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A Cross-layer Packet Scheduling and Subchannel Allocation Scheme in 802.16e OFDMA System

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***Abstract*— The IEEE 802.16e standard is a rapidly developing technology for broadband wireless access system. Its PHY OFDMA mode defines two subchannel building methods: diversity permutation and contiguous permutation (AMC subchannel). In this paper we propose a joint packet scheduling and subchannel allocation scheme applicable for the IEEE 802.16e OFDMA AMC subchannel. Since it is a multiuser, multi-service and multichannel packet-switched system, we define a distinct scheduling priority for each packet on each subchannel that integrates MAC QoS requirements, service type and PHY Channel State Information (CSI). Based on these scheduling priorities and specific scheduling mechanism, efficient QoS guaranteed resource allocation is achieved in our scheme. Intensive simulations show that our scheme outperforms throughput-oriented Maximum C/I (MCI) and QoS-oriented Priority schemes under various conditions.**

I. INTRODUCTION

The IEEE 802.16e standard (or WiMAX) is an emerging broadband wireless access technology to provide users with high speed multimedia services. In physical layer 802.16e defines multiple modes: PHY SC, SCa, OFDM and OFDMA [1]. Moreover, for OFDMA system, two types of subchannel building methods: diversity subcarrier permutation and contiguous subcarrier permutation (AMC subchannel) are defined to support various types of physical channel condition. The former draws sub-carriers pseudo-randomly to form a subchannel. It provides frequency diversity and inter-cell interference averaging. The latter groups a block of contiguous subcarriers to form a subchannel which enables multiuser diversity by choosing the subchannel with the best frequency response. The multiuser diversity gain promotes system throughput substantially while it requests AMC scheduler to consider PHY channel state information (CSI) as well as MAC QoS requirements. Besides, separate QoS-oriented packet scheduling and throughput-oriented subchannel allocation will result in inefficient resource utilization. Due to these considerations, in this paper we propose a MAC-PHY cross-layer scheduling scheme that joins packet scheduling and subchannel allocation together for AMC subchannel.

For both the IEEE 802.16 and general OFDMA systems, there are many papers aiming at resolving the scheduling problem. In [2], the author presents a solution for the IEEE 802.16 PHY SC and OFDM system in that the scheduler schedules a single connection at a time. The strategy proposed in [3] is QoS-oriented in which the adverse channel conditions are compensated. Because PHY OFDMA diversity subchannel provides such compensation and AMC does not, the strategy is suitable for diversity subchannel only. [4] gives out a cross-layer adaptation architecture for the IEEE 802.16e OFDMA while concrete scheduling scheme is uncertified. There are a lot of works on the scheduling of general OFDMA systems like [5], [6] and [7]. In [6], the author defines a novel cost function-utility. Nevertheless, the scheme can not schedule real time (RT) and non real time (NRT) services simultaneously. [7] resolves the problem whereas it is based on fluid flow model and each connection takes up a subchannel per frame. It overlooks the burst nature of packets and cannot take advantage of the statistical multiplexing gain.

The IEEE 802.16e OFDMA system is a multiuser, multi-service and multi-channel packet-switched network. The schemes presented above do not cover all these aspects and hence cannot be directly applied. As far as our scheme is concerned, it defines a distinct scheduling priority for each packet on each subchannel that integrates MAC QoS requirements, service type and PHY CSI. Based on these scheduling priorities and specific scheduling mechanism, efficient QoS guaranteed resource allocation is achieved in our scheme.

The rest of the paper is organized as follows. In Section II, the IEEE 802.16e AMC subchannel composition manner is given. Section III describes the optimal allocation target and introduces our scheme in detail. Then in Section IV, the scheme performance is investigated through simulation. Finally the paper is concluded in Section V.

II. SUBCHANNEL COMPOSITION MANNER IN 802.16E OFDMA AMC SUBCHANNEL

In this section, we briefly specify the subchannel composition manner in the IEEE 802.16e OFDMA AMC subchannel. As stated above, contiguous subcarriers are grouped together to form a subchannel in this mode. We refer to Fig.1 for further description.

Fig.1 is the time-frequency structure in the IEEE 802.16e OFDMA AMC subchannel. First a bin consists of 9 contiguous subcarriers in a symbol, with 8 assigned for data and one assigned for a pilot as shown in Fig.1. The position of the

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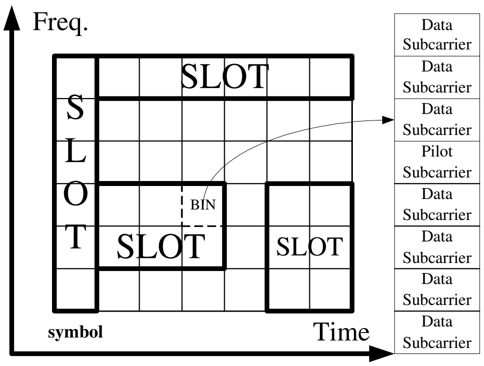

Fig. 1. Time-Frequency Structure in 802.16e OFDMA AMC

TABLE I
A SUMMARY OF SYSTEM PARAMETERS

System BW	10MHz
Sampling BW	11.2MHz
FFT size	1024
frame time	5ms
DL No. of slots	10
N_{used}	864
Number of subchannels	48

pilot is predefined. Then a slot, the minimum possible data allocation unit, is defined as a collection of bins of the type ($N * M = 6$), where N is the number of contiguous bins and M is the number of contiguous symbols. Thus the allowed combinations are (6 bins, 1 symbol), (3 bins, 2 symbols), (2 bins, 3 symbols) and (1 bin, 6 symbols). They are all depicted in this figure. Finally the bandwidth of a subchannel equals to the bandwidth of N contiguous bins.

The standard defines four system bandwidths: 1.25M, 5M, 10M and 20M with corresponding subcarriers number: 128, 512, 1024 and 2048. In this study, we select the 10M system bandwidth and (2 bins, 3 symbols) combination to demonstrate our scheme, and all the other combinations can be obtained in the same way. In this combination, 160 subcarriers are reserved for guard subcarriers and DC subcarrier with the rest 864 ones used for data and pilot. The modulation and coding (MC) scheme is determined by the adaptive modulation coding (AMC) table based on the instantaneous signal-noise-ratio (SNR) prescribed in [1]. A summary of system parameters is shown in Tab. I.

III. ALGORITHM DESCRIPTION

In this section we first describe the optimal allocation algorithm and then our algorithm is introduced in detail as a practical one. The IEEE 802.16 system defines four types of service: Ungranted Service (UGS), real time Polling Service (rtPS), non real time Polling Service (nrtPS) and Best Effort (BE). Because of the constant-rate requirements of UGS in the MAC, we presume fixed numbers of symbols are allocated for UGS ahead of scheduling and thus it is reasonable not considering UGS service in our analysis.

A. Optimal Resource Allocation

Basically this paper investigates a downlink OFDM system with N subchannels and M time slots. We suppose that there are K users, J connections and L packets in the system. The objective of the resource allocation is to maximize the overall system throughput while guaranteeing the provision of QoS, which is formulated into the following constrained optimization problem:

$$\arg \max_{C_i(m,n),\ g(j)} \sum_{i=1}^{L} \sum_{m=1}^{M} \sum_{n=1}^{N} C_i(m,n) R_i(m,n) \qquad (1)$$

subject to

$$\sum_i C_i(m,n) - 1 \leq 0, C_i(m,n) \in \{0,1\} \quad \forall\ m,n \qquad (2)$$

$$W_i \leq T_j \quad \forall\ i,\ i \rightarrow j \qquad (3)$$

$$g(j) \geq \min(\frac{C_{min}(j)}{d(j)}, P_j(t)) \quad \forall\ j \qquad (4)$$

where $C_i(m,n)$ identifies whether packet i is allocated to slot (m,n) and $R_i(m,n)$ is equivalent data rate packet i can obtain on this slot. Since CSI is usually assumed to keep constant per frame, it simplifies as $R_i(n)$. (2) is to ensure one slot can only be allocated to one packet while (3) and (4) correspond to the QoS requirements in terms of delay and throughput. Here T_j and $C_{min}(j)$ are maximum latency of rtPS connection and minimum reserved data rate of nrtPS connection respectively with $d(j)$ being connection j's packet length and $P_j(t)$ being number of packets present in connection j. Moreover, W_i denotes waiting time of packet i and $g(j)$ is number of connection j's scheduled packets.

The optimization problem above is an interesting topic for further study. However, the optimal solution is of no viability in practice due to practical considerations such as the implementation complexity of modulator/demodulator, the limited capacity of MAP message defined in the standard to inform users on which slots their packets are loaded and so on. Thus here we propose a practical scheme that allows trade-off between implementation complexity and spectrum efficiency.

B. Proposed Algorithm Description

Our algorithm can be mainly divided into two phases as below: (1) First we design the scheduling priority of each packet based on its channel quality, QoS satisfaction, and service priority. As a packet has diversified channel qualities on different subchannels, priorities of one packet vary over subchannels. Thus for each subchannel we can obtain one particular scheduling priority queue. (2) Then we search a valid subchannel which has free space available and is out of deep fading. From scheduling priority queue of this valid subchannel obtained in (1), we get the packet with the highest scheduling priority on this subchannel. However, the packet may have highest priority on more than one subchannels. To maximize the system throughput, we should choose the best subchannel for this packet in the subchannel set in which the packet owns the highest priority. Finally we allocate the packet on this very subchannel. This procedure is repeated until no packet is to be transmitted or the valid subchannels are used up.

1) Design of Scheduling Priority: As mentioned above, we design the scheduling priority of each packet based on its channel quality, QoS satisfaction, and service priority. For each type of service, QoS satisfaction has a distinct definition and it necessitates classifying service type of packets when defining their scheduling priorities [2].

For a rtPS packet i, we define $\Phi_{i,n}$, its scheduling priority on subchannel n as

$$\Phi_{i,n} = \begin{cases} \beta_{rtPS} \frac{R_i(n)}{R_{max}} \frac{1}{F_i} & \text{if } F_i \geq 1, R_i(n) \neq 0 \\ \beta_{rtPS} & \text{if } F_i < 1, R_i(n) \neq 0 \\ 0 & \text{if } R_i(n) = 0 \end{cases} \quad (5)$$

$$F_i = \frac{T_j - W_i}{T_g} \quad (6)$$

β_{rtPS} is the priority of rtPS over other types of service, which is similar to PQ (Priority Queue) scheduling in wireline system. $\frac{R_i(n)}{R_{max}}$ is normalized data rate with R_{max} being the highest MC mode. $R_i(n) = 0$ denotes packet i under deep fading on subchannel n and should avoid being scheduled. F_i is the service satisfaction level packet i obtains, which is defined as the ratio of waiting time packet i can continue enduring to the guard time. Suppose $F_i < 1$, in other words, the time packet i can continue to wait is smaller than guard time T_g. At this time, the priority of packet i is promoted to β_{rtPS} enabling the scheduling precedence over other packets. Usually T_g is set as frame length, i.e., interval between two times of scheduling. In case not scheduled, packet i will exceed the maximal delay, be deemed invalid and discarded at the time of next scheduling. On the other hand, if $F_i \geq 1$, the scheduling priority becomes directly related to the CSI packet i experiences on subchannel n. Intuitively good CSI upgrades scheduling opportunity and vice versa.

Similarly, for a nrtPS packet i, $\Phi_{i,n}$ is defined as

$$\Phi_{i,n} = \begin{cases} \beta_{nrtPS} \frac{R_i(n)}{R_{max}} \frac{1}{F_i} & \text{if } F_i \geq 1, R_i(n) \neq 0 \\ \beta_{nrtPS} & \text{if } F_i < 1, R_i(n) \neq 0 \\ 0 & \text{if } R_i(n) = 0 \end{cases} \quad (7)$$

$$F_i = \frac{\overline{C}_j(t)}{C_{min}(j)}, \quad i \to j \quad (8)$$

$$\overline{C}_j(t+1) = \overline{C}_j(t)(1 - 1/t_c) + C_j(t)/t_c \quad (9)$$

where β_{nrtPS} is the priority of nrtPS service. F_i for nrtPS packet i is determined by its connection j in that it is defined as ratio of average throughput of connection j over the prescribed minimum reserved data rate. The average throughput is estimated during a time window t_c. Obviously packets of a single nrtPS connection have the same priority over one subchannel and we only need calculate once for one connection's packets. Suppose $F_i < 1$, i.e., nrtPS connection's average throughput is less than its prescribed minimum reserved rate, scheduling priorities of this connection's packets are upgraded to β_{nrtPS}.

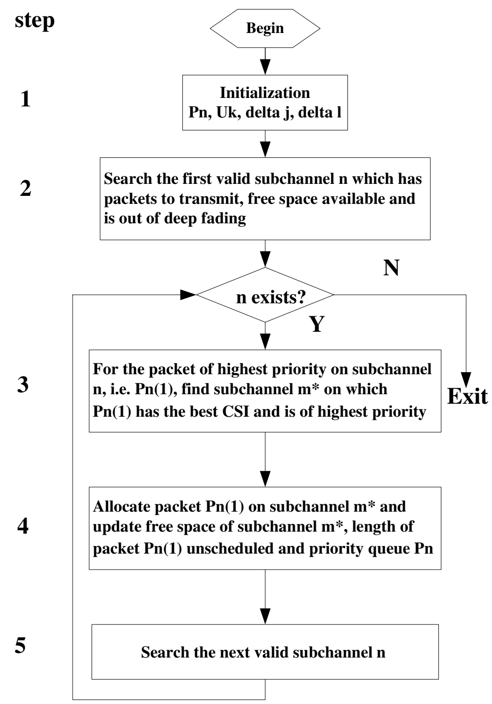

Fig. 2. Allocation Algorithm Flow Chart

Similar to design in rtPS service, once QoS is met, scheduling priorities are immediately connected to packets' CSI. The larger the CSI, the higher the priority. In fact, the design is a transformation of PF scheduling, which proves to be the optimal utility-based scheduling scheme [6].

Finally for a BE packet i, we define $\Phi_{i,n}$ as

$$\Phi_{i,n} = \beta_{BE} \frac{R_i(n)}{R_{max}} \quad (10)$$

where β_{BE} is the priority of BE service. Since no QoS requirements are prescribed for BE service in the standard, its priority is only related to CSI and service type.

2) The Packets Allocation Scheme: The algorithm flow chart is shown in Fig.2.

- Step one: After calculation of $\Phi_{i,n}(n \in \{1, 2, ..., N\})$, we get N priority queues corresponding to N subchannels

  $$P_n = \{i_1, i_2, \cdots, i_L : \Phi_{i_1,n} \geq \Phi_{i_2,n} \geq \cdots \geq \Phi_{i_L,n}\}$$

  where First In First Out (FIFO) is applied for packets with the same priority.
  Ordering from the best subchannel to the worst one, the user k's channel quality queue $U_k(k \in \{1, 2, ..., K\})$is defined as

  $$U_k = \{n_1, n_2, \cdots, n_N : \gamma_{k,n_1} \geq \gamma_{k,n_2} \geq \cdots \geq \gamma_{k,n_N}\}$$

  $$\Delta j = M(1 \leq j \leq N), \Delta l = d(l)(1 \leq l \leq L)$$

  Δj denotes the available space of subchannel j; Δl indicates length of unscheduled part of packet l; $d(l)$ is the initial length of packet l.

TABLE II

SIX TAP MODEL

tap number	1	2	3	4	5	6
tap delay (ns)	0	100	200	300	400	500
tap power (dB)	0	-6	-12	-18	-24	-30

- Step two: Search the first valid subchannel n.

  $$V = \{n : P_n \neq \phi, \Delta n \neq 0, R_{P_n(1)}(n) \neq 0\}, n = min(V)$$

  $P_n \neq \phi$ indicates subchannel n has packets to transmit, $\Delta n \neq 0$ implies free space is available on subchannel n. Then $P_n(1)$ denotes the packet with the highest priority on subchannel n and $R_{P_n(1)}(n) \neq 0$ excludes the possibility that subchannel n falls in deep fading.
- Step three: If valid subchannel n exists, search the best subchannel $m^\star$ for packet $P_n(1)$. $m^\star \in \{m : P_m(1) = P_n(1)\}$ and $m^\star$ queues the first in U_k, where packet $P_n(1)$ belongs to user k.
- Step four: $\Delta P_n(1)$ denotes length of untransmitted part of packet $P_n(1)$ while $\Delta m^\star$ represents the free space of subchannel $m^\star$. And finally P_n is the N priority queues. The calculation of the number of slots that packet $P_n(1)$ takes up is denoted as S.
  If $S \leq \Delta m^\star$, $\Delta P_n(1) = 0, \Delta m^\star = \Delta m^\star - S$
  else

  $$\Delta P_n(1) = \Delta P_n(1) - \Delta m^\star * Th_{P_n(1)}(n), \Delta m^\star = 0$$

  $Th_{P_n(1)}(n)$ is the slot unit capacity of packet $P_n(1)$ on subchannel n. The former hypothesis corresponds to the situation that subchannel $m^\star$ has enough space for packet $P_n(1)$ while the latter does not. Finally, delete all transmitted packet from $P_n(n \in \{1, 2, ..., N\})$.
- Step five: Search the next valid subchannel.
  Update valid subchannel set V. If V is empty, the allocation is finished. If some elements in V are larger than n, n is updated to the first such element, else updated to the first element in V. Then go to step three.

IV. SIMULATION RESULTS

A. Simulation Configuration

In this section we investigate the performance of the proposed scheme by comparing it with that of Maximum C/I (MCI) and Priority scheduling schemes. On one hand, MCI schedules packets on certain subchannels according to SNR of packets on these subchannels and first selects the pair of user and subchannel owning the best SNR. If the user has packets to transmit and free space is available on the subchannel, MCI schedules this user's packets on the subchannel. Then goes to the next pair of user and subchannel with smaller SNR and repeats the operation until no packets are to be transmitted or no free subchannels are available. On the other hand, Priority scheduling is a transformation of proposed algorithm by omitting the CSI dimension ($\frac{R_i(n)}{R_{max}}$) in the design of scheduling priorities. Therefore there exists one single priority queue for all subchannels. Finally packets are scheduled according to the queue and then for these scheduled packets best subchannels are selected. Essentially this scheduling manner is an enhancement of the hierarchical mechanism in [3]. When QoS of a certain packet is satisfied, it is scheduled the way similar to the hierarchical scheme.

TABLE III

SCENARIO ONE

user ID	rtPS	nrtPS	BE
1	1 ppf, 30 ms	1 ppf, 350$kbits$	2 ppf
2	1 ppf, 30 ms	2 ppf, 700$kbits$	2 ppf
3	1 ppf, 25 ms	1 ppf, 350$kbits$	2 ppf
4	1 ppf, 25 ms	2 ppf, 700$kbits$	2 ppf
5	1 ppf, 20 ms	1 ppf, 350$kbits$	2 ppf
6	1 ppf, 20 ms	2 ppf, 700$kbits$	2 ppf
7	1 ppf, 15 ms	1 ppf, 350$kbits$	2 ppf
8	1 ppf, 15 ms	2 ppf, 700$kbits$	2 ppf
9	1 ppf, 10 ms	1 ppf, 350$kbits$	2 ppf
10	1 ppf, 10 ms	2 ppf, 700$kbits$	2 ppf

In the simulation we suppose there are 10 users in the system and each has a rtPS, nrtPS and BE connections respectively. Here we heuristically define length of rtPS packets 1024 bits, nrtPS 2048 bits, BE 4096 bits and priorities of each type of service as: $\beta_{rtPS} = 1.0, \beta_{nrtPS} = 0.8, \beta_{BE} = 0.6$. Moreover, we assume that packet arrival process is Poisson distributed, each connection with its own average arrival rate. CSIs of different users are independent from each other. We use Jakes model [8] to incorporate Doppler shift. The carrier frequency is 3.2 GHz and user velocity is 50 km/h. Multipath model is in Tab.II. We simulate two scenarios: users with the same average received SNR but different traffic loads; and users with different SNRs but the same traffic load.

- Scenario one: The same SNR implies the distances between all the users and BS are identical. Configuration is in Tab.III. Besides service source traffic, QoS parameters in terms of maximum latency for rtPS packets and minimum reserved data rate for nrtPS connections are given as well. Here "ppf" means "packets per frame" and we set the minimum reserved rate to be 85% of average data rate as usually defined in the standard.
- Scenario two: Ten users are classified into three groups with SNRs [12,12,12,15,15,15,15,18,18,18](dB). Their traffic load is the same as the user 2 in Tab.III.

B. Performance Evaluation

1) Scenario One: In Fig.3, overall system throughput under different scheduling schemes is investigated. We can see that in the low SNR region, performance of proposed algorithm is closer to that of Priority scheduling when they are both low. Nevertheless proposed performs a bit but undeniably better than Priority. Then in a specific area (11dB-12dB) a great improvement of proposed scheme's performance occurs in that its system throughput immediately rises to the vicinity

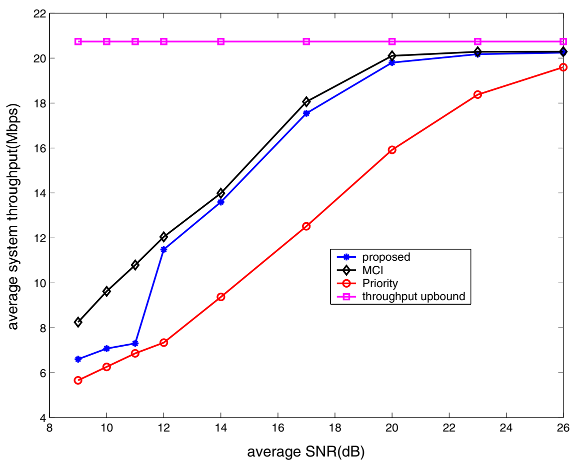

Fig. 3. System Throughput vs. Average SNR

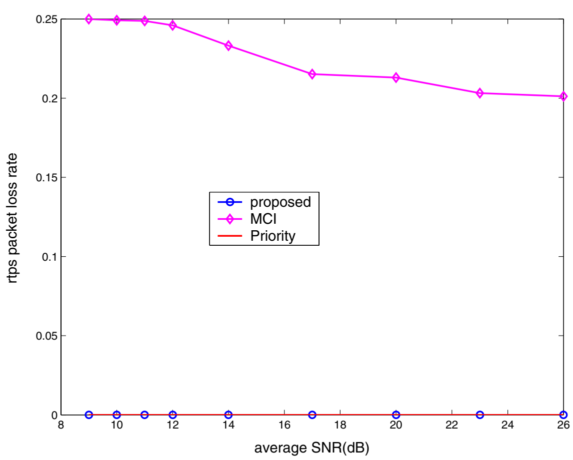

Fig. 4. rtPS Packet Loss Rate vs. Average SNR

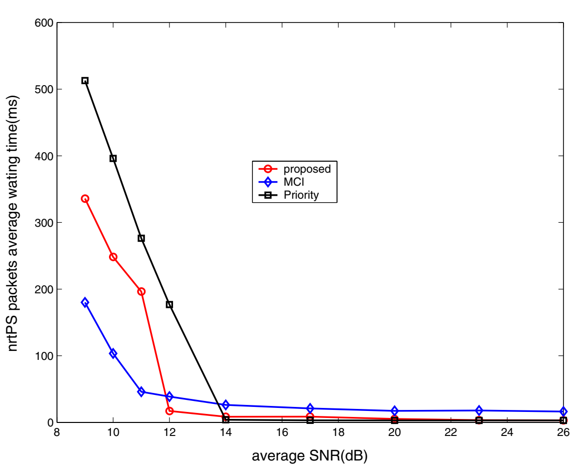

Fig. 5. nrtPS Packets Average Waiting Time vs. Average SNR

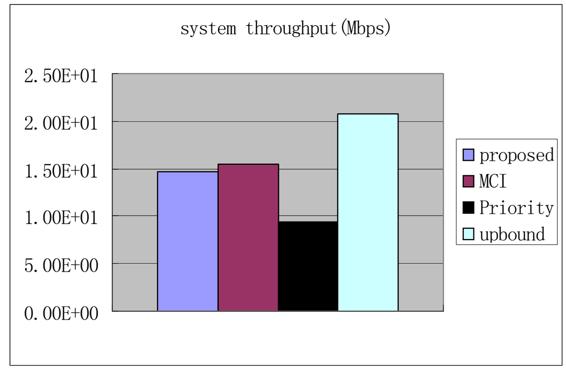

Fig. 6. System Throughput Comparison

of MCI's. The leap is due to the incontinuity in our design of scheduling priority. Once QoS of a packet is meet, its priority becomes directly related to its CSI. After the leap, still a slim gap exists between proposed and MCI because MCI schedules packets and users just by CSI while proposed scheme also concerns about QoS requirements. However, they are both much higher than Priority, for Priority does not take CSI into account and cannot utilize good subchannels. When SNR is large enough, system throughput achieves its limit. It can be seen that capacity limits of MCI and Proposed still have a deficiency compared to theoretical capacity upperbound. Inability to make full use of slots' space explains the point.

Though MCI performs slightly better than proposed in terms of system throughput, Fig.4 shows it is much inferior to our proposed scheme in the rtPS packet loss rate (PLR) comparison. Here PLR is defined as the ratio of overtime packets to transmitted the ones. MCI's performance is awful because it just cares about users' CSI and totally ignores the QoS requirements. Under this assumption, it is common that transmission of NRT packets of users with good CSIs blocks that of rtPS packets of users with not so good ones. The phenomenon results in high PLR for users of the latter type. Contrary to MCI, both proposed and Priority schemes concern about QoS. Under this traffic setting and in our simulation time, no rtPS packets are lost under the two strategies.

nrtPS packets waiting time is closely related to the terminal users' experience and is an important metric to evaluate. Then the waiting time under these three schemes are compared in Fig.5. In the low SNR region where QoS is not satisfied (smaller than 12dB), the proposed scheme outperforms Priority because the transmission opportunities are given to nrtPS packets with good CSI instead of rtPS with bad channel state. Moreover, at this time MCI performs much better than the proposed and Priority because of larger overall throughput and more discarded rtPS packets. When QoS is fulfilled, Priority's performance is trivially better than the proposed and finally equals it as SNR rises. The slight superiority of Priority is because nrtPS packets do not strictly precede BE packets in proposed scheme. In other words, portion of nrtPS' bandwidth is allocated to BE service.

TABLE IV
RTPS PACKET LOSS RATE

	group 1	group 2	group 3
proposed	0	0	0
MCI	0.4867	0.0375	0
priority	0	0	0

TABLE V
NRTPS PACKETS AVERAGE WAITING TIME(MS)

	group 1	group 2	group 3
proposed	350.67	64.383	8.291
MCI	1945.5	23.619	5.067
priority	264.6	290.4	269.6

2) Scenario Two: we compare the system throughput of these scheduling strategies under the given traffic setting in Fig.6. Obviously the proposed and MCI have 50% gain over Priority. Reasons resulting in gaps between these schemes are already illustrated in scenario one. Tab.IV is the rtPS PLR comparison. The severe PLR of users with a bad SNR under MCI scheme excludes it as a candidate. In addition, Tab.V is nrtPS average waiting time. It can be seen that nrtPS waiting time of users with good CSI is substantially less than that of users with bad one in proposed scheme. We can deduct that in case QoS is sufficient, the proposed algorithm grants enormous precedence to users of the former type over those of the latter. Differ from it, performance of all the users are almost the same in Priority scheme because users' diverse CSIs have nothing to do with the scheduling scheme. Finally Tab.VI is the fairness comparison. Since traffic loads of each user are identical, the disparity between users stems from varied CSIs. We just consider the NRT service in fairness comparison because rtPS is almost totally served. We use the fairness index defined by Jain [9] to evaluate the degree of fairness for each algorithm. This fairness index is defined as:

$$FairnessIndex = \frac{(\sum_i \frac{T_i}{\alpha_i})^2}{K \sum_i (\frac{T_i}{\alpha_i})^2}$$

where K is the number of users, T_i is the sum throughput of nrtPS and BE of user i , α_i is the weight of the user (we assume all users have the same weight in the simulation due to the same SNR). From Cauchy-Schwartz inequality, we obtain $FairnessIndex \leq 1$, the equality holds if and only if all $\frac{T_i}{\alpha_i}(i = 1, 2, ..., N)$ are equal. The definition implies that the higher the fairness index (i.e., closer to 1), the better in terms of fairness. From Tab.VI, we conclude that our proposed scheme's fairness is between MCI and Priority's.

TABLE VI
FAIRNESS INDEX COMPARISON

Scheduling scheme	Fairness index
proposed	0.7691
MCI	0.7058
priority	1.0000

V. CONCLUSIONS

In this paper, we propose a cross-layer packet scheduling and subchannel allocation scheme appropriate for the IEEE 802.16e OFDMA AMC subchannel. Each packet admitted in the system is assigned a priority on each subchannel, which integrates QoS requirements, CSI and service priority. Then according to such priority queues on each subchannel and our proposed mechanism, efficient QoS guaranteed resource allocation is achieved. On the one hand, the scheme satisfies the maximal delay requirement of rtPS connections as well as the minimum reserved rate of nrtPS sessions. On the other hand, it exploits multiuser diversity by choosing users with good CSI and thus greatly enhances spectrum efficiency. Comparison of our scheme with MCI and Priority schemes are carried out by intensive simulations and the results show that our scheme can have better performance under various conditions.

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