User Based Resource Scheduling for Heterogeneous Traffic in the Downlink of OFDM Systems

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Abstract—Besides avoiding inter-symbol interference and leading to high capacity, wireless orthogonal frequency division multiplexing (OFDM) provide fine granularity for resource allocation since they are capable of dynamically assigning sub-carriers to multiple users and adaptively allocating transmit power. The current dominate layered networking architecture, in which each layer is designed and operated independently, results in inefficient and inflexible resource use in wireless networks due to the nature of the wireless medium, such as time-varying channel fading. Thus, we need an integrated adaptive design across different layers. In this paper, we focus on resource allocation and scheduling in wireless multiuser OFDM networks based on joint physical and medium access control (MAC) layer optimization. An adaptive cross-layer design for the downlink multiuser OFDM systems, to maximize the weighted sum capacity of all users, where each user has multiple heterogeneous traffic queues simultaneously is proposed. A packet dependent (PD) scheduling scheme is employed at the MAC layer, which determines the packet transmission order by assigning different weights to different packets, and is shown by simulations more efficient than the previous methods where all packets in a queue have the same weight. The weight design in PD scheduling considers the delay, size and quality of service (QoS) priority level of packets. Each user weight employed in resource allocation at the physical (PHY) layer is obtained by summing up the weights of selected packets for the user. We also deeply investigate the various resource scheduling schemes for comparisons.

Keywords— Cross-layer design, quality of service, packet scheduling, orthogonal frequency division multiplexing systems.

1 Introduction

The allocation and management of resources are crucial for wireless networks, in which the scarce wireless spectral resources are shared by multiple users. In the current dominate layered networking architecture, each layer is designed and operated independently to support transparency between layers. Among these layers, the physical layer is in charge of raw bit transmission, and MAC layer controls multiuser access to the shared resources. However, wireless channels suffer from time-varying multipath fading; moreover, the statistical channel characteristics of different users are different. The sub optimality and inflexibility of this architecture result in inefficient resource use in wireless networks. We need an integrated adaptive design across different layers. Therefore, cross-layered design across the physical and MAC layers are desired for wireless resource allocation and packet scheduling [1]. For cross-layer design channel-aware scheduling strategies are proposed to adaptively transmit data and dynamically assign wireless resources based on channel state information (CSI). The key idea of channel-aware scheduling is to choose a user with good channel conditions to transmit packets [2]. Taking advantage of the independent channel variation across users, channel-aware scheduling can substantially improve the network performance through multiuser diversity, whose gain increases with the number of users [3]. To guarantee fairness for resource allocation and exploit multiuser diversity, utility-pricing structures in network economics are usually preferred for scheduling design [4]. The growth of Internet data and multimedia applications requires high-speed transmission and efficient resource allocation. To avoid inter-symbol interference, orthogonal frequency division multiplexing

(OFDM) is desirable for wireless high-speed communications. OFDM-based systems are traditionally used for combating frequency-selective fading. From a resource allocation point of view, however, multiple channels in an OFDM system naturally have the potential for more efficient MAC since subcarriers can be assigned to different users [5]. Another advantage of OFDM is that adaptive power allocation can be applied for a further improvement. The basic problem that we need to solve in this paper is how to effectively allocate resources on the downlink of Internet protocol (IP)-based OFDM networks by exploiting knowledge of CSI and the characteristics of traffic to enhance the system throughput and guarantee quality of service (QoS).

Section II presents the system model and problem formulation. The maximum weighted sum capacity (MWSC) based resource allocation is discussed in Section III. Channel aware, joint channel and queue aware, packet dependent resource scheduling schemes are analysed in Section IV. Section V shows the simulation results and Section VI draws the conclusion.

2 System Model & Problem Formulation

We consider a general downlink time division duplexing (TDD) OFDM system, where the base station can acquire the channel state information (CSI) through the uplink dedicated pilots from all mobile stations at the beginning of each time slot, and use it for resource allocation and scheduling. The subcarrier and power controller at the PHY layer performs subcarrier and power allocation, and the traffic controller at the MAC layer performs data scheduling. With a cross-layer design, the QoS information obtained by the traffic controller is transferred to the subcarrier and power controller for resource allocation, and the resource allocation results are feedback to the traffic controller in the base station for scheduling of the data to be sent out in each slot. The cross-layer scheduling architecture is depicted in the Fig.1.

We assume a total bandwidth of B which is divided into independent subcarriers and shared by K users. The total transmit power from the base station is assumed to be P_t. The OFDM signalling is time-slotted and each time slot is of length T_{slot} [6]. We consider a quasi-static fading channel, where the channel gain is constant during each slot and is independent of the channel for other slots. We assume that each user has I_k traffic queues with heterogeneous delay constraints for the queues. Define Ω_k as the index set of subcarriers allocated to user k. Without loss of generality and for simplicity, we assume that each subcarrier is allocated to only one user [7]. Let $p_{k,n}$ denote the power allocated to user k on subcarrier n, $h_{k,n}$ the corresponding channel gain, and N_0 the single-sided power spectral density of additive white Gaussian noise (AWGN). Assuming perfect channel estimation, the achievable instantaneous data rate of user k on subcarrier n is expressed as

$$R_{k,n} = \frac{B}{N}\log_2\left(1 + p_{k,n}.\gamma_{k,n}\right) \tag{1}$$

where

$$\gamma_{k,n} = \frac{\left|h_{k,n}\right|^2}{N_0 B / N} \tag{2}$$

is the channel-to-noise power ratio for user k on subcarrier n. The total achievable instantaneous data rate of user k is given by

$$R_k = \sum_{n\in\Omega_k} R_{k,n} \tag{3}$$

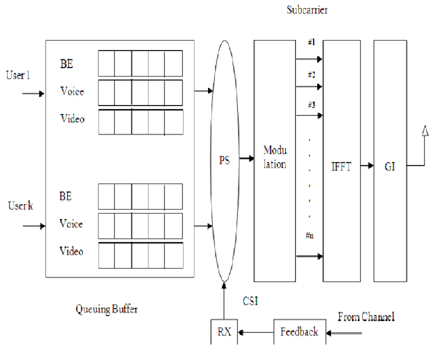

Fig.1 Cross-layer scheduling architecture

We employ a general maximum weighted sum capacity (MWSC) based cross-layer design, which is to maximize the weighted sum of all users instantaneous capacities [8]. Letting W_k denote the weight for user k, which contains the QoS information and is determined by scheduling at the MAC layer, the cost function to be maximized is given by

$$J = \sum_{k=1}^{K} W_k R_k \tag{4}$$

Subject to (C1) $p_{k,n} \geq 0$,

(C2) $\sum_{k=1}^{K}\sum_{n\in\Omega_k} p_{k,n} \leq p_T$,

(C3) $R_k T_{slot} \leq Q_k$,

$$\text{(C4)} \quad \Omega_1 \cup \ldots \cup \Omega_k \subseteq \{1,2,\ldots N\},$$

$$\text{(C5)} \quad \Omega_k \cap \Omega_j = \phi (k \neq j),$$

where Q_k is the queue length of user *k.* The constraint in (C3) is to guarantee that no more resource is allocated to the user *k* if the user already obtains sufficient resources to send all data out in current slot, to avoid waste of resources.

The above user based cross-layer design can be easily extended to the queue based cross-layer design, by replacing the user index *k* with the queue index *i.* Assuming that all users have *w* queues each, *i.e* $I_k = w$ there are total number of *wK* queues in the system. The queue based MWSC cross-layer design is to maximize the following cost function.

$$J = \sum_{i=1}^{wK} W_i R_i \tag{5}$$

The MWSC based cross-layer design is general in that the weights W_k and W_i can be obtained by using a wide range of scheduling schemes.

3 Maximum Weighted Sum Capacity Based Resource Allocation

To make a good trade off between complexity and performance, we propose a suboptimal resource allocation algorithm which performs subcarrier allocation and power allocation separately. We first perform subcarrier allocation, assuming equal power across all subcarriers, and then perform power allocation. With equal power on each subcarrier, the subcarrier allocation should assign subcarrier n to user *k* rather than user j, if $W_k R_{k,n} > W_j R_{j,n}$. After subcarrier allocation, power allocation is performed by using Karush-Kuhn-Tucker (KKT) conditions. Let Φ denote the user index set. The dynamic algorithm to implement the suboptimal MWSC based subcarrier and power allocation is described as follows

1) Initialize the set for all users and for all subcarriers

$$\Phi = \{1,2,\ldots k\}, \; R_k = 0, \Omega_k = \phi, \; p_{k,n} = \frac{p_T}{N} \tag{6}$$

2) For all the subcarriers, find

$$k^*(n) = \arg\max_{k \in \Phi} \{W_k R_{k,n}\} \tag{7}$$

3) Assign subcarrier *n* to user $k^*(n)$ and then update $k^*(n)$ carrier index and data rate.
4) Allocate the power to subcarrier by

$$p_{k,n} = \begin{cases} \dfrac{W_k \left(p_T + \sum_{m=1}^{K} \sum_{q \in \Omega_m} \dfrac{1}{\gamma_{m,q}} \right)}{\sum_{m=1}^{K} W_m \, |\Omega_m|} - \dfrac{1}{\gamma_{k,n}} & \mathrm{k} = \mathrm{k}^*(n) \\ 0 & \mathrm{k} \neq \mathrm{k}^*(n) \end{cases} \tag{8}$$

5) For all subcarriers if power is less than zero for particular user than there is no enough power for subcarrier n which has small weight and/or signal to noise ratio, thus subcarrier *n* will be ignored for power allocation.
6) Repeat the step 3 and 4 until the power is greater than zero.

4 Resource Scheduling Schemes

The weight of the MWSC based cross-layer design described in section III contain the QoS information, and can be obtained from scheduling at the MAC layer. In this section we will analyse the various resource scheduling schemes and then packet based scheduling scheme is proposed. Notice that all scheduling schemes are performed in every time slot and the weights are updated in every slot as well.

4.1 Maximum Sum Capacity

The maximum sum capacity (MSC) rule is a channel aware scheduling scheme that maximizes the total throughput in the system [9]. The weight is given by

$$w_k = 1 \tag{9}$$

Although the MSC rule makes the most efficient use of the bandwidth, it can lead to unfairness and instability, especially for non symmetrical channel conditions and non uniform traffic patterns.

4.2 Proportional Fairness (PF)

The PF scheduling is a channel aware scheduling rule aiming to maximize average data rate of user *k* [10]. The weight is given by

$$w_k = \frac{1}{\overline{R_k}} \tag{10}$$

4.3 Modified Largest Weighted Delay First Scheduling

The modified largest weighted delay first (MLWDF) [11] scheduling scheme is a queue based scheme designed using the cost function given by (5) and it can keep the delays of most queues below a bound. Letting U_i and $T_{HOL,i}$ respectively denote the delay tolerance and HOL packet delay for queue *i*, define

δ_i as the maximum allowed probability that $T_{HOL,i} > U_i$. The weight of queue *i* is given by

$$w_i = \frac{T_{HOL,i}\log(\delta_i)}{U_i \overline{R_i}} \quad (11)$$

Substituting (9) into (5), it can be deduced that with M-LWDF, the queue which has a higher HOL packet delay relative to the delay bound, a higher instantaneous data rate relative to the average data rate, and a higher requirement for outage probability is given a higher priority to be served.

4.4 Exponential Rule (EXP)

The EXP scheduling [10] rule is designed for single carrier CDMA networks with a shared downlink channel and it is a queue based scheduling scheme. The structure of the EXP rule is very similar to the M-LWDF, but with different weights. The multichannel version is given by

$$w_i = \frac{1}{\overline{R_i}} \exp\left(\frac{T_{HOL,i}}{1+\sqrt{\overline{T}_{HOL}}}\right) \quad (12)$$

4.5 Maximum delay utility scheduling (MDU)

The so-called MDU [10] scheduling scheme is to maximize the utility functions with respect to the delay. Define $f_i(\overline{T_{HOL,i}})$ as a decreasing utility function of the average HOL packet delay $\overline{T_{HOL,i}} = \frac{\overline{Q_i}}{\overline{\lambda_i}}$ for queue *i* ,where, $\overline{Q_i}, \overline{\lambda_i}, \overline{T_{HOL,i}}$ denote the average queue length, the average arrival rate and the short-term average HOL delay of queue *i* calculated in current slot, respectively. Similar to M-LWDF, MDU is a queue based scheduling scheme, with the weight in (5) expressed as

$$w_i = \frac{-1}{\overline{\lambda_i}} \cdot \frac{\partial f_i(\overline{T_{HOL,i}})}{\partial \overline{T_{HOL,i}}} \quad (13)$$

4.6 Packet Dependent Scheduling (PD)

The mechanism of the conventional queue based scheduling such as M-LWDF and MDU is to assign the same weight to all packets in a queue, and serve the selected queues until either the data or PHY layer resources are exhausted during each slot. This however leads to inefficiency if some packets in the unselected queues are more urgent than some packets in the currently served queues. We now analyse a packet dependent (PD) scheduling scheme, which assigns different weights to different packets contained in the same queue. The packet weights are determined based on the delay, packet size and QoS priority level of the packets. Therefore, it is more flexible and efficient than the queue based scheduling.

Defining $U_{k,i}$ as the delay tolerance for queue *i* of user *k* , a packet within this queue will be dropped if its waiting time is larger than $U_{k,i}$. In general, the delay tolerance of the voice, variable bit rate (VBR) video and BE traffic queues is set to be low, medium and high, respectively. A guard interval $G_{k,i}$ is introduced to reduce the packet drop rate, which means that the urgent packets belonging to queue *i* of user *k* should be given a high priority within the last $G_{k,i}$ duration before they timeout. Letting $t_c \in [0, \infty)$ denote the current time, for the *l*th packet that belongs to queue *i* of user *k* and arrives at time $t_l \in [0, t_c]$, the delay is given by $S_{k,i,l} = t_c - t_l$. Thus, the time left that the packet becomes urgent is denoted by $C_{k,i,l}$, which is expressed as

$$C_{k,i,l} = U_{k,i,l} - S_{k,i,l} - G_{k,i,l} \quad (14)$$

If $C_{k,i,l} < 0$, *i.e.,* $S_{k,i,l} > U_{k,i} - G_{k,i}$, it means that the packet is urgent, and will timeout within the guard interval of $G_{k,i}$. Hence the packets with $C_{k,i,l} < 0$ should be given a high priority during this guard interval.

Further, let $D_{k,i,l}$ denote the packet size (in bits) of the packet that belongs to queue *i* of user *k*, and arrives at time t_l. Define $\beta_{k,i} \in [1, \infty)$ as the QoS priority level for queue *i* of user *k*. In general, the QoS priority levels for the voice traffic queues, video traffic queues and BE traffic queues are high, medium and low, respectively.

We design $W_{k,i,l}$, the weight of the to-be-served packets that belong to queue *i* of user *k*, and arrive at time t_l by using the following equation

$$W_{k,i,l} = \begin{cases} \beta_{k,i} D_{k,i,l} / (C_{k,i,l}+1) & (C_{k,i,l} \geq 0) \\ \beta_{k,i} D_{k,i,l} & (C_{k,i,l} < 0) \end{cases} \quad (15)$$

According to (15), the PD scheduling scheme assigns a higher weight to the packets in a queue which have a higher QoS priority level, a larger data amount and a fewer time left to become urgent. The packets with higher weights will be transmitted first, regardless if they are in the same queue or not. Each packet is assigned a unique sequence number, which ensures that it can be reassembled during transmission. Therefore, the PD scheduling scheme is more flexible and efficient than queue based scheduling schemes, where all packets in the same queue are assigned the same weight.

If $C_{k,i,l} \geq 0$, i.e., $S_{k,i,l} \leq U_{k,i} - G_{k,i}$ the weight in (15) increases with the decrease of $C_{k,i,l}$. In particular, we have

$$\partial W_{k,i,l} / \partial C_{k,i,l} = -\beta_{k,i} D_{k,i,l} / (C_{k,i,l} + 1)^2 \tag{16}$$

This implies that with a large valued $C_{k,i,l}$, *i.e.,* a relatively small packet delay, the variation of the weight $W_{k,i,l}$ is less sensitive to the variation of $C_{k,i,l}$. In this case, the QoS priority level and data amount play a more important role in weight calculation. On the other hand, the fewer time left for the packet to become urgent, the larger the packet delay and the faster the weight increases.

If $C_{k,i,l} < 0$, *i.e.,* $S_{k,i,l} > U_{k,i} - G_{k,i}$, it means that the packets arriving at time t_l will timeout in less than $G_{k,i}$, and should be given a high priority during the guard interval to avoid the drop of packets. In this case, $W_{k,i,l}$ in (15) maintains its maximum value, which is determined by the data amount and QoS priority level of the packets. For instance, if two voice packets (of the same QoS priority level) both fall in the guard interval, the packet with a larger data amount will be assigned a higher weight. On the other hand, if two packets are of the same data amount, the packet with a higher QoS priority level will obtain a higher weight.

Using (15) the weight W_k in (4) for the current slot is given by

$$W_k = \sum_{i=1}^{I_k} \sum_{l} W_{k,i,l} \tag{17}$$

The PD scheduling scheme can also be easily combined with the queue based MWSC resource allocation, whose complexity is higher than that of the user based MWSC with heterogeneous traffic.

5 Simulation Results

We use simulation results to demonstrate performance of the various resource scheduling schemes for a system with a total transmit power P_T = 1 W, a slot duration of T_{slot} = 2 msec, and a total bandwidth of B = 5 MHz which is divided into N = 512 subcarriers. We assume that each user has I_k = 3 queues: voice, VBR video and BE traffic queues. The delay tolerance $U_{k,i}$ for voice, video and BE traffic is set to be 100 msec, 400 msec and 1000 msec respectively. The guard interval $G_{k,i}$ is set to be 10 msec for all types of traffic. The packets arrive at an interval of 1 msec .The packet arrival rates of voice and BE traffic are constantly 64 Kbps and 500 Kbps respectively. The packet arrival rate of the variable bit rate (VBR) video traffic follows a truncated exponential distribution in each state, with the maximum, minimum and mean of 420 Kbps, 120 Kbps and 239 Kbps, respectively, where the duration of each state follows an exponential distribution with mean 160 msec. It can be calculated that the average packet sizes for voice, video and BE traffic are 64 bits, 239 bits and 500 bits, respectively. The QoS priority levels $\beta_{k,i}$ for the voice, video and BE traffic are respectively set to be 1024, 512 and 1 as a result of testing, to provide the best performance. The channel is modelled to be of six independent Rayleigh fading paths with an exponentially delay profile and a root-mean-square (RMS) delay spread of 0.5 μsec. The signal-to-noise ratio (SNR) is defined as the average ratio of the received signal power to noise power for each user.

In the following, we present a performance comparison of various resource scheduling schemes used in MAC layer. In the PHY layer the MWSC based suboptimal resource allocation discussed in section III is employed.

The parameters taken for comparisons are average system throughput and average packet delay. Average system throughput is defined as the average transmitted bit per second in the system. Average packet delay is the average time that a packet must wait when trying to access a communication network. The proportional fairness rule is used in system where fairness is the main criteria.

Fig.2 and Fig.4 demonstrate the impact of the number of users on performance of different resource scheduling schemes with k = 50 users. Fig. 2 shows the impact of the number of users on the average system throughput. PD demonstrates significant performance advantages over other scheduling schemes except MSC since it depends on the instantaneous data rate, it schedules the packet with best channel conditions in each subcarrier. As the users increasing and higher multi-user diversity, the total cell data rate of MSC algorithm is getting light increase. However, the MSC algorithm does not think about the user average data rate requirements. In particular, the system throughput achieved by PD increases with the increase of the number of users, due to enhanced multiuser diversity. With given resources, when the number of users increases, there is a higher degree of freedom for resource allocation, resulting in enhanced multiuser diversity. Fig.3 shows the zoomed version of Fig.2

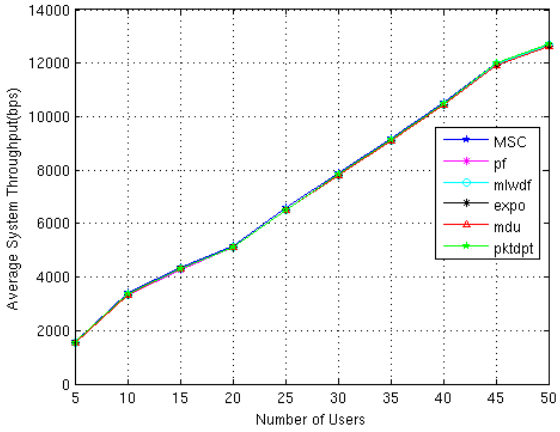

Fig.2 Impact of number of users on average system throughput

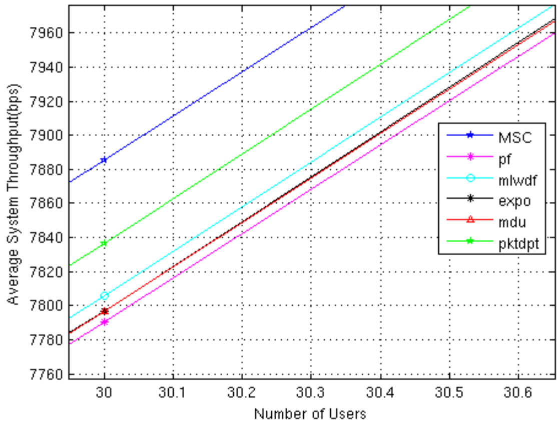

Fig.3 Zoomed version of fig. 2.

On the other hand, the increase in the number of users would cause the increase in the weight difference of the HOL packets of various queues, and thus the average system throughput decreases. This impact on the average system throughput is more significant with MDU, M-LWDF, EXP than with PD. With PD, the packets with larger weights are served first on packet basis, whichever queues they belong to, whereas with MDU, M-LWDF, EXP all packets in a queue which has a larger weight are served first on queue basis. Therefore, average system throughputs of MDU, M-LWDF, EXP benefit less from multiuser diversity. With a large number of users, the average system throughput achieved by PD is much higher than that achieved by MDU, M-LWDF, EXP scheduling schemes.

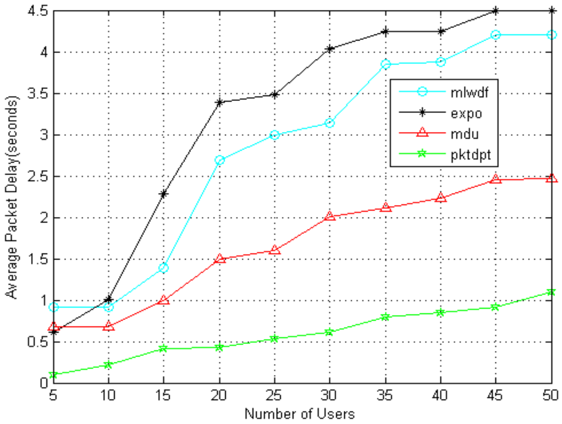

Fig.4 Impact of number of users on average packet delay

Fig. 4 shows the impact of the number of users on the average packet delay. The EXP scheduling is poor compared to the M-LWDF and the MDU approaches. This is due to the mechanism of the EXP rule. If one user has a larger delay than others, the weight of this user becomes very large because of the exponential function used in the weight, and then this user may occupy all of the subcarriers with high probability. Because the frequency-selective fading is present, assigning the whole bandwidth to one user is less efficient.

As can be seen, the M-LWDF works well compared to EXP. However, since the MDU policy uses the average queue lengths (delays) as the weights, which is a more moderate way, the MDU policy can allocate resources more efficiently compared to M-LWDF. PD achieves a much lower delay than M-LWDF, MDU, EXP since it determines the packet transmission order by assigning different weights to different packets, and therefore is more efficient than the conventional queue dependent scheduling.

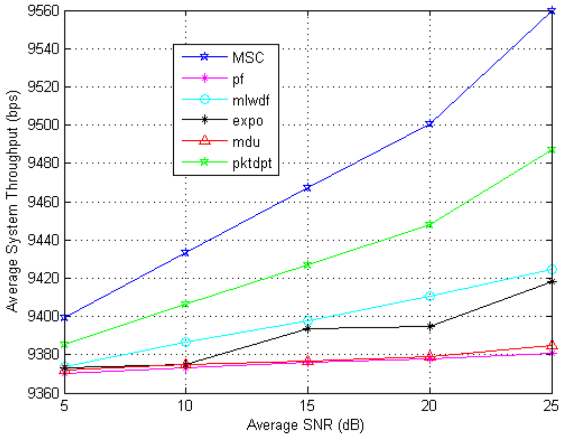

Fig.5 Impact of SNR on average system throughput

Meanwhile, since PD allocates more resources to QoS traffic, it achieves up to two times lower delays for QoS traffic than M-LWDF and MDU.

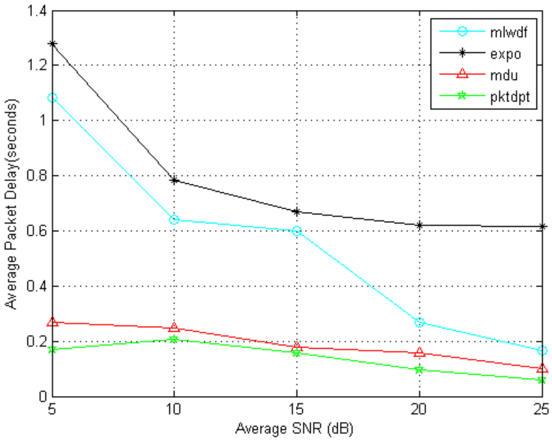

Fig.6 Impact of SNR on average packet delay

Fig.5 and Fig.6 show the impact of SNR on performance of different resource scheduling schemes with $k = 50$ users. Fig.5 shows that the average system throughput for all the schemes increases with the average SNR. PD outperforms MDU, M-LWDF, EXP scheduling schemes. Fig.6 demonstrates the impact of SNR on average packet delay and PD outperforms all other resource scheduling schemes.

Thus the packet scheduling is performed better compared to other queue based resource scheduling schemes such as M-LWDF, MDU, EXP in terms of throughput and delay.

6 Conclusion

In this paper, we have investigated various resource allocation and scheduling schemes in the wireless OFDM based downlink that serves multiple users with heterogeneous traffic and supports various applications based on joint physical and MAC layer design. We have proposed an adaptive cross-layer design with the PD scheduling at the MAC layer, for downlink multiuser multitasking OFDM systems with heterogeneous traffic. The proposed PD scheduling scheme provides significant performance advantages over the queue based M-LWDF, MDU, EXP scheduling schemes in terms of the average system throughput, QoS traffic delays with a wide range of the number of users, and a moderate to high SNR range.

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