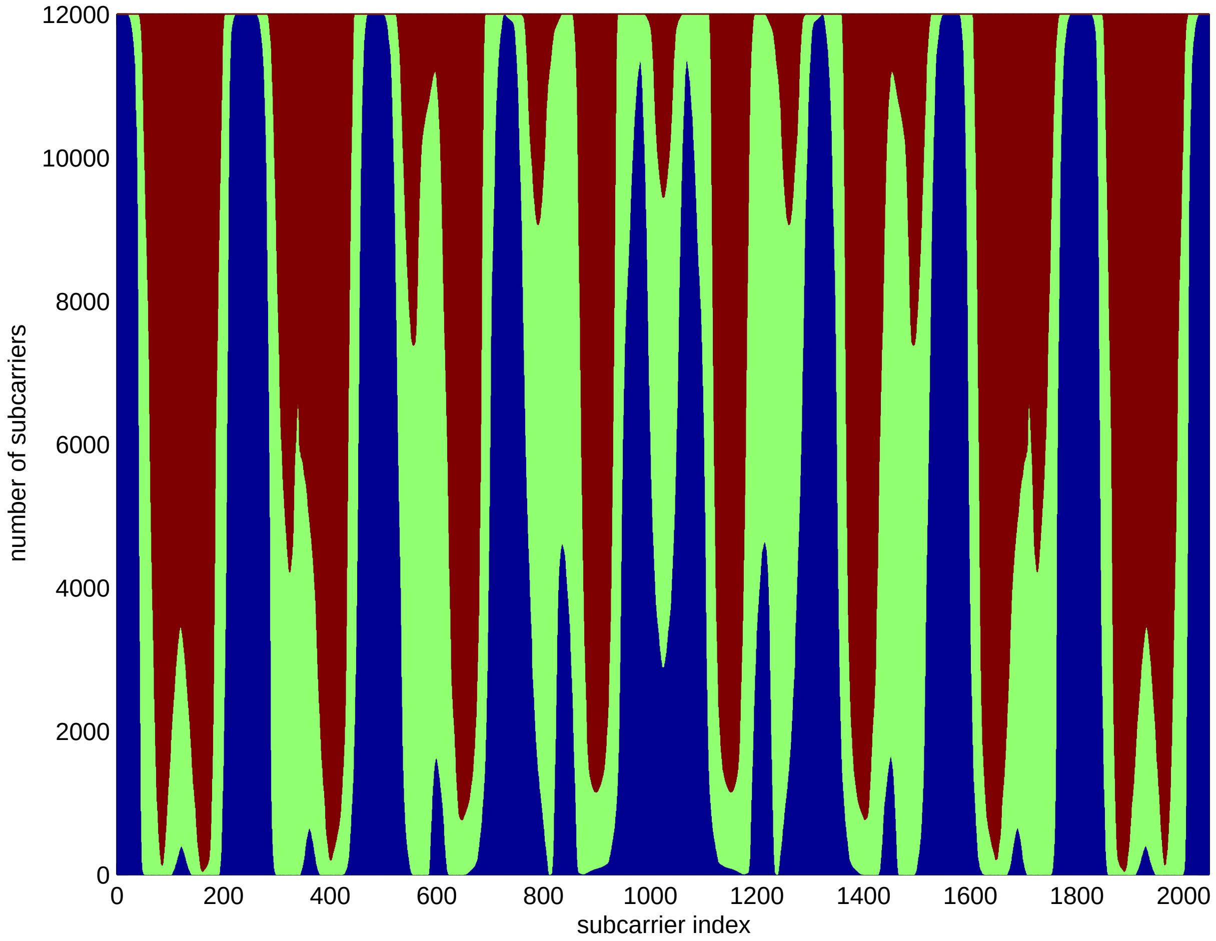

Fig. 4.3: The stack presentation of OFDMA channel characterisitcs

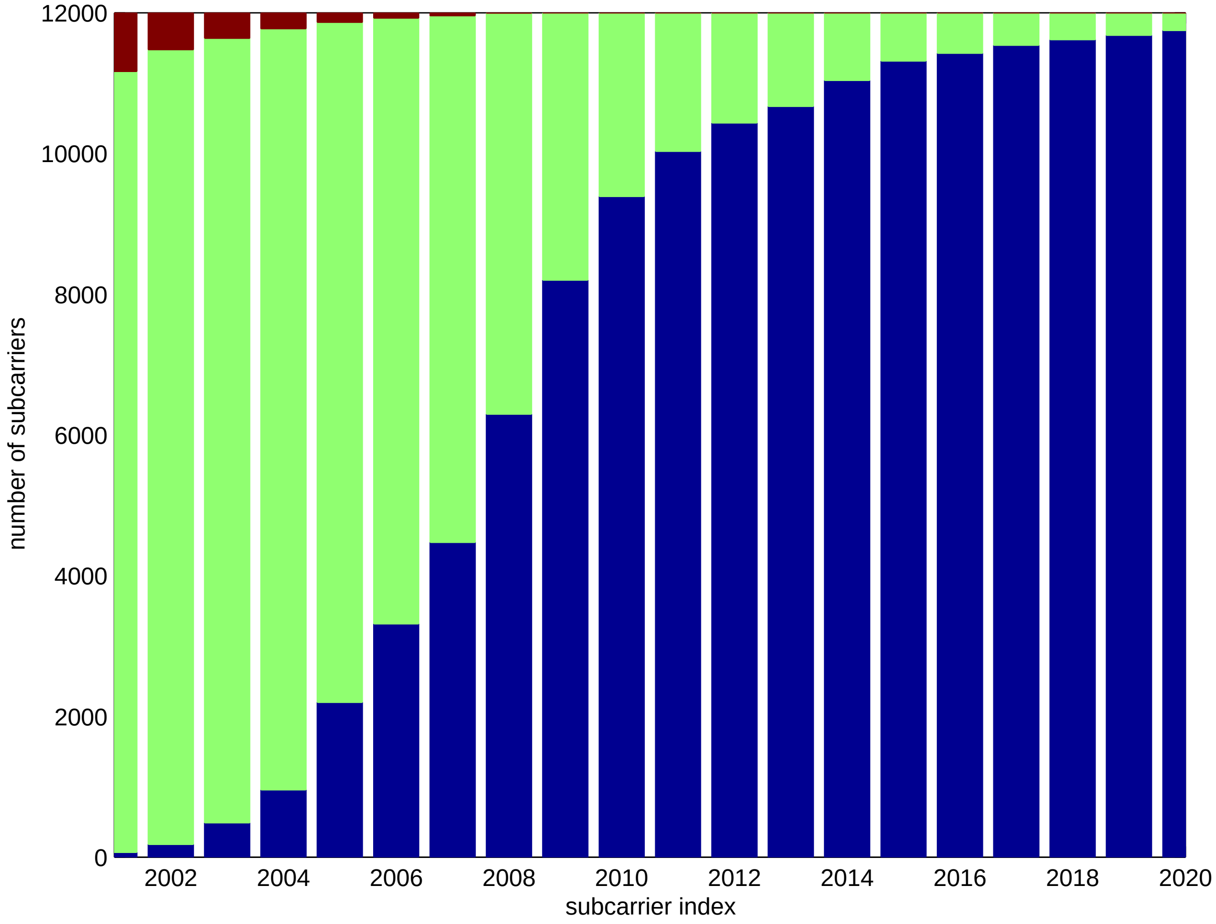

Fig. 4.4: The stack presentation of parts of the OFDMA channel characterisitcs. We take from the 2001th to 2020th subcarriers for examples

In the integrated service networks, we initially divide services into two parts, real-time voice and non-real-time data services. The demand of real-time voice service is that the delay can not exceed a certain threshold W_{th}. On the contrary, the non-real-time data service is tolerant of delay, but takes best efforts to achieve the maximum throughput. Consequently, the goal is to achieve the maximum throughput of non-real-time data users under QoS constraints of real-time users. We mathematically formulate this problem by the following equations.

$$\max_{\rho_{n,m}} \sum_{n=n_{rt}+1}^{N} \sum_{m=m_{rt}+1}^{M} \frac{B\rho_{n,m}}{M} \log_2\{1 + \frac{h_{n,m}^2}{N_0 \frac{B}{M}}\} \tag{4.1}$$

subject to

$$\rho_{n,m} = \{0, 1\}\ \forall n, m \tag{4.2}$$

$$\sum_{n=1}^{N} \rho_{n,m} = 1\ \forall m \tag{4.3}$$

$$\sum_{m=m_{rt}+1}^{M} \rho_{n,m} = \begin{cases} \frac{M-m_{rt}}{N-n_{rt}} & if\ \ (M - m_{rt})\ \ mod\ \ (N - n_{rt}) = 0 \\ \lfloor \frac{M-m_{rt}}{N-n_{rt}} \rfloor\ \ or\ \ \lfloor \frac{M-m_{rt}}{N-n_{rt}} \rfloor + 1 & \\ & if\ \ (M - m_{rt})\ \ mod\ \ (N - n_{rt}) = r(r \neq 0) \end{cases} \tag{4.4}$$

To find a large enough m_{rt} s.t.

$$W_{rt} \leq W_{th}, \tag{4.5}$$

where n is the user index, m is the subcarrier index. n_{rt} means the number of real-time users, while m_{rt} is the number of real-time subcarriers. N is the number of total users while M is the number of total subcarriers. $\rho_{n,m}$ means whether the $m-th$ subcarrier is assigned to the $n-th$ user. $\rho_{n,m} = 1$ means the $m-th$ subcarrier is assigned to the $n-th$ user while $\rho_{n,m} = 0$ means the $m-th$ subcarrier is not assigned to the $n-th$ user. $h_{n,m}$ is the $m-th$ subcarrier channel response to the $n-th$ user. N_0 is the noise spectral density and B is the total bandwidth. W_{rt} is the waiting time of real-time service while W_{th} is the delay constraint.

We would like to maximize the throughput of non-real-time users described by (4.1). The constraint (4.2) represents whether the $m-th$ subcarrier is assigned to the $n-th$ user. The constraint (4.3) means that each subcarrier is allocated to the only one user. In (4.4), $(M-m_{rt})\ mod\ (N-n_{rt}) = r \neq 0$, there are r users allocated $\lfloor \frac{M-m_{rt}}{N-n_{rt}} \rfloor + 1$ subcarriers, and $M - m_{rt} - r$ users allocated $\lfloor \frac{M-m_{rt}}{N-n_{rt}} \rfloor$ subcarriers. In (4.5), W_{rt} is calculated by queueing analysis to find the suitable number of real-time subcarriers.

4.5 The Proposed Categorized Subcarrier Allocation (CSA) Algorithm

In the wireless network systems, the channel suffers from multipath effect which causes fading effect. Furthermore, the mobility of user causes Doppler effect, which makes channel time-varying. The two impacts give challenges to wireless communication but imply some benefits to radio resource management. In order to utilize the limited radio resource more efficiently, understanding the environments and exploit the existed advantage is very necessary and can improve the system performance.

In the single carrier systems, resource allocation is operated in the form of TDMA (time division multiple access) [14]. Coordinated by CDMA (code division multiple access) [14], how many users using the radio resource for transmission at the same time depends on the code length. However, the multicarrier modulation technology is proposed to mitigate the inter-symbol interference phenomenon due to the multipath effect. OFDM or single carrier, the two classes of block transmission are compared in [36]. We focus on multicarrier transmission techniques such as OFDM here. In addition, the multicarrier scheme bring the frequency dimension for radio resource management.

Now we propose a channel-aware and QoS provisioning subcarrier allocation scheduling algorithm called *categorized subcarrier allocation* (CSA) algorithm for the multimedia [37] multicarrier OFDMA systems. There will be multi-type traffic services in the communication networks. Therefore, our proposed algorithm considers the QoS requirements of real-time and non-real-time service flows, and takes advantage of the characteristics of the communication environments to achieve better system performance. For real-time services, we can not tolerant of too much delay while for non-real-time services, the system throughput and fairness among users are emphasized. The CSA scheduler architecture are showed in Fig. 4.5. The proposed categorized subcarrier allocation follows the listed procedure.

1. We categorize the service flows in two classes, real-time and non-real-time.

2. Define the priorities of all users. In general, the priorities of real-time users $P_i, i = 1, 2, \cdots, N_{rt}$ is higher than the non-real-time users $Q_i, i = 1, 2, \cdots, N_{nrt}$, where N_{rt} is the total number of real-time users and N_{nrt} is the total number of non-real-time users.

$$P_1 > P_2 > \cdots > P_{N_{rt}} > Q_1 > Q_2 > \cdots > Q_{N_{nrt}} \tag{4.6}$$

3. Determine the number of real-time subcarriers m by (4.9) such that the waiting time does not exceed the given threshold W_{th}.

   We have to determine the number of subcarriers of real-time users depending on the inter-arrival rate and service rate of the traffic under the delay constraints. If the inter-arrival time and service time are exponentially distributed, we apply the $M/M/m$ queueing model [38] to calculate the mean waiting time showed by (4.9). Real-time voice service traffic is a similar typical example of this case [39] [40].

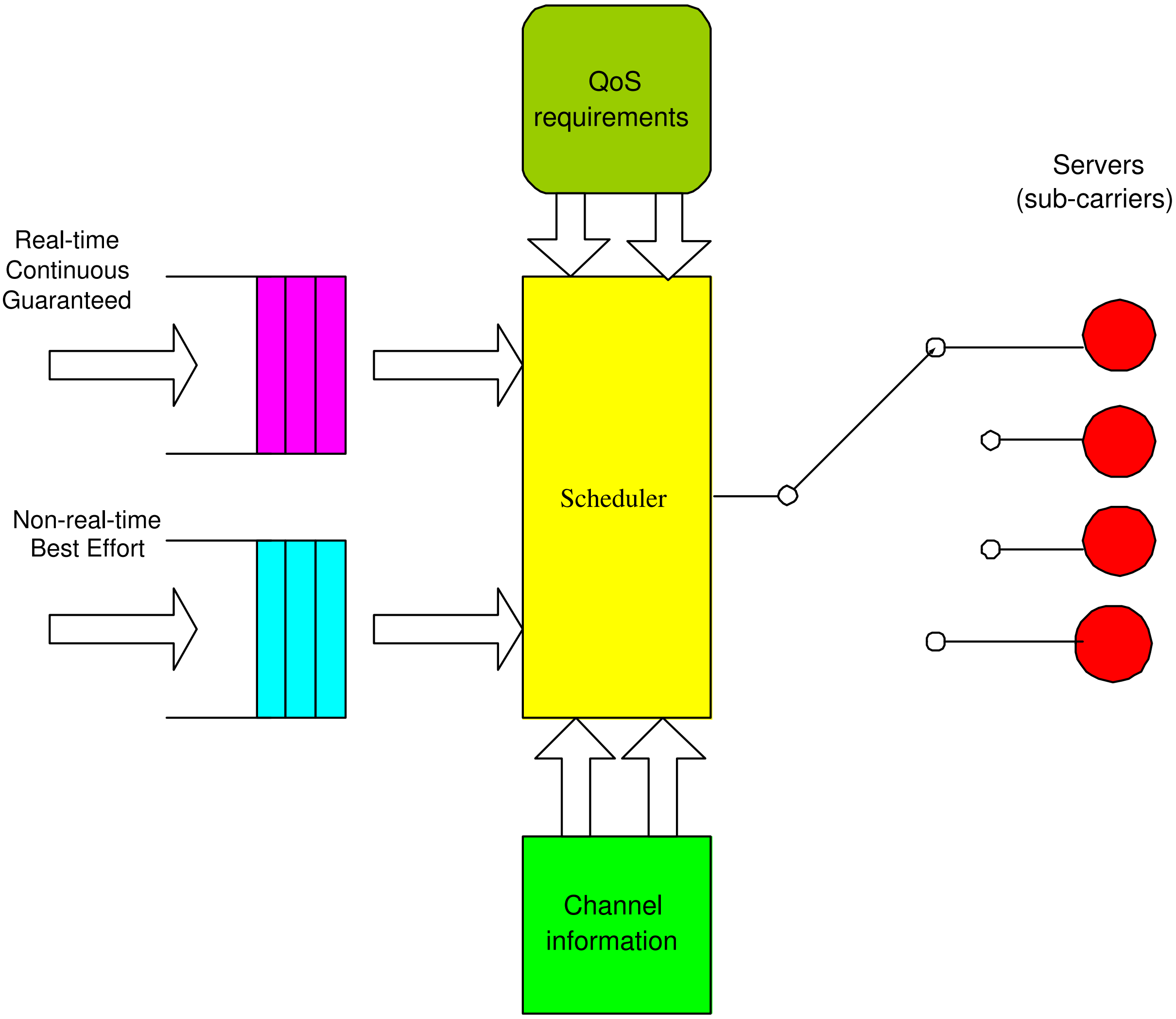

Fig. 4.5: Proposed scheduler architecture

$$\begin{aligned} W_{M/M/m} &= \frac{\overline{N_q}}{\lambda} && (4.7)\\ &= \frac{\sum\limits_{k=m}^{\infty}(k-m)P_k}{\lambda} && (4.8)\\ &= \frac{\sum\limits_{k=m}^{\infty}(k-m)(\frac{\lambda}{\mu})^k\frac{1}{m!m^{k-m}}\frac{1}{\sum\limits_{k=0}^{m-1}(\frac{\lambda}{\mu})^k\frac{1}{k!}+(\frac{\lambda}{\mu})^m\frac{1}{m!}\frac{1}{1-\frac{\lambda}{m\mu}}}}{\lambda} && (4.9)\end{aligned}$$

However, there are other services, such as data or video, not suited to be modelled as *M/M/m* queueing problem. Based on [38], we can model as *M/G/m* queueing analysis to describe the more general cases.

$$W_{M/G/m}=\begin{cases}\frac{1+c_B^2}{(1-\frac{\lambda}{m\mu})\mu 2m}\frac{(\frac{\lambda}{m\mu})^m+\frac{\lambda}{m\mu}}{2}, & if\ \ \frac{\lambda}{m\mu}>0.7\\ \frac{1+c_B^2}{(1-\frac{\lambda}{m\mu})\mu 2m}(\frac{\lambda}{m\mu})^{\frac{m+1}{2}}, & if\ \ \frac{\lambda}{m\mu}<0.7\end{cases} \qquad (4.10)$$

In this paper, we focus on the queueing delay of the real-time voice users. Hence, we just model the real-time voice traffic as *M/M/m* queueing model in out simulation.

4. For each user, the total subcarriers are given a rank, *good*, *medium* or *bad*.

5. The real-time users first select the enough medium subcarriers to support voice transmission in order depending on their priorities. Users with lower priority does not select the selected subcarriers of the users with higher priority and they can only select the rest subcarriers.

6. The non-real-time users allocated subcarriers based on DSA described in Section IV. In this step, users with higher priorities select the best subcarriers for themselves. Users with lower priority does not select the selected subcarriers

The CSA subcarrier allocation scheduler considers the QoS requirements of different types of traffic and takes advantage of channel state information. Furthermore, in the OFDMA system, multiuser diversity and frequency diversity are also exploited by the proposed algorithm. However, the subcarrier channel response to each user is not thoroughly independent. Therefore, our proposed algorithm let the real-time users just use the medium subcarriers. Consequently, the throughput sensitive non-real-time users have the higher probability to get the subcarriers with better condition to enhance the system throughput. On the other hand, based on queueing analysis, we assure the real-time services. Meanwhile, the DSA scheme used in subcarrier allocation of the non-real-time services make the throughput increase. Moreover, the frequency diversity provide good fairness performance among non-real-time users. In the next section, we will evaluate the performance of our proposed algorithm and compare the performance between FSA, RSA, DSA and the proposed CSA algorithms.

4.6 Numerical Results

4.6.1 Simulation Methodology

Then, we apply the practical IEEE 802.16 SUI-5 channel model to our simulation. In [28], six SUI channel delay profiles are specified. For the multicarrier OFDMA system, we first take the appropriate 2048 samples of the channel delay profiles where the sample time

$$T_s = \frac{1}{B} \ , \tag{4.11}$$

where B is total bandwidth and 2048 is FFT size corresponding to the number of subcarriers. In this $B = 1.75MHz$ case, the T_s calculated is 1.2 ms, which is also the length of a time slot showed as follows. And then we use the fast Fourier transform

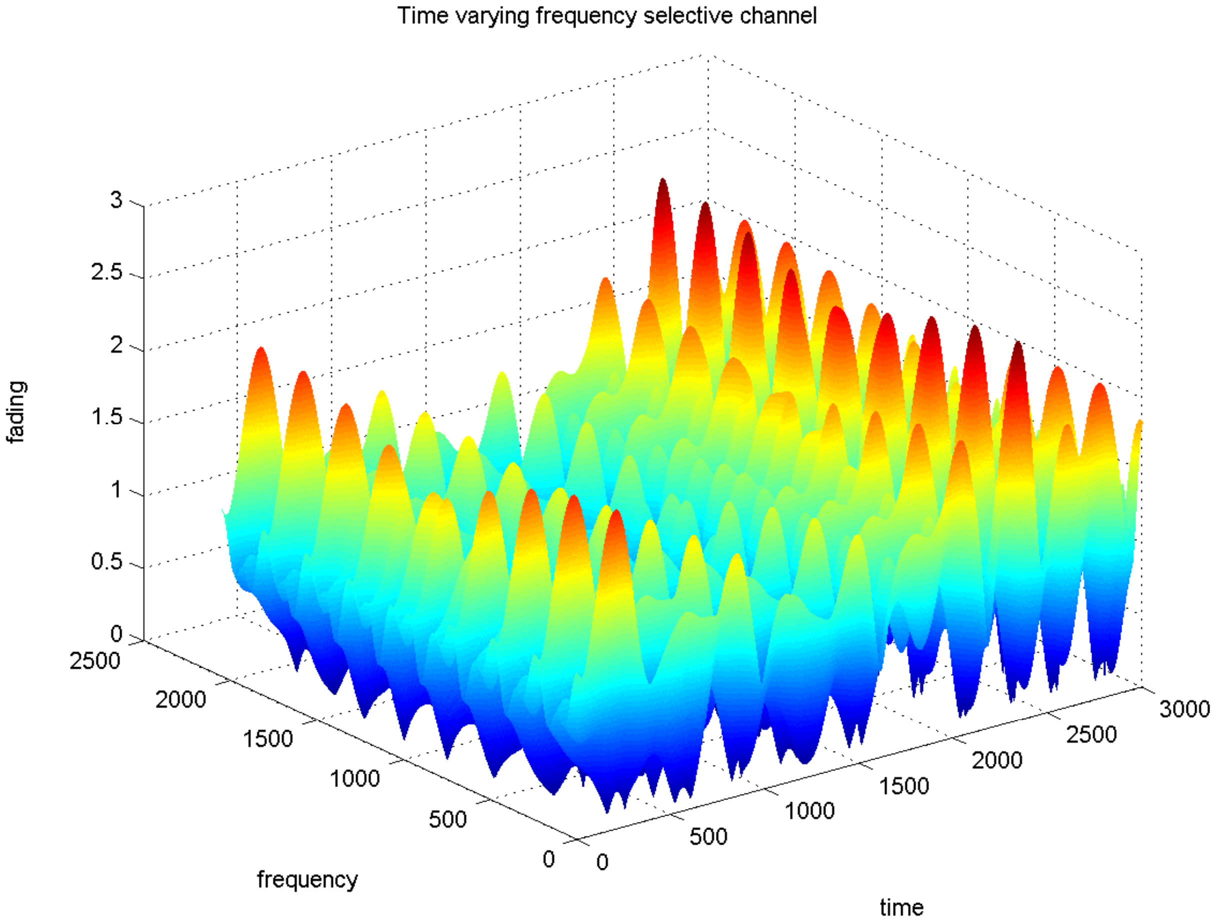

Fig. 4.6: Time varying with multipath fading model

(FFT) technique [32] to transform from time domain to frequency domain. Hence, we can observe the multipath fading effect in the frequency domain with considering the Doppler effect, (see Fig. 4.6). Finally, observing a long time period of this frequency domain channel models, we pick different time points to represent the channel response of different users. Therefore, we can form a practical channel matrix for simulation to evaluate the system performance. The simulation parameters are listed in Table 3.5.

Tab. 4.1: Simulation Parameters

No. of user	32
FFT size	2048
Total badwidth	1.75 MHz
Channel model	SUI-5

4.6.2 Blocking Probability Comparison of Real-time Users

First, we compare the delay performance of real-time services between our proposed subcarrier allocation and the conventional subcarrier allocation algorithms. In Fig. 4.7, we only observe the blocking probability of real-time users because if the non-real-time traffic load is too heavy, it is queued while the non-real-time data services are tolerant of delay. We see the variation of blocking probability of different subcarrier allocation schemes depending on inter-arrival rate.

In this simulation, The assumption is that there are 96 subcarriers and the number of the total served users is 24. Moreover, we assume that the mean service rate is $\frac{1}{180} = 0.0056(1/sec)$, which is corresponding to the mean time of a phone with 3 minutes period. From Fig. 4.7, we find the first three subcarrier allocation schemes without queueing analysis consideration are very sensitive to the inter-arrival rates. When the inter-arrival rate exceeds about 0.015 $(1/sec)$, the blocking probability almost approach 10^{-1} that is a very bad performance. Therefore, We determine the number of real-time subcarriers by queueing waiting analysis 4.9 under the delay threshold $W_{th} = 200ms$. The CDSA (categorized dynamic subcarrier allocation) is the DSA described in Section II with queueing model consideration. Compared to our proposed CSA algorithm, the CDSA schemes that the real-time users choose the best subcarriers at first, while the proposed scheme that users that do not sensitive to throughput select the medium enough good subcarriers. In Fig. 4.7, the two queueing-aware subcarrier allocation are both good on blocking probability, and our proposed scheme has a bit of better performance.

4.6.3 Fairness Performance on Different Number of Subcarriers

In the following, we see the fairness performances of different subcarrier allocation policies when the number of subcarriers changes. In general, the more the number of subcarriers, the better the fairness performance because of more frequency diversity gain. In Fig. 4.8, the various subcarrier allocation scheduling schemes achieve good performance by exploiting frequency diversity and multiuser diversity. Moreover, the proposed CSA algorithm outperforms the other existed multicarrier allocation schemes in the field of fairness. Even there are only 64 subcarriers in the system, the fairness performance of the proposed CSA algorithm is very good by thoroughly exploiting the both diversity gains.

4.6.4 Throughput and Fairness Performance of Non-real-time Users

In this subsection, we evaluate the throughput and fairness performances of the non-real-time users in the practical IEEE 802.16 WMAN OFDMA environments. First, we observe the through of non-real-time users in the wireless time-varying environments. From Fig. 4.9, we see that the throughput performances of FSA and RSA are almost the same. The two schemes do not take the channel state information into consideration. Nevertheless, we find that the RSA exploits the frequency to achieve better fairness performance than that of FSA from Fig. 4.10. Seeing Fig. 4.9, we observe that the DSA scheme exploits both multiuser diversity and frequency diversity to improve the throughput perfomance rather than FSA and RSA. Furthermore, the proposed CSA algorithm take advantage of the characteristics of OFDMA channel. Real-time users do not select the best subcarriers but use the medium subcarriers instead. Hence, the non-real-time users have higher probability to utilize the subcarriers with good conditions, which make the throughput of CSA achieve the best throughput performance among the four resource allocation policies, FSA, RSA, DSA and CSA. Moreover, the proposed CSA algorithm has the best fairness performance because it has the channel effects and characteristics comprehensively in mind.

Figures 4.11 and 4.12 show that the mean throughput and fairness performances after an amount of iteration. From Fig. 4.11, it is showed that throughput performances of FSA and RSA are almost the same. DSA improve the throughput of non-real-time users about 5% rather than FSA and RSA. The DSA scheme also improves the quality of real-time voice service but we do not care very much. Moreover, the proposed CSA algorithm improves the throughput about 20% rather than the DSA scheme. The CSA resource management policy maintains the real-time transmission quality and utilizes the gain due to taking advantage of the specific characteristics of OFDMA systems to support the non-real-time throughput sensitive services. In Fig. 4.12, we find that the mean fairness performances of the four schemes are very good in the multicarrier systems. However, the proposed CSA algorithm is the best fair allocation approach.

4.6.5 Discussions

For radio resource scheduling, it is generally discussed that the trade-off multiuser diversity and delay [41]. In other words, throughput and fairness are not considered complete in both respects. However, frequency diversity inherently exists in the multicarrier system. Therefore, we make use of frequency diversity to support fairness requirements. Moreover, understanding the specific characteristics of OFDMA channel, we try our best to enhance the throughput of non-real-time service flows with allocating subcarriers with enough good conditions. In a word, compared DSA, our proposed CSA schemes remove the diversity gain from real-time services to provide extra gain to non-real-time services.

4.7 Conclusions

In this paper, we propose an efficient QoS provisioning multicarrier allocation scheme to satisfy QoS requirements of multi-type services. By queueing analysis, we satisfy the demand of real-time users. Besides, we observe the channel characteristics of OFDMA systems and make use of it to improve the system performance. Furthermore, we exploits frequency diversity and multiuser diversity to enhance throughput and maintain the fairness performance of non-real-time service with considering delay constraint of real-time service.

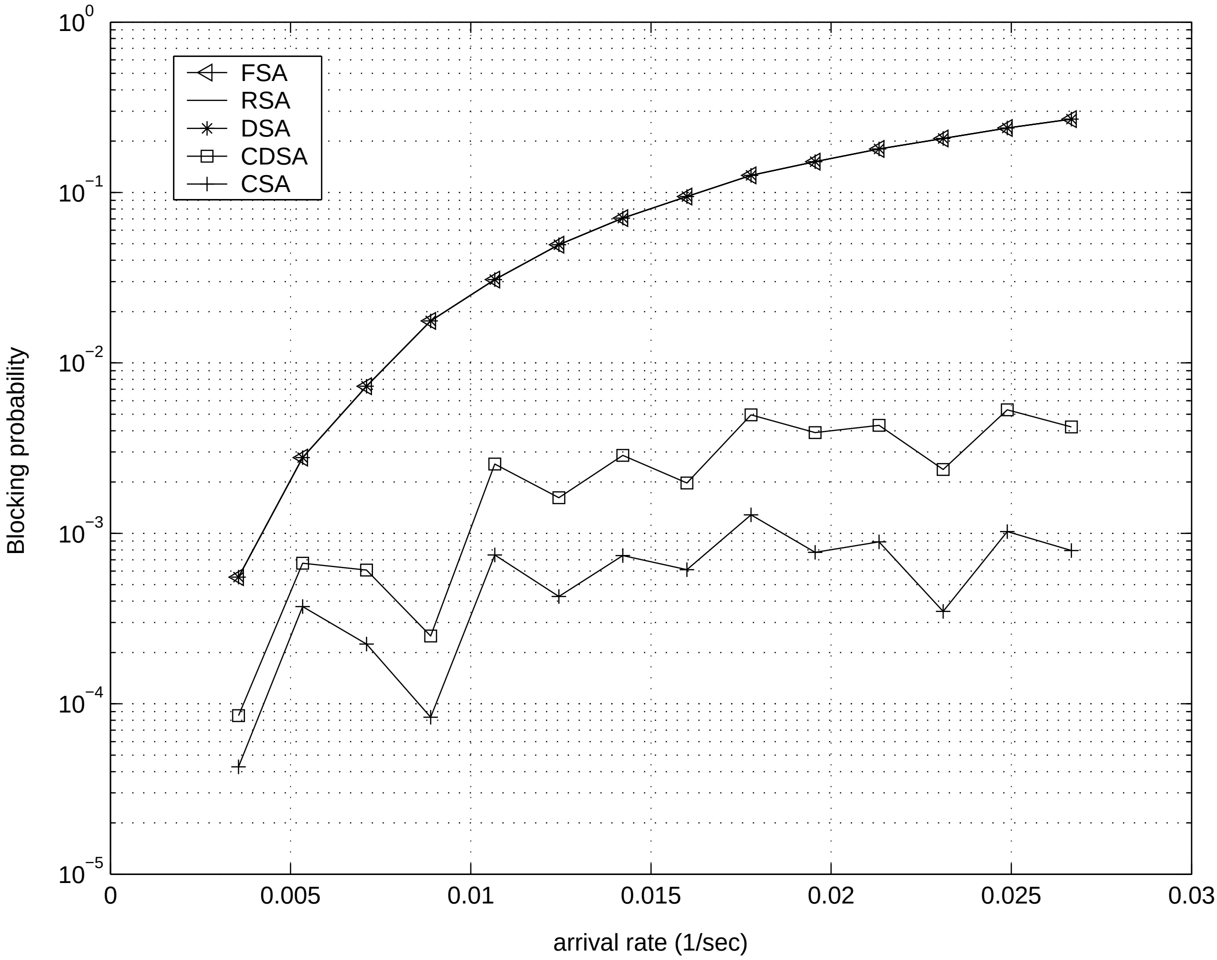

Fig. 4.7: Blocking probability of real-time services when the inter-arrival rate changes.

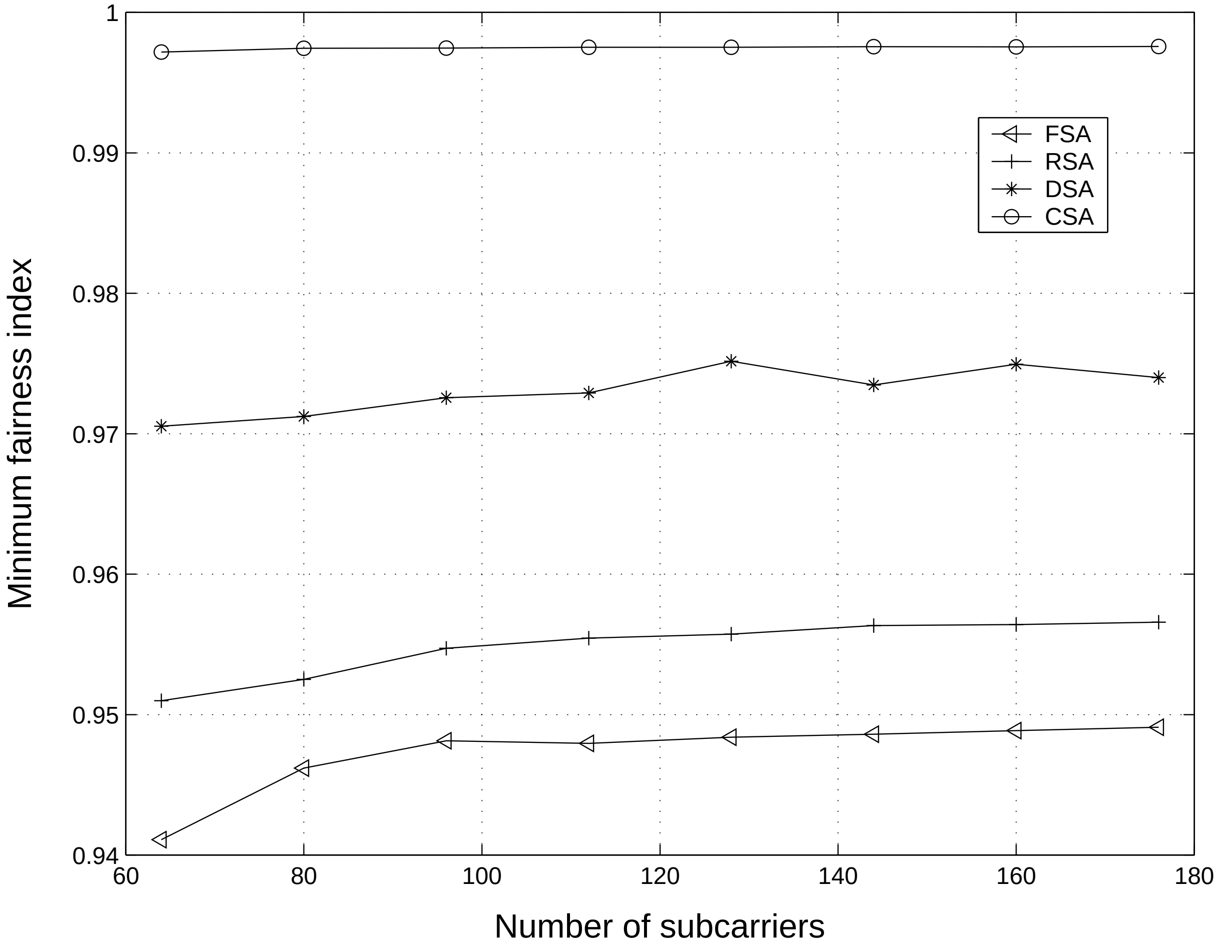

Fig. 4.8: The worst case of fairness when the number of subcarriers changes.

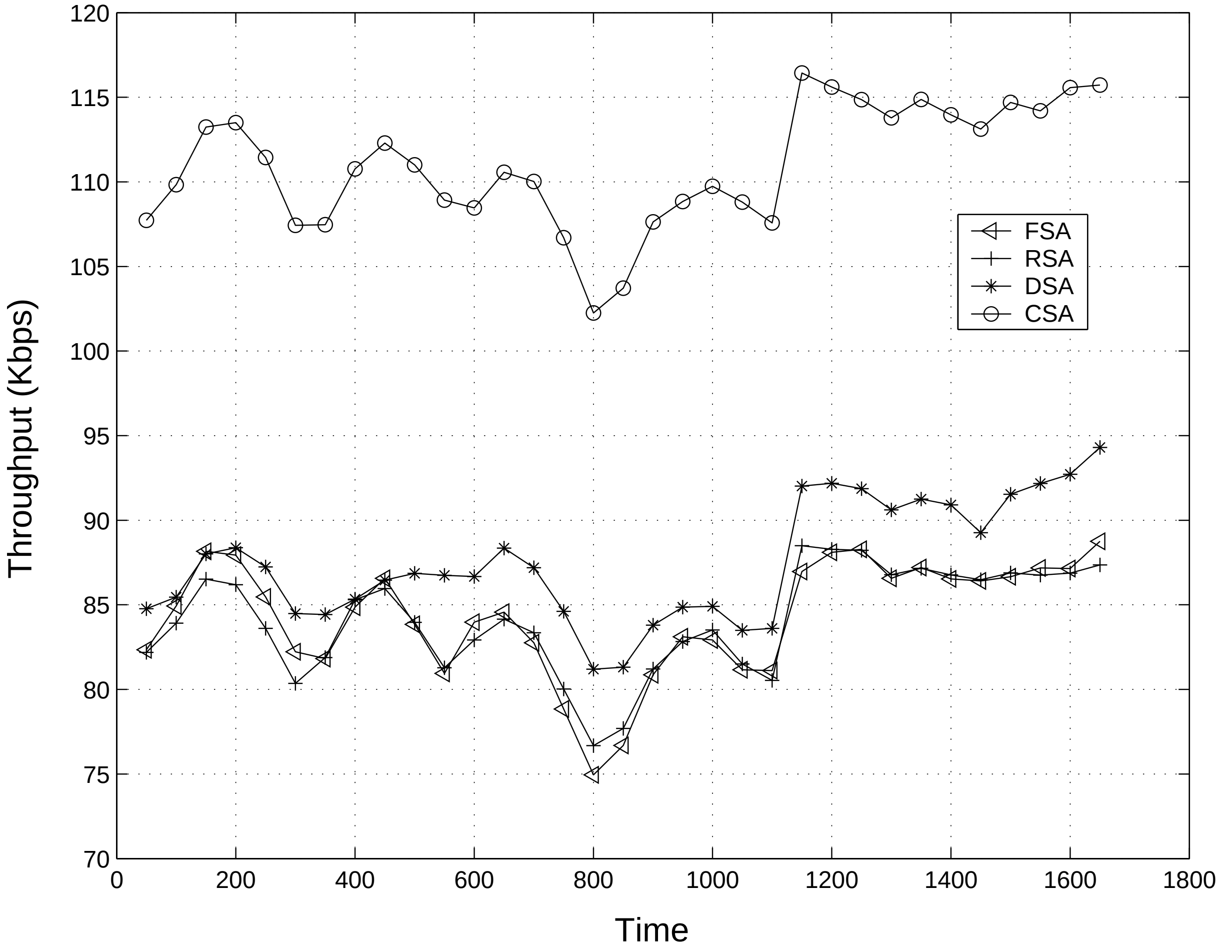

Fig. 4.9: Comparison of system throughput.

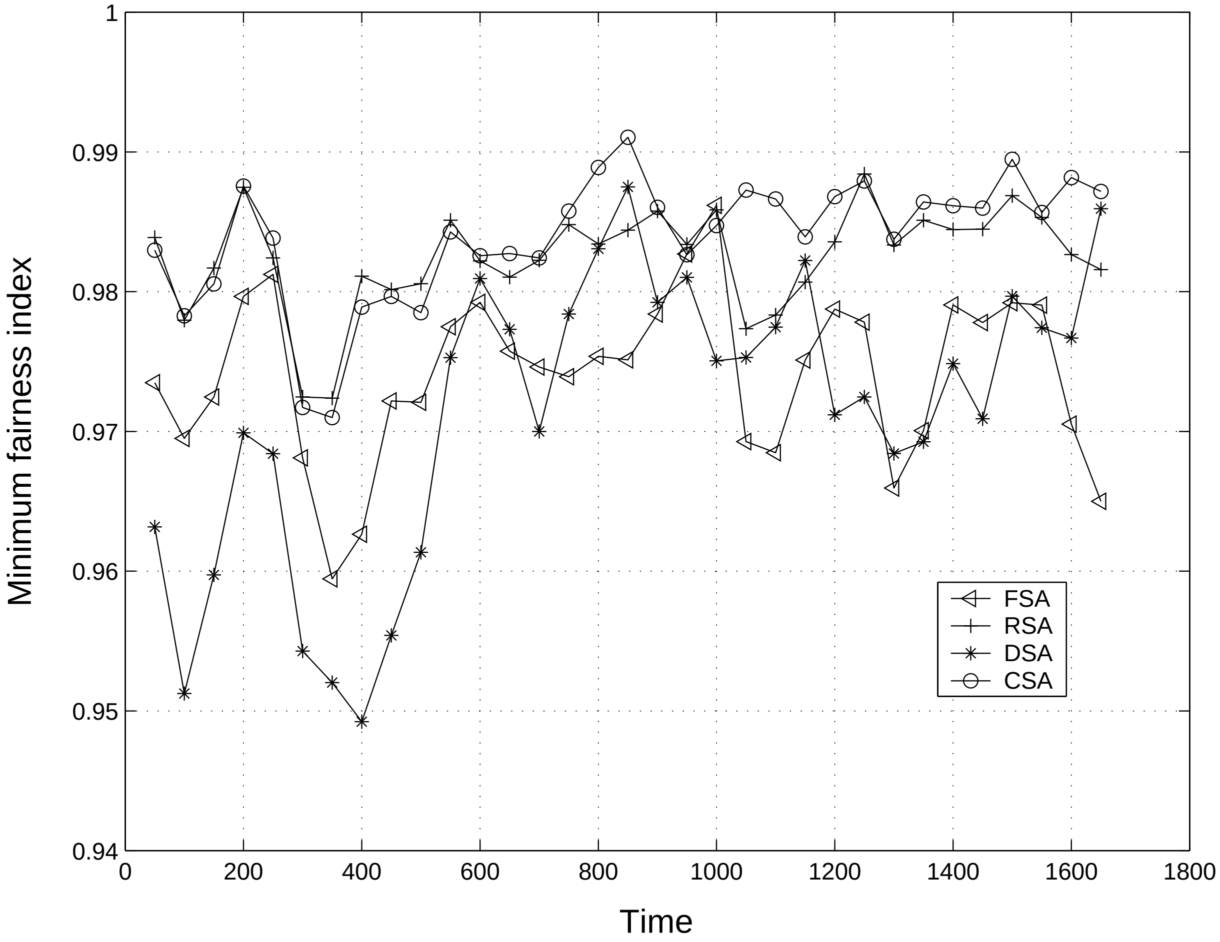

Fig. 4.10: Comparison of fairness performances.

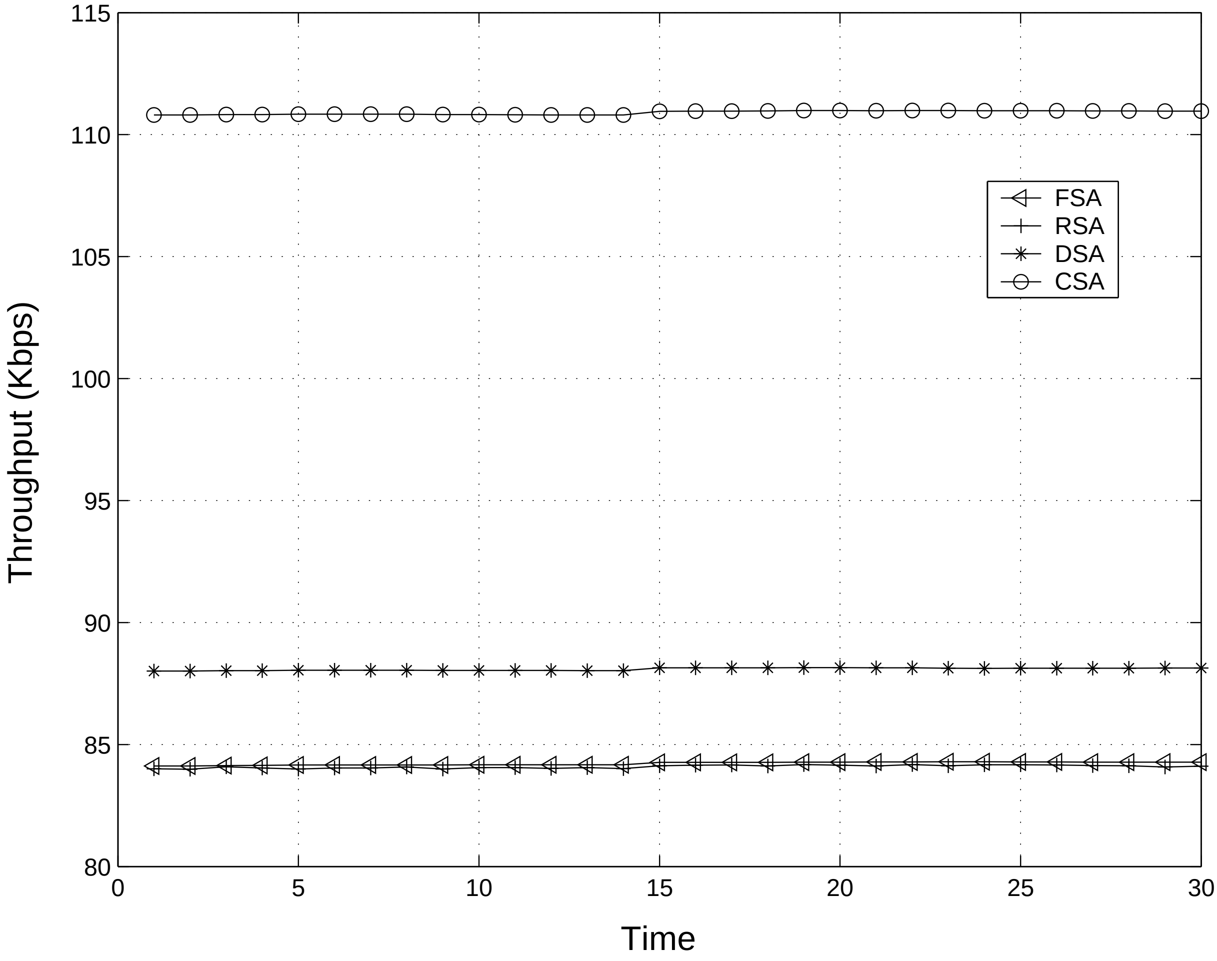

Fig. 4.11: Mean throughput performances

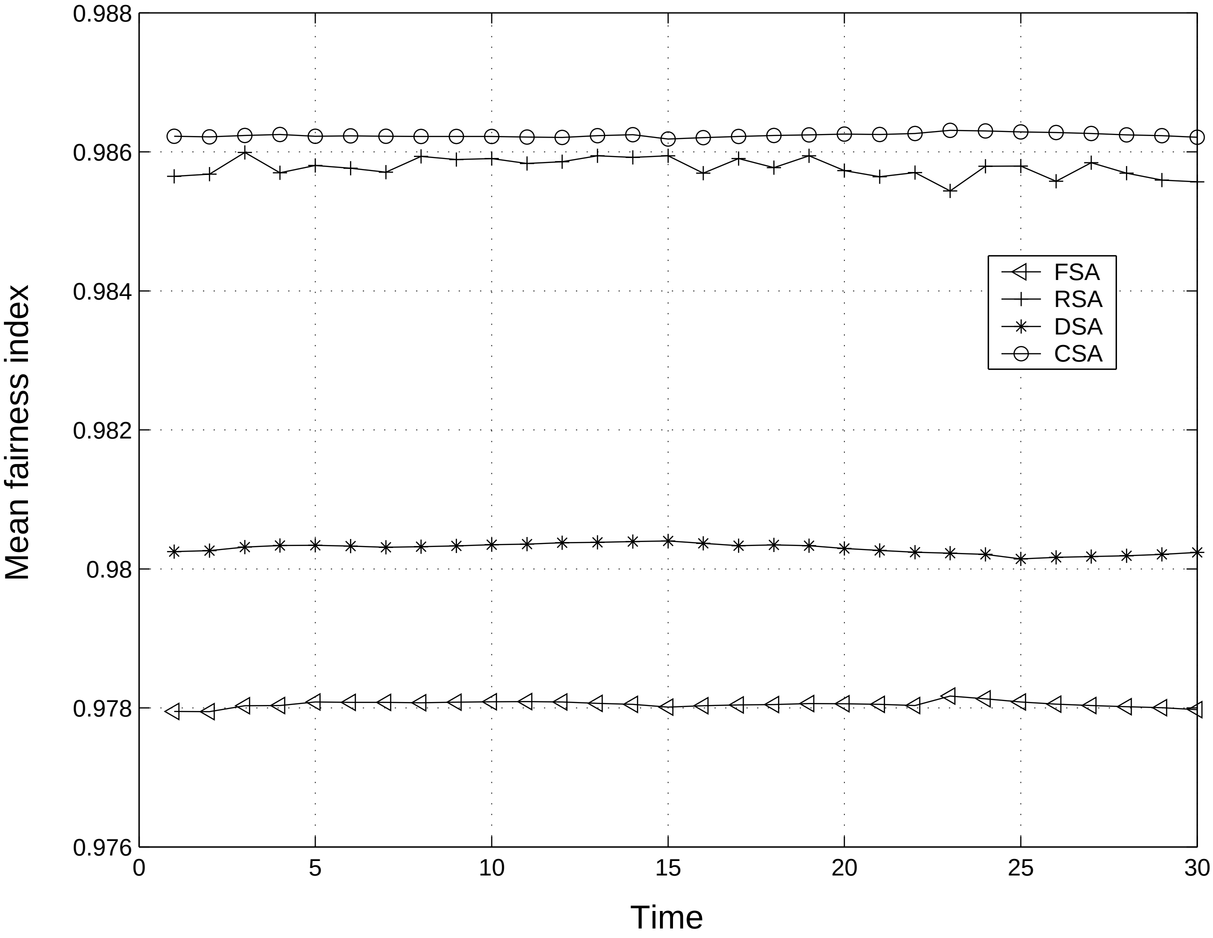

Fig. 4.12: Mean fairness performances

Chapter 5

Concluding Remarks

The objective of this thesis is to exploit both frequency diversity and multiuser diversity with adopting dynamic resource allocation in OFDMA systems to improve the system performances. This thesis includes the following research topics:

1. Analyze the frequency diversity and multiuser diversity gains in the multicarrier OFDMA systems.

2. Demonstrate that the simple maximum carrier-to-interference (C/I) scheduling scheme can both enhance system throughput and maintain fairness performances for OFDMA systems.

3. Observe the specific characteristics of the OFDMA channel.

4. Propose a resource allocation scheme that exploits frequency diversity and multiuser diversity and makes use of the specific OFDMA channel characteristics to enhance throughput of non-real-time services; while satisfying the delay constraint of real-time services

5. We provide a service-oriented water-pouring resource allocation scheme and cross-layer design.

5.1 Throughput and Fairness Enhancement for OFDMA Broadband Wireless Access Systems Using the Maximum C/I Scheduling

In Chapter 3 and [42], we have demonstrated that the simple maximum carrier-to-interference scheduling scheme can be a fair scheduler in the OFDMA system, although it is viewed as an unfair scheduling scheme in the single carrier TDMA/CDMA systems. Using this simple maximum C/I scheduling algorithm in the OFDMA system can exploit multiuser diversity and frequency diversity thoroughly, thereby achieving both high throughput and good fairness performances. Moreover, using this simple maximum C/I scheduling algorithm can combat the worse channel effect and observe the good fairness performance in a multiuser OFDM system.

5.2 Channel-aware Subcarrier Allocation and QoS Provisioning for OFDMA Systems with Multi-type Traffic

In Chapter 4 and [43], we propose an efficient QoS provisioning subcarrier allocation scheme to satisfy QoS requirements of multi-type services. By queueing analysis, we satisfy the demand of real-time users. Besides, we observe the channel characteristics of OFDMA systems and make use of it to improve the system performance. Furthermore, we exploits frequency diversity and multiuser diversity to enhance throughput and maintain the fairness performance of non-real-time service with considering delay constraint of real-time service.

5.3 Suggestion for Future Work

For the future research of the thesis, we provide the following suggestions to extend our work:

- Combine rate adaptation and power allocation techniques to enhance the system performances with considering channel characteristics.
- Compare the performances of scheduling schemes among CDMA and OFDMA systems. Furthermore, we can try to make use of this approach in the multi-carrier CDMA (MC-CDMA) systems.
- Considering more types of service flows, such as voice, video, data and other applications with different traffic models and QoS requirements.
- To design a criterion to describe the tradeoff between throughput and fairness.

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Vita

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