A Channel-Condition and Packet-Length Dependent Scheduler in Wireless OFDM Systems

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Abstract— **In this paper, a new scheduler, called Channel-Condition and Packet-Length Dependent Packet Generalized Processor Sharing (CPLD-PGPS) scheduler is proposed for orthogonal frequency-division multiplexing (OFDM) wireless communication systems. Based on PGPS, CPLD scheduler considers the condition of the physical channel and the length of packets at the same time, and optimally allocates the sub-carriers in a frame. With this scheduler, improved system BER, and correspondingly superior PER performance can be achieved. The system throughput is improved, while guaranteeing the required bandwidth, and providing long term fairness for all the traffic in the system. In order to reduce the algorithm complexity, a simplified CPLD is proposed, which maintains the system throughput as the original scheduler, and guarantees the system performance with properly set system parameters. Simulation results demonstrate the superior performance of the proposed scheduler.**

I. INTRODUCTION

Scheduling in wireless networks plays a key role in resource allocation. Many schemes for packet scheduling in wireless networks have emerged, based on the concept of fair queueing. The original idea of fair scheduling, generalized processor sharing (GPS) is proposed in [1, 2]. The packet generalized processor sharing (PGPS) is proposed for packet level scheduling, and has been integrated into time-division multiple access (TDMA) [3] and code-division multiple access (CDMA) [4, 5] based wireless systems. See [6] for a complete reference on wireless scheduling algorithms. Later, channel state dependent packet scheduler [7] is extended to wireless network to enhance the system performance, but no bandwidth and fairness guarantees are provided for the mobile users.

In OFDM [8] systems, the frequency channel is divided into a number of sub-carriers. For multi-user OFDM systems, [9] presented an optimal algorithm to adaptively allocate the sub-channels to the users, but the scheduler is a bit level allocation. The resource management in OFDM systems for downlink packet transmission is studied in [10], in which a truncated GPS (TGPS) is proposed to implement the scheme. However the packet length is fixed, which is unrealistic in practical systems.

We consider a system in which a number of OFDM symbols are grouped into an OFDM data frame, and packets with variable lengths are transferred in the frame. Since the number of good sub-channels of each user is variable, when a packet is to be accommodated in the current OFDM frame, the number of good sub-channels may be much less than the number of sub-channels this packet needs, even though the sub-carrier allocation is optimized, and this packet may still have a high probability to experience errors. The whole system performance strongly depends on the channel condition and the packet length. So a new packet scheduler for OFDM systems is needed.

In this paper, we propose a new packet scheduler based on user channel condition and packet length (CPLD-PGPS). By considering the sub-channel conditions and the length of the packet together and the optimal sub-channel allocation in the frame, the CPLD scheduler is able to guarantee the required bandwidth, the system packet error rate performance, and the system throughput. Then a simplified CPLD scheduler is given, while guaranteeing the system performance by properly setting parameters. We assume the physical channels around the base station have nearly the same statistical property. This scheduler can provide fairness in the long term. Simulation results show that the proposed scheduler can achieve better PER performance and system throughput than the conventional PGPS scheduler.

The remainder of this paper is organized as follows. In Section II, the OFDM system architecture is introduced. The algorithm of CPLD scheduler is given in Section III. Then the scheduler is simplified in Section IV. In Section V, the simulation results are shown. The conclusions are made in Section VI.

II. OFDM SYSTEM ARCHITECTURE

In this section, we describe the considered OFDM system architecture. The system description is given in Fig.1. This system consists of one cell with one base station (BS) communicating simultaneously with K mobile terminals. All the mobile terminals are randomly distributed in the cell. We group N_s OFDM symbols as a frame. Each sub-carrier in the frame can only be allocated to one packet. All the sub-carriers have the same modulation scheme. The base station establishes one individual queue for each user. Arriving packets from each user is stored in its own individual FIFO (first-in first-out) queue. The system monitors the downlink channel condition for each mobile user. According to the current channel condition and the length of the packet, the packet scheduler decides which user's packet should be transmitted. The system will allocate the sub-carriers to different selected packets based on the channel conditions of all users. The whole sub-carrier can only be allocated to one packet, and according to channel conditions, the sub-carriers are optimally allocated to achieve

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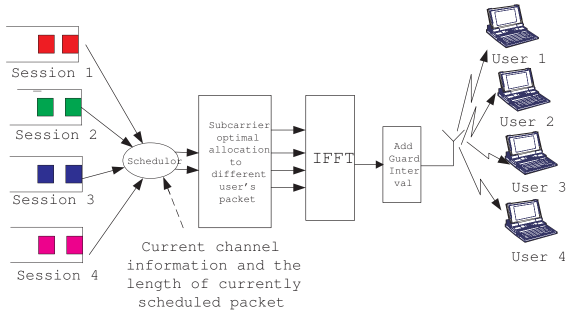

Fig. 1. The OFDM System Description

a better PER system performance. After inverse fast fourier transform (IFFT) and the addition of the guard interval, the frame is sent out. The sub-carrier allocation map is transferred to the users by another control channel. According to the sub-carrier allocation map, a user will judge whether there are packets in the received frame: if yes, the packet is extracted from the frame.

We assume the channels between users and the BS are independent with the same statistical property. Without loss of generality, we assume the average channel gain is 1, and all the receivers have the same noise figure. If the energy E_s of the sub-channel is larger than E_0, (the value E_0 is set by the system), the sub-carrier is regarded as a good channel; otherwise, it is a bad sub-carrier. We also assume that BS has perfect knowledge of the channel information of all users and all the sub-carriers have the same transmission power.

III. CPLD-PGPS SCHEDULING IN OFDM SYSTEMS

A. *Virtual Time Update*

Generalized processor sharing (GPS) assigns each data flow a weight so that the amount of processor power received by each flow is proportional to its weight. GPS is an ideal scheduling policy that assumes packets are infinitely divisible. To apply GPS to a server with different arriving streams, each stream is allocated an infinite buffer and only the first job in each buffer is served by the weighted service power.

Since packets can not be divided in practice, a packet-by-packet transmission scheme called packetized generalized processor sharing (PGPS) is presented to approximate GPS in [5]. The basic principle of PGPS is as follows: when the server is ready to transmit, and assuming no packet arrivals after the current time, it picks the packet which would complete the service in the GPS scheduler first among all the packets.

To implement GPS in an OFDM system, in each frame, we regard the total number of bits in the frame as the server power P. There are N sessions and the ith session is assigned a positive weight ϕ_i . A session is said to be backlogged at time instant k if there are packets of that session queued in the buffer at time instant k. Let $\mathbf{B}(\mathbf{k})$ be the set of backlogged sessions at time instant k. We assume time interval Δk is an integral multiple of the frame time T_{Frame}.

Since the packet length is variable, the number of packets accommodated in a frame is not fixed. In this case, the actual capacity $r(k)$ of the GPS server is variable depending on the actual number of bits in the current frame. The time-varying capacity $r(k)$ is piecewise constant between two successive frames. According to [2], the virtual time $V(w(k))$ in the original PGPS should be modified. Whenever k is not in a busy period, $w(k)$ and $V(w(k))$ is set to be 0.

$$w(k_{j-1} + \Delta k) = w(k_{j-1}) + r(k_{j-1})\Delta k \qquad (1)$$

$$V(w(k_{j-1}) = V(w(k_{j-1})) + r(k_{j-1})\Delta k/\Sigma_{j\in B(k)}\phi_j \qquad (2)$$

where $\Delta k \leq k_j - k_{j-1}$, $j = 2, 3\ldots$. Let a_i^l be the lth packet arriving from the ith user and L_i^l be its packet size. Under the new clock, the time a_i^l is transformed to $w(a_i^l)$. So when the lth packet of the ith user arrives, the packet is stamped with the virtual finishing time

$$F_i^l = max[F_i^{l-1},\ V(w(a_i^l))] + \frac{L_i^l}{\phi_i} \qquad (3)$$

$$with\ F_i^0 = 0\ for\ all\ i.$$

B. *CPLD-PGPS Algorithm Description*

In this sub-section, we describe the algorithm of the channel condition and packet length dependent CPLD-PGPS scheduler.

In order to guarantee fairness, we set a fair value V for each user in the system. All V are set to 0 at start time.

Step 1: In this scheduler, we only consider the packet at the head of queue for each user. When a packet arrives, by (1),(2), and (3), the virtual time is updated and the packet is stamped with its virtual finishing time.

Step 2: Based on the virtual finishing time of the head-of-line packet in each queue, the scheduler serves packets in an increasing order of virtual finishing time. The packets are arranged in the frame until the remaining sub-carriers are not enough to accommodate the next packet. If the number of remaining sub-carriers N_r is not small, we can make use of these vacant sub-carriers. For each packet in the queue, the length is known. In the order of increasing finishing times, the scheduler will choose a packet which can be accommodated in the remaining sub-carriers. This operation will increase the system throughput. In order to be fair to all users, subtract 1 from the fair value V of this user.

Step 3: Now the scheduler has finished packet selection. Due to the time varying channel of each user, it is necessary to optimize sub-carrier allocation to different packets in the frame. We assume N sub-carriers can be used for data transmission. So the total number of sub-carriers are fixed, and the sub-carrier allocation functions, each of which represents the sub-carrier distribution of the given packet in the frame, can be denoted as $\{f(p,n),\ n = 0, 1, ..., N\}$. $f(p,n)$ has two values,

$$f(p,n) = \begin{cases} 1, & if\ subcarrier\ n\ is\ allocated \\ & to\ the\ packet\ p \\ 0, & otherwise \end{cases} \quad (4)$$

Due to the different fading on different sub-carriers, the power received on each sub-carrier is variable. Let P_T be the transmit power on each sub-carrier which is a constant and $P_{R,n}$ be the received power on the nth sub-carrier. The BER performance on each sub-carrier is related to the received power by

$$BER_n = \Gamma(P_{R,n}). \quad (5)$$

As $P_{R,n}$ increases, BER decreases. As BER decreases, PER decreases. So the more received power in all sub-carriers, the less system PER.

In this algorithm, our objective is to minimize BER, and hence minimizing PER. This solution can optimally allocate the sub-carriers to all packets in the frame. Let $\xi(k)$ be the set of packets in the frame at time k, and ψ be the total number of packets in the frame. The optimal resource management in the OFDM frame can be described as follows :

$$\begin{cases} Min\ \sum_{p=1}^{\psi} \sum_{n=1}^{N} \Gamma(P_T H_{p,n}) f(p,n) \\ Subject\ to \\ \sum_p \sum_n f(p,n) \leq N \ \ (I) \\ f(p_1,n) f(p_2,n) = 0;\ \forall p_1, p_2 \in \xi(k),\ p_1 \neq p_2 \ \ (II) \\ \sum_{n=1}^{N} f(p,n) = \lceil L_p / N_b \rceil;\ \forall p \ \ (III) \end{cases} \quad (6)$$

where $H_{p,n}$ denotes the channel gain of the nth sub-channel of packet p. Condition I states that the total numer of sub-carriers allocated to all the users are less than or equal to N. Condition II means that each sub-carrier can only be allocated to one packet in a frame. Condition III says that the number of sub-carriers allocated to the packet is related to the packet's length.

The solution of (6) will give the optimal sub-carrier allocation function $f(p,n)$ in the frame. Since the channel information $H_{p,n}$ is provided and P_T is constant, $\Gamma(P_T H_{p,n})$ is known to the system and is independent of $f(p,n)$. First, according to the optimal sub-carrier allocation algorithm in [9], an initial allocation is obtained via a constructive algorithm. We order the sub-carriers' gains for each user in a descending order, and we consider the first sub-carriers in the ordered lists of all users, user by user, and continues until all the sub-carriers are allocated. So each packet gets the number of sub-carriers it needs. Let $\{D_1, D_2 ... D_\psi\}$ be the set of sub-carriers each packet occupies and D_{left} be the set of idle sub-carriers in the frame. Second, the allocation scheme can be improved by iterative swapping of sub-carriers between users to reduce the total bit errors. In each iteration, we try to swap the sub-carriers between two users such that the total bit error is reduced. The algorithm in c language is given in Algorithm 1. For each sub-carrier in the frame, the scheduler will exchange it with all the other sub-carriers in other sets, and compare the function value $\sum_{p=1}^{\psi} \sum_{n=1}^{N} \Gamma(P_T H_{p,n}) f(p,n)$, and the optimal sub-carrier allocation $f(p,n)$. According to the function $f(p,n)$, the scheduler reallocates all sub-carriers to the packets.

Algorithm 1 Sub-carriers allocation optimization in the frame

```
  min=1000000;
 For(i=0;i<N;i++)
 For(j=i+1;j<N;j++)
 { if(pkt(i)!= pkt(j))
  { X=exchange_assume();
  if (value< min )
   { exchange( );
      min=X;
     }
  }
 }
```

Step 4: We check the goodness of sub-carriers for each packet, and count the total number of good sub-channels N_{good}, and calculate the ratio r between N_{good} and N_{packet}. N_{packet} denotes the total number of sub-carriers this packet occupies. If the value r of all the packets in the frame is larger than r_0, which is set by the system, the frame will be sent out. If the fair value V of the r unsatisfied packet is equal to or larger than V_0, which means it has given too many chances to others, the frame should be sent anyway. Otherwise, go to step 5.

Step 5: We assume a packet A in the frame has a value of $r < r_0$. We should exchange the packet A with the next packet B whose V value is the largest. Then the V value of the user to whom the packet A belongs adds 1, while 1 is subtracted from the V value of the user owning B; then return to step 3. If there is no appropriate packet to substitute packet A, we still select A, and this frame will be sent. On the other hand, because the other user's channel is not good enough, the user's packet is transmitted ahead of schedule (according to the finishing time), the scheduler will subtract 1 from the V value of this user.

In this scheduler, both the channel condition and the packet length affect the scheduling result. If the packet length is short, and the number of good sub-channels needed are also small, even though the total channel quality is not good, it is easy to find a set of good sub-channels for the packet. From the algorithm, we find that the performance of the scheduler actually depends on the proportion between the number of good sub-channels and the packet length. The flow chart is presented in Fig. 2.

In practice, if the packet transmitted experiences errors and is detected by the receiver, this packet will be retransmitted, and this retransmission will waste system resource. This CPLD scheduler can guarantee the quality of packet transmission and reduce the resource wastage.

C. Fairness Discussion

If the server transmits the packet in the stamped finishing time order [4], it is fair for every user. However, if the channel condition does not allow packet transmission, the packet is deferred, and the transmission opportunity is given to other packets. Thus, it is unfair for that user. But with the fair value V, the scheduler will keep long term fairness. When a packet is deferred, the V value is incremented by 1, and the scheduler

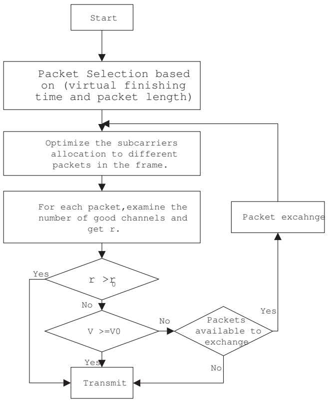

Fig. 2. The program flow

will select another packet whose fair value is the largest. Once a packet is transmitted, the fair value also is decremented by 1. Since we assume the wireless physical channels around the base station are statistically identical for all users, CPLD is fair in the long term.

There is another condition we should consider. If the wireless channel of the user remains unsatisfactory for a long time period, no packet is transmitted for this user. Then we set a threshold value V_0 , if the fair value V is larger than or equal to V_0, the packet must be included in the current frame anyway. This operation will avoid the "starving" phenomena, but the transmission quality of these packets can not be guaranteed. In practice, the wireless channel is divided into a great number of sub-channels in the frequency domain, it is not very difficult for the packet to find sufficient number of good sub-channels.

IV. SIMPLIFIED CPLD-PGPS

If the CPLD-PGPS algorithm described above can be implemented, it will give optimal resource management, and greatly improve the system performance. However, the computational complexity is very high. In the algorithm, the packets are selected to fill up the OFDM frame, and the sub-channels are optimally allocated to different packets, then packets may be exchanged, and finally the frame is sent out. In order to increase the feasibility and guarantee the system performance, we propose a simplified CPLD-PGPS scheduler.

Step 1: When the packet arrives at the queue, the scheduler will calculate the finishing time, and stamps it on the packet.

Step 2: The scheduler will select the packet of each session to fill up the OFDM frame, but different from above, the selection is based not only on the finishing time, but also on the proportion between the packet length and the number of good sub-channels. Once we pick a packet, packet length is known, and the modulation of each sub-carrier is fixed, so we can calculate the number N_{packet} of sub-carriers that should be allocated to this packet. We can also get the total number N_{good} of good sub-channels for this user. In the OFDM system, if one sub-channel is a good channel for one user, it may also be a good channel for other users. So there is competition for good channels among users. For a packet, the good sub-channels may not all be allocated to it after sub-carrier allocation optimization. When we design the system, this point should be considered. We denote N_{good}/N_{packet} by r'. If r' is larger than r'_0, the packet should be sent in the frame. Here r'_0 is also set by the system and should be a little larger than r_0. If the fair value V is larger than or equal to V_0, the packet should be selected in this frame.

According to the finishing time and the r' value, the packets are selected to fill up the OFDM frame until the remaining sub-carriers can not accommodate the next packet. In the order of increasing finishing times, the scheduler will choose a packet which can be accommodated in the remaining sub-carriers, and its r' is also satisfied. The V value of each user whose head-of-line packet's finishing time is smaller than this packet should be incremented by 1. This operation will improve the system throughput.

Step 3: After optimal sub-carrier allocation in the frame, the frame is transmitted.

In this simplified algorithm, the total computational complexity is reduced. Further, system performance can be guaranteed by properly setting the system parameters r'_0.

V. SIMULATION RESULTS

In this paper, we consider an OFDM downlink system using QPSK modulation. The total system bandwidth is 20MHz, which is divided into 64 sub-carriers, among which 48 are used for data. Each OFDM symbol lasts $4\mu s$, in which $0.8\mu s$ is the guard interval. We group 100 OFDM symbols into a frame, so the frame length is $400\mu s$. We consider quasi-static flat fading channel with multipath. The multipath channel for each antenna has 6 taps of Rayleigh-faded paths at an interval $0.05\mu s$, and the power delay profile follows a decay rule of $[1, e^{-1}, e^{-2}, e^{-3}, e^{-4}, e^{-5}]$. Different users have independent channels with the same statistics.

In the simulation, video, voice and data traffics are all considered. Video traffic is modeled by an 8-state Markov-Modulated Poision Process (MMPP). In each state, the packet arrival satisfies a Possion process. The average dwell time in each state is selected to be $40ms$. The voice traffic generation model is the On-Off model. The packets arrive at a constant rate of 8 packets/s in the On state. The activity rate of the model is 0.4. The data packet arrival also follows a Possion process, and the mean inter-arrival time is $0.1s$. The packet length is uniformly distributed between 1500 and 2500 bits. The simulation time is 2 minutes. Forward error control coding is also applied in this system.

First, four homogeneous video traffics are simulated with the same weight, $\phi_1 = \phi_2 = \phi_3 = \phi_4$. The PGPS scheduler [7] with varying capacity is also simulated for performance comparison. For CPLD, the system parameter r_0 is set to be 1. The wireless channel is normalized, and the parameter E_0 is set to 0.3. In wireless transmission, AWGN noise is added. The PER performance is given in Fig 3. Since CPLD considers the wireless channel quality and the packet length at the same time, the performance is better than PGPS. The PER performance of simplified CPLD scheduler is greatly affected by the system parameter r'_0. From the figure, we find

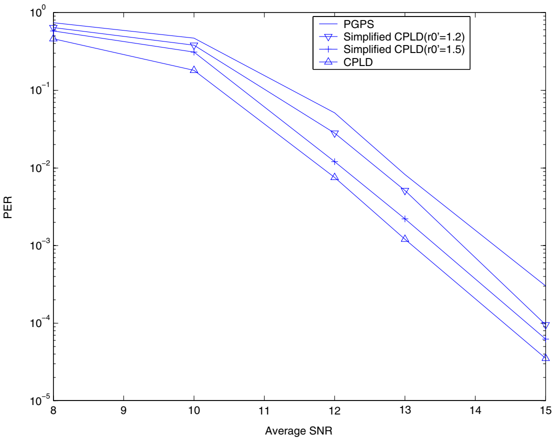

Fig. 3. PER performance comparison

TABLE I
THE SYSTEM THROUGHPUT COMPARISON

Scheduler / Throughput	PGPS	CPLD	Simplified CPLD
System packet throughput (packets/s)	129.78	156.26	155.34
System bit throughput (bits/s)	2.81×10^{5}	3.66×10^{5}	3.38×10^{5}

TABLE II
PERFORMANCE FOR HETEROGENEOUS TRAFFIC: $\phi_1, \phi_2, \phi_3 = 3$; $\phi_4, \phi_5, \phi_6 = 2$; $\phi_7, \phi_8, \phi_9 = 1$;

	Traffic Type	Max.delay (s)	Aver.delay (ms)	PER ($\times 10^{-2}$)
Flow 1	voice	0.0005	0.1772	1.42
Flow 2		0.0004	0.1821	1.34
Flow 3		0.0004	0.1961	1.39
Flow 4	video	0.0015	0.2001	1.38
Flow 5		0.0022	0.3108	1.36
Flow 6		0.0018	0.2523	1.32
Flow 7	data	0.0032	0.3911	1.32
Flow 8		0.0022	0.3592	1.32
Flow 9		0.0035	0.3012	1.38

that the system performance is improved as r_0' increases. By comparing CPLD and the simplified CPLD, the complexity of the scheduler is reduced while the performance can be guaranteed by the properly designed parameters. Table I gives the system packet throughput comparison. The r_0' is set to be 1.2. The results show that the throughput is greatly improved with the CPLD scheduler because of the utilization of the residual sub-carriers, and the simplified CPLD maintains the system throughput.

To demonstrate the performance of the proposed resource management scheme in a heterogeneous traffic environment, three data flows, three VBR video flows, and three voice flows are simulated. The weight of the voice flows, video flows and data flows are set to be 3, 2, and 1, respectively. The SNR of the system is set to 12dB. The simulation results including maximum delay, average delay and packet error ratio are summarized in Table II. It can be seen that voice flows have lower maximum and average transmission delays than video and data flows with smaller weights. All the flows have good PER performance, and the system performance is guaranteed.

VI. CONCLUSION AND FUTURE WORK

In this paper, a new packet scheduler CPLD for packet wireless OFDM systems is proposed. Based on the PGPS scheduler, this scheduler considers the channel condition and the packet length simultaneously in OFDM systems. The sub-carriers are optimally allocated to different packets in the frame. Compared with PGPS, the PER performance and the total system throughput of CPLD are all improved. Simulation results have demonstrated that the proposed scheduler is suitable for supporting heterogeneous traffic flows and guaranteeing good system performance.

Acknowledgment

This research is supported in part by the Research Grants council of the Hong Kong Special Administration Region, China (Project No. HKU 7047/00E).

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