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Research Article

Fading-Aware Packet Scheduling Algorithm in OFDM-MIMO Systems

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To maximize system throughput and guarantee the quality of service (QoS) of multimedia traffic in orthogonal frequency division multiplexing (OFDM) systems with smart antennas, a new packet scheduler is introduced to consider QoS requirements, packet location in the frame, and modulation level. In the frequency domain, several consecutive subchannels are grouped as a frequency subband. Each subband in a frame can be used to transmit a packet, and can be reused by several users in a multiple-input and multiple-output (MIMO) systems. In this paper, we consider the adaptive packet scheduling algorithms design for OFDM/SDMA system. Based on the BER requirements, all traffics are divided into classes. Based on such classification, a dynamic packet scheduler is proposed, which greatly improves system capacity, and can guarantee QoS requirements. Adaptive modulation is also applied in the scheduler. Then, the complexity analysis of these algorithms is given. When compared with existing schedulers, our scheduler achieves higher system capacity with much reduced complexity. The use of adaptive modulation further enhances the system capacity. Simulation results demonstrate that as the traffic load increases, the new scheduler has much better performance in system throughput, average delay, and packet loss rate.

1. INTRODUCTION

Next-generation wireless communication networks are expected to provide a wide range of services, such as multimedia, internet access, and video conferencing. Orthogonal frequency division multiplexing (OFDM) is considered as a multiple access scheme for wireless broadband networks, and has been adopted in wireless LAN standards IEEE 802.11a/ETSI HIPERLAN2 and digital audio/video broadcasting (DAB/DVB) [1, 2].

Spectrum is an important wireless resource, and the scarcity of the spectrum demands high bandwidth efficiency. Space division multiple access (SDMA) allows the reuse of bandwidth by multiplexing users in the same frequency band [3]. SDMA has been applied to TDMA and CDMA systems. Shad et al. [4] propose several dynamic slot allocation schemes for TDMA systems with smart antennas at the base station, and simulation results show that the system capacity is greatly improved. In [5], a smart channel assignment algorithm is introduced in mobile cellular SDMA/TDMA systems. In [6], smart antenna is applied to CDMA systems.

The employment of smart antennas in the physical layer raises significant issues in the medium access control (MAC) layer. Many papers [7] have treated the resource management problem in OFDM systems. In [8], the whole bandwidth of an OFDM system is divided into several subbands, and each subband is composed of several successive subchannels. Three schemes are proposed to schedule the bandwidth resource. However, SDMA is not considered. An overview on the dynamic packet assignment for high-efficiency resource management in OFDM systems can be found in [9]. Compared with OFDM systems, OFDM/SDMA systems have larger capacity but are also more complex. In [10], several efficient approaches are proposed to adopt SDMA in OFDM systems. In [11], an algorithm is proposed to allocate spatially separable users in the same subchannel by adjusting beam patterns of individual users at the transmitter. However, this paper considers each subchannel separately, and the scheduler is on the bit level, not on the packet level. Thus the complexity is very high.

In multimedia OFDM/SDMA networks, different traffics have different BER requirements. If packets of different traffics are allocated to the same channel, the system must satisfy the most stringent BER requirements of all the packets transmitted at the same channel. When users with low BER requirements are transmitted together with users with high BER requirements on the same channel, the BER performance exceeds their needs. Therefore, the number of users that can be accommodated in the channel is reduced.

In this paper, we consider an OFDM/SDMA system, in which the bandwidth is divided into subbands composed of several consecutive subchannels. The same subband can be used by several users at the same time. Further, a number of OFDM symbols are grouped as an OFDM frame. The transmission power is adaptively allocated among active users to optimize wireless channel capacity. We first apply the Random-Fit, First-Fit, and Best-Fit packet allocation schemes proposed in [4] to OFDM/SDMA systems. Then, based on the Best-Fit scheme, we propose a BER-classified Best-Fit packet scheduler. The scheduler classifies all traffics into classes according to the BER requirements, and allocate packets of the same class to the same frequency subband. Adaptive modulation is applied. We also compare the complexity of our algorithm with those in [4], and find that our complexity is lower than that of Best-Fit. In the simulation, the system capacity of these algorithms are compared. It is found that the BER-classified Best-Fit scheduler always has the best performance, in terms of system throughput, average delay, and packet loss rate. Adaptive modulation also improves the system performance when combined with the scheduler.

The remainder of this paper is organized as follows. In Section 2, we introduce the system architecture. Basic packet scheduler algorithms are given in Section 3. Then, the BER-classified Best-Fit scheduler is illustrated in details in Section 4. The simulation results are shown in Section 5. Section 6 is the conclusion.

2. SYSTEM MODEL

In this section, we describe the structure of the mobile terminal and base station. When a terminal has packets to transmit, it places an admission-request packet through a reservation request slot, from which the base station obtains the spatial signature and traffic information of the terminal. Then, the base station assigns frequency-space subbands to the terminal depending on the QoS request and the traffic information. In this paper, we only consider the scheduling of packets after the terminals are admitted.

2.1. System structure

We consider an OFDM/SDMA system which consists of N_u mobile terminals, each equipped with a single antenna. The base station has an M-element adaptive linear antenna array, capable of separating $K \leq M$ users. In OFDM systems, the total wireless bandwidth is divided into N_c orthogonal subchannels. In this paper, we group a fixed number of subchannels into a subband, which is called a frequency subband.

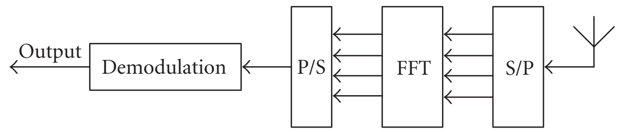

FIGURE 1: Mobile terminal structure.

Figures 1 and 2 give the structures of the mobile terminal and base station in an OFDM/SDMA system. We consider the downlink of the system and assume that the base station has perfect user channel information. The scheduler will distribute user packets into the subband. After beamforming, adaptive modulation is applied. These packets are then feeded in blocks of symbols into an N-tap inverse fast Fourier transform (IFFT) operator to generate the time domain sequence. Power is also adaptively allocated among the users. The sequence is then converted into a serial stream, and is finally transmitted. At the mobile terminal, the signal is converted to a parallel data stream, processed by FFT, then converted to serial data stream, and finally demodulated.

2.2. Channel model and beamforming

We assume the multipath fading channel is wide-sense stationary with uncorrelated scattering. With tolerable leakage, the time domain channel impulse response is modeled as a tapped delay line at a tap spacing of a sampling interval. The channel impulse response between the bth antenna of the base station and mobile terminal k can be expressed as

$$h_{b,k}(t,\tau) = \sum_{i=1}^{L} \alpha_{b,k}^{i}(t)\delta(t-\tau_i), \tag{1}$$

where $\alpha_{b,k}^{i}(t)$ is the complex gain of path i, τ_i is the corresponding path delay, L is the number of paths, and $\delta(\tau)$ is the Dirac delta function. Here $\tau_i = i\Delta t$, where Δt is the sampling interval of the OFDM system. Superscripts T and H denote the transpose and complex conjugate transpose of a vector or matrix. Here, we assume the base station has all channel information about mobile terminals. In real systems, such information can be achieved by channel estimation [12].

In the frequency domain, the channel response is represented as

$$H_{b,k}(n,j) = \sum_{i=1}^{L} a_{b,k}^{i}(nT_s)W^{ij}, \tag{2}$$

where n is the index for an OFDM symbol, j is the subchannel index, T_s is the duration of an OFDM symbol, $W = e^{-j2\pi/N_c}$, and N_c is the number of OFDM subchannels. Let $\mathbf{H}_k(n) = [H_{1,k}(n), H_{2,k}(n), \dots, H_{B,k}(n)]^T$ be the channel response between user k and the B antennas of the base station on subchannel n. Let $\mathbf{H}(n) = [\mathbf{H}_1(n), \dots, \mathbf{H}_K(n)]^T$ be the channel matrix between the base station antennas and the K mobile terminals, let $\mathbf{X}_n = [x_{n,1}, \dots, x_{n,K}]^T$ be the data at subchannel n of all users, and let $\mathbf{Y}_n = [Y_{n,1}, \dots, Y_{n,K}]^T$ be the received signal at subchannel n of all K active mobile terminals.

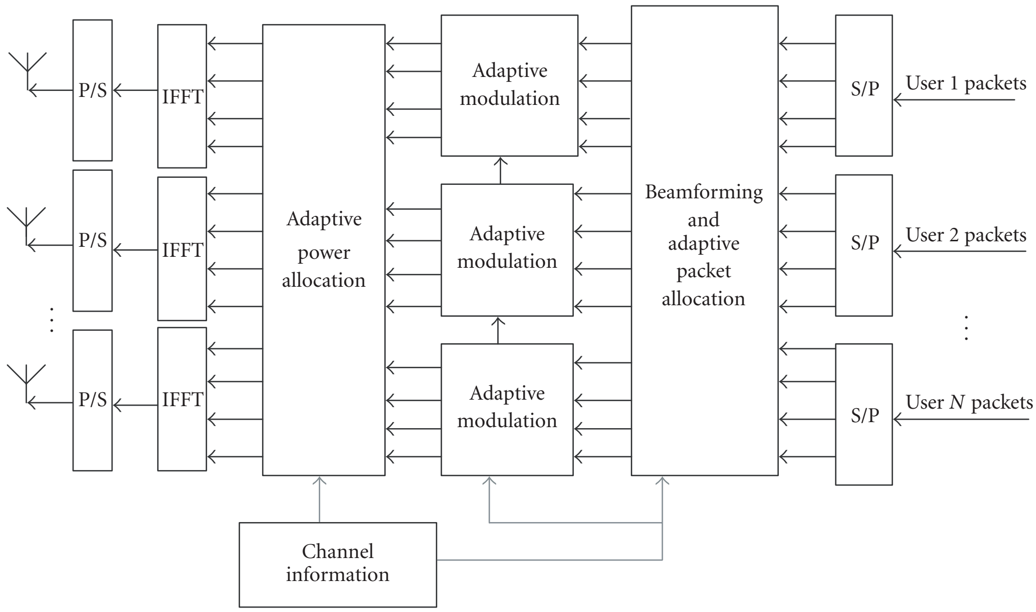

Figure 2: Base station downlink structure.

At the base station, the SDMA module generates a set of weight vectors for each subchannel of each user. The weight vector can be denoted as

$$\mathbf{V}_{n,k} = [v_{n,k}^1, v_{n,k}^2, \dots, v_{n,k}^M]^T, \tag{3}$$

which is one of the eigenvectors of the channel matrix $(\mathbf{H}(n))^H(\mathbf{H}(n))$, and all these eigenvectors are orthogonal to each other [13], that is,

$$E\{\mathbf{V}_{n,k1}\mathbf{V}_{n,k2}^H\} = \begin{cases} 0 & \text{if } k_1 \neq k_2, \\ A_{n,k} & \text{if } k_1 = k_2 = k, \end{cases} \tag{4}$$

where $A_{n,k}$ is the kth eigenvalue of matrix $H(n)^H H(n)$. By steering the set of beamforming vectors, the signal of different users on the same subchannels can be separated at the mobile terminals.

2.3. Power allocation between cochannel users

To achieve good system throughput with smart antennas, we need to optimally allocate the power to all users. Let $P_1, P_2, \dots, P_K$ be the power allocated to each user. The power for each user should satisfy

$$\sum_{j=1}^{K} P_j = P, \tag{5}$$

where P is a constant corresponding to the power constraint. As in [14], the power allocated for user i should be

$$P_i = \left(\mu - \frac{1}{\lambda_i}\right)^+, \tag{6}$$

λ_i is the eigenvalue of the channel matrix $H(n)(H(n))^H$, and μ is the Lagrange coefficient. Then, all power factors should satisfy

$$\sum_{i=1}^{K} \left(\mu - \frac{1}{\lambda_i}\right)^+ = P. \tag{7}$$

The signal received by the kth mobile terminal can be expressed as

$$\begin{aligned} \mathbf{Y}_{n,k} &= (\mathbf{V}_{n,k})^H \sqrt{P_k}\mathbf{H}_k(n)x_{n,k} \\ &\quad + \sum_{j \neq k}^{K} (\mathbf{V}_{n,j})^H \sqrt{P_j}\mathbf{H}_k(n)x_{n,j} + \eta_{n,k}, \end{aligned} \tag{8}$$

where $\mathbf{H}_k(n)$ is the channel vector of subchannel n between user k and the base station, $x_{n,k}$ and $x_{n,j}$ are the signal for each user. The first term in (8) is the desired signal, the second term is the interference from other users, and $\eta_{n,k}$ is the additive white Gaussian noise with variance σ^2. The signal-to-interference-and-noise ratio ($\text{SINR}_{n,k}$) at subchannel n of user k is

$$\frac{P_k(\mathbf{V}_{n,k}^H\mathbf{H}_k\mathbf{V}_{n,j}x_{n,k})(\mathbf{V}_{n,k}^H\mathbf{H}_k\mathbf{V}_{n,j}x_{n,k})^H}{\sum_{j\neq k}^{K} P_j(\mathbf{V}_{n,k}^H\mathbf{H}_j\mathbf{V}_{n,j}x_{n,j})(\mathbf{V}_{n,k}^H\mathbf{H}_j\mathbf{V}_{n,j}x_{n,j})^H + \sigma^2}. \tag{9}$$

In this paper, we consider the wireless channel as slow fading, and suppose the channel gains on these subchannels in a subband have small variations. Then, the channel quality can be represented by the average SINR. Let $\overline{\text{SINR}}_{b,k}$ be the average SINR of the bth frequency subband which is assigned to user k. The average SINR value can be given as

$$\overline{\text{SINR}}_{b,k} = \frac{\sum_{q=q_s}^{q_e} \text{SINR}_{n,k}}{q_e - q_s + 1}, \tag{10}$$

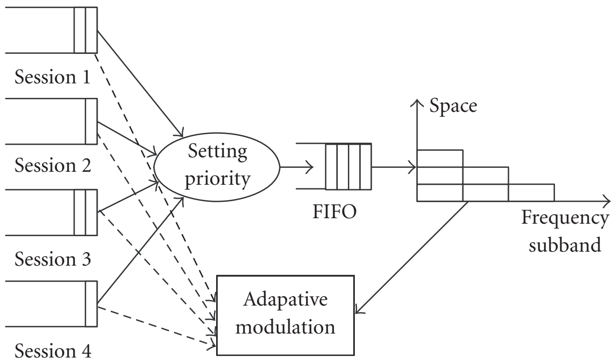

Figure 3: Description of scheduler.

where the q_s and q_e denote the subchannel indices of the start and the end of the frequency subband. The average SINR value determines the BER performance.

Next, we discuss the relationship between SINR and the BER performance. We consider a family of M-QAM signal constellations, where M denotes the number of points in each signal constellation. From [15], we know that the BER of a user with M-QAM modulation is approximated as

$$\mathrm{BER} \approx 0.2e^{-1.5(\mathrm{SINR}/(M-1))}. \tag{11}$$

Then, the minimum SINR value to support BER $\leq p$ for M-QAM modulation is

$$\mathrm{SINR}_{\mathrm{threshold}} = -\frac{\ln(5p)}{1.5}(M-1). \tag{12}$$

3. BASIC OFDM/SDMA PACKET ALLOCATION ALGORITHMS

3.1. OFDM/SDMA packet scheduling

We consider a scheduler as shown in Figure 3. All packets will be assigned a priority before being put into a first-in-first-out (FIFO) queue. Then, the packets are allocated into frames. We require a packet to be allocated in the subband of a frame once the SINR requirements of all packets in the subband are satisfied. After packet allocation, the frame is transmitted. Then, another round of operation starts.

The job of the scheduler is to allocate the packets in the space-frequency subbands, which greatly affects the system capacity. In TDMA systems with smart antennas employed at the base station [16], several schemes are proposed to dynamically allocate time slots to different users. Such schemes can be extended to OFDM systems. These algorithms are described in an increasing order of complexity as Random-Fit, First-Fit, and Best-Fit.

To facilitate the algorithm description, the following definitions and variables are used. All terminals are numbered from the set $\{1, 2, \ldots, K\}$, and each terminal can be referred to by its ID. $\xi(i)$ is defined to be the set of terminals currently allocated in frequency slot i. Let χ be the set of mobile terminals with unallocated packets, and let $\mathrm{SINR}_{\mathrm{threshold}}$ be the SINR threshold value to guarantee the BER performance. The packets have to be transmitted above a SINR threshold $\mathrm{SINR}_{\mathrm{threshold}}$ to guarantee the QoS requirement. Due to the property of SDMA, only one packet of the same user can be allocated in the same frequency subband.

3.2. Basic scheduling algorithms

The Random-Fit algorithm is very simple and works as follows. The system randomly picks a terminal from χ. Suppose the packet has been put into the current frequency subband d. Then, the scheduler will check each packet in set $\xi(d)$ to see if the SINR value is above the desired threshold. If not, the scheduler moves to the next subband. The algorithm ends when no frequency subband is available. The shortcoming of Random-Fit is that if two consecutive packets cannot be accommodated in the same subband, the algorithm will advance to the next subband even though another unallocated packet can be put into the current subband.

The second is the First-Fit algorithm. This algorithm is similar to Random-Fit. For each frequency subband, the system will check all packets of the terminals in set χ to see if they can be assigned in the frequency subband. Once a suitable subband is found, the packet is allocated to the subband.

The third one is the Best-Fit scheme. Since the base station has perfect channel knowledge of all terminals, the scheduler is able to predict the received power at the receiver terminal if the packet is transmitted in the frequency subband. Due to changes in wireless channel condition, the received power in each subband is different. The received signal power of subchannel q allocated to user k can be expressed as

$$\mathrm{Pr}_k = P_k\left(\mathbf{V}_{q,k}^H \mathbf{H}_{q,k} \mathbf{V}_{q,k} x_{q,k}\right)\left(\mathbf{V}_{q,k}^H \mathbf{H}_{q,k} \mathbf{V}_{q,k} x_{q,k}\right)^H. \tag{13}$$

From (10), we can get $\overline{\mathrm{SINR}_b}$ for the bth frequency subband. The SINR margin value for each subband is calculated as

$$\mathrm{SINR}_{\mathrm{margin},b} = \overline{\mathrm{SINR}_b} - \mathrm{SINR}_{\mathrm{threshold}}. \tag{14}$$

We pick a subband b with the largest SINR margin value. We then check whether the SINR requirements of the packets in $\xi(b)$ can be satisfied if the packet is allocated in the subband. If not, we try the next subband. This algorithm will stop when all subbands are tried.

3.3. Performance comparison

We compare the system capacity of the above three scheduling algorithms. We assume all packets have the same BER requirement, that is, the same SINR threshold value. In the system, there are 100 active users, each of which has the same transmission rate and Poisson arrival traffic. Figure 4 compares the capacity versus the average transmission rate for the three schedulers. It is found that the Best-Fit algorithm has the largest capacity as the system traffic load increases, followed by First-Fit, and Random-Fit. Here, the systems have four transmission antennas.

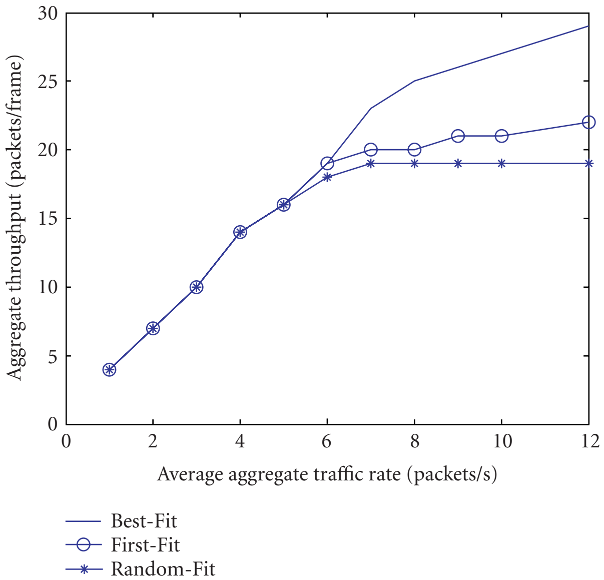

Figure 4: Capacity comparison among basic algorithms.

The three packet scheduler algorithms have not considered the QoS characteristics of multimedia traffic. Since different traffics have different BER requirements, the scheduler must satisfy the most stringent BER requirement among all the packets in the subband, thus degrading the system throughput.

4. BER-CLASSIFIED BEST-FIT AND ADAPTIVE MODULATION ALGORITHM

In wireless networks, traffic will be a mixture of voice, data, and video. Each service has its special QoS requirements, such as maximum tolerable BER and timeout requirements. When multimedia traffic is transmitted in OFDM/SDMA systems, the system capacity is largely limited by the traffic with the highest BER requirement [17, 18]. For example, voice packets can typically tolerate BER of up to 10^{-3}, while data packets require BER below 10^{-6}. As a result, it is wasteful to schedule voice and data packets in the same frequency subband, since the system must be able to satisfy the most stringent BER requirements among the packets that are being transmitted in the same frequency subband in the frame.

The main objectives of our scheduler are to maximize the throughput and to minimize the packet error rate. In this algorithm, traffic is classified by BER requirements. Then, packets of the same class are allocated in the same frequency subband. In this way, bandwidth can be used efficiently. Consider that each traffic class C_q, for $q = 1, 2, \ldots, T$, has a BER specification given by $B(C_q)$. BER is only determined by SINR given FEC and modulation.

These objectives can be achieved by the scheduler with two steps: (1) packet priority determination and (2) packet allocation in the frame. Particularly, the packet prioritizer minimizes the packet loss, while the packet allocator maximizes the frame throughput. The scheduler selects the packets with the highest priority for transmission, then allocates packets in the frequency subband. Packets with different priorities can be transmitted in the same OFDM/SDMA frequency subband as long as they have equal or similar BER requirements. We will illustrate these two steps in the following.

4.1. *Packet priority determination*

Many papers have proposed methods to determine packet priority, such as [9, 17, 19, 20]. The packet priority is used primarily when there are more packets for transmission than can be accommodated. The computation of packet priority is done dynamically at the start of each frame.

In this paper, we consider the case that each mobile terminal only supports one type of traffic. It is straightforward to extend the results to the heterogeneous traffic case.

We assume the buffer of terminal k has L_k packets, whose deadlines are $t_1, t_2, \ldots, t_{L_k}$. Let the current time be t_c. Then for the ith packet in the buffer, the minimum transmit rate is $r_i = 1/(t_c - t_i)$. If the transmission rate is larger than r_i, the packet can be transmitted before the timeout; otherwise, the packet will be discarded. Then, the total transmission rate at the current frame should be $\sum_{i=1}^{L_k}(1/(t_c - t_i))$, which indicates how many frequency subbands should be allocated in the frame for terminal k. Based on this idea, we define the priority of each packet in the queue as

$$\text{Priority}_k(i) = \sum_{j=i}^{L_k} \frac{1}{t_c - t_j}. \tag{15}$$

This priority definition is based on the total transmission rate of the packet and the remaining packets backlogged after it. If there are many packets in the buffer, the priority of the head of line packet is higher. This priority reflects the required transmission rate of the terminal. It is only related to packets in the same queue and is calculated independently, which reduces the complexity. On the other hand, the priority calculation is based on all packets in the buffer. Thus the longer the queues are, the higher the priority is. Though the priority calculation is based on heuristics, it works well as shown in the simulations.

4.2. *BER-classified Best-Fit packet allocation*

After packet prioritization, all the packets enter a buffer. The task of the allocator is to arrange the packets into OFDM/SDMA frequency subbands, so that the maximum packet throughput is achieved.

Based on the Best-Fit algorithm, we present a new packet scheduler. First, the scheduler tries to find the subbands having the same class packets, then empty subbands, then the subbands with more stringent SINR thresholds, and finally the subbands with more relaxed thresholds. The Best-Fit algorithm will be applied to these subbands.

The scheduler also keeps track of packets in subbands. For each packet, the scheduler needs two parameters.

(1) An ID to identify the mobile terminal. In an OFDM/SDMA frame, only one packet of a mobile can be transmitted in the same frequency subband.
(2) Traffic class C_q. It is used for BER scheduling.

The packet allocator will attempt to arrange the packets in the following steps.

Step 1. Search the subbands that contain the same traffic class C_q. If a set of such subbands are found, check if the number of packets is less than M; if not, ignore this subband. Then, the scheduler attempts to insert the packet into the frequency subband which has the largest SINR margin value. Then, it checks whether the SINR requirements of all the packets in the subband can be satisfied. If yes, the packet is allocated in the subband. If not, the subband with the second largest SINR margin is selected. If the packet cannot be allocated when all subbands with traffic class C_q are tried, go to Step 2.

Step 2. Search an empty subband. If found, arrange the packet in the empty subband. If no empty subband is found, the packet scheduler proceeds to Step 3.

Step 3. Search the frequency subband that has packets with more stringent BER requirements and has less than M packets. In other words, the scheduler will search for a frequency subband with traffic class C_{q-1}, which has more stringent BER requirements than C_q. If such subbands are found, the scheduler will try to place the packet into the frequency subband by the Best-Fit algorithm. If the subbands cannot accommodate the packet, the scheduler tries to find subbands of traffic classes $C_{q-2}, \ldots, C_1$ until the packet is allocated. In this step, the packet is allocated in the subband with more stringent BER requirement. If the packet still cannot be allocated, go to Step 4.

Step 4. Search the frequency subband that has packets with more relaxed BER requirements and has less than M packets. The scheduler looks for a frequency subband with traffic class C_{q+1}. If such subbands are found, based on the Best-Fit algorithm, the scheduler will test whether the packet can be added into the subbands. Then, the packets in this subband are converted into class C_q since more stringent BER requirement in the subband must be satisfied. Similarly, the scheduler looks for subbands with traffic classes $C_{q+1}, C_{q+2}, \ldots, C_T$. This operation will stop until the last subband with traffic class C_T is reached.

It is obvious that the packet scheduling algorithm finishes when the algorithm reaches Step 4. In the packet allocation procedure, the scheduler will check the ID of each packet to ensure that no more than one packet of the same mobile terminal is transmitted in the same frequency subband.

4.3. Adaptive modulation

Adaptive modulation can be applied to make better use of wireless resource and improve the system throughput.

Table 1: Complexity comparison.

Algorithm	First-Fit	Best-Fit	BER-classified
Complexity	$\frac{x+1}{2}$	$\frac{Mx}{2} + x!$	$\sum_{i=1}^{x/2} 1 + \frac{Mi}{2} + i!$

We consider a family of M-QAM signal constellations of BPSK, QPSK, and 16-QAM. All packets have the same fixed length. BER performance is related to both SINR and modulation. A high SINR value in a frequency subband enables the utilization of high M-QAM modulation level, which increases the system throughput.

After the above four steps of the scheduler operation, we consider adaptive modulation for users who still have packets in the buffer waiting for transmission. First, we should find out the frequency subband that contains the packets of these users. Second, we increase the modulation level of these packets. Since the packet length is fixed, if we increase the modulation level by one step, the number of bits that a subband can accommodate doubles, and two packets of the same user can be merged as one. Then, the scheduler will check in that frequency subband to determine if the SINR of all packets can be satisfied. If it can be satisfied, then the packet modulation level is increased. Otherwise, find the next frequency subband that contains the packet of that user. This operation will continue until all the frequency subbands are considered or there is no packets in the queues.

4.4. Complexity comparison

The complexity of an algorithm is important for practical systems. In this section, the complexity of each algorithm is given. As a measure of complexity, we consider the average number of operations to allocate a packet in the frame. Let x be the number of subbands in the frame, and let M be the maximum number of packets a subband can accommodate. The First-Fit algorithm tests all subbands in the frame, and the average number of operations to allocate a packet is $(x+1)/2$. The Best-Fit scheduler calculates the maximum SINR margin for each subband, then the subbands are ranked in decreasing order of the margin value. We assume the average number of packets in the subband is $M/2$, the number of operations for SINR margin is $Mx/2$, and $x!$ for subband ranking. The average complexity expression is shown in Table 1 and Figure 5. Here, M is set to be 4. Compared with the Best-Fit algorithm, the BER-classified Best-Fit complexity is much reduced.

5. SIMULATION RESULTS WITH MULTIMEDIA TRAFFIC

In this section, we present the simulation results for multimedia traffic. The packet scheduling algorithms include the Random-Fit, First-Fit, Best-Fit, and BER-classified Best-Fit. Adaptive modulation is combined with the BER-classified Best-Fit algorithm.

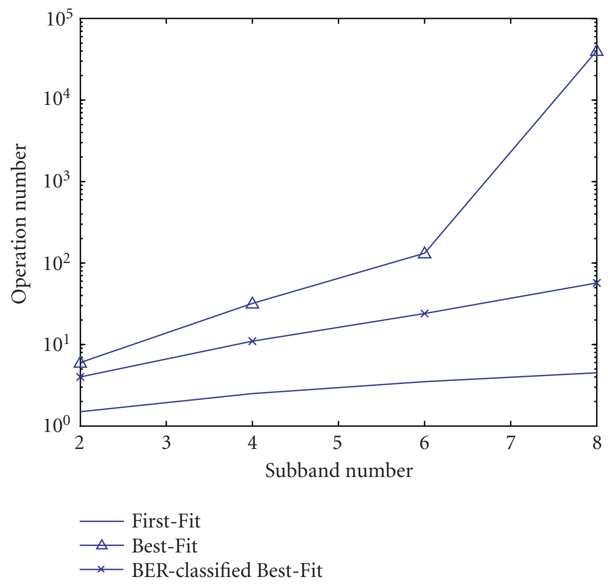

Figure 5: Complexity comparison.

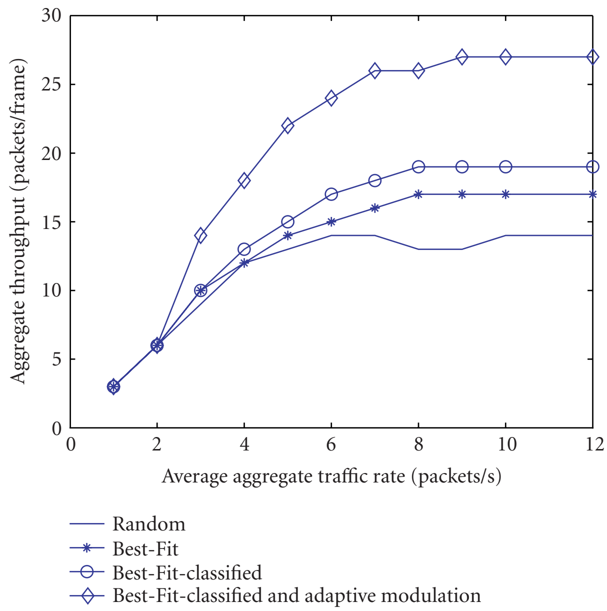

Figure 6: System capacity comparison.

5.1. Simulation setup

The base station has four antennas serving 100 mobile users. In OFDM, the bandwidth is divided into 64 subchannels. Only 48 subchannels are used to transport data packets, which are divided into eight frequency subbands. In other words, six subchannels in a frame are grouped as a frequency subband. We group 1000 OFDM symbols as a frame, which lasts for 4 milliseconds. Here, the total simulation time is 1 hour. Here, the wireless channel is a Rayleigh fading channel.

All packets have the same fixed length. The channel response during one frame time is regarded as a constant. The base station has perfect channel information for each user.

5.2. System capacity comparison with Poisson traffic

Figure 6 shows the system capacity of each algorithm with respect to the average packet arrival rate. There are two classes of packets whose SINR thresholds are 5 dB and 10 dB. As the packet arrival rate increases, it is found that the BER-classified Best-Fit scheduler has higher capacity than the original Best-Fit algorithm since the former considers the BER requirements of different users. Combining adaptive modulation with the proposed scheduler also improves the system capacity.

5.3. Simulation for multimedia traffic

We perform simulations with several different traffic models including the following:

(i) voice traffic,
(ii) CBR digital audio traffic,
(iii) CBR video traffic,
(iv) VBR video traffic,
(v) computer data traffic.

Table 2: Voice traffic model parameter.

State	Average duration time (s)
Principal talkspurt	1.00
Principal gap	1.35
Minispurt	0.275
Minigap	0.05

They generate different traffic classes with notable differences in the traffic characteristics and BER requirements.

5.3.1. Multimedia traffic models

The details of the different traffic models are described as follows.

Voice traffic: this model is based on the three-state Markov model presented in [21]. The speech source creates a patten of talkspurts and gaps. The duration of all spurts and gaps are exponentially distributed, and independent of each other. During the spurt states, the mobile generates a data rate of 16 kb/s. All the parameters of this model are listed in Table 2.

CBR digital audio traffic: this model represents the production of continuous bit stream of digital FM stereo audio. The constant bit rate of the stream is 128 k/s, and the average holding time of an audio call is 360 seconds with an exponential distribution [22]. The packet transmission rate is 10 packets/s.

CBR video traffic: in this model, a continuous bit stream is generated at 220 kbps. The interval between two packet transmissions is 0.05 second.

VBR video traffic: the video traffic is modeled by an eight-state Markov-modulated Poisson process (MMPP). In each state, the packet arrival satisfies a Poisson process. The

Table 3: Multimedia QoS requirements.

Traffic type	BER	Modulation	SINR (dB)	Time out (ms)
Voice	10^{-3}	BPSK QPSK	3 10	6
CBR digital audio	10^{-4}	BPSK QPSK	5 15	25
CBR video	10^{-5}	BPSK QPSK	6 18	15
VBR video	10^{-6}	BPSK QPSK	7 21	15
Computer data	10^{-7}	BPSK	8	200

Table 4: The breakdown of the traffic.

Traffic class	Percentage
Voice	50%
CBR audio	10%
CBR video	10%
VBR video	10%
Computer data	20%

average duration in each state is set to be 40 milliseconds. The bit rate values for different states are exponentially distributed. The average bit rate is also 220 kbps, the same as in CBR video traffic, but the BER threshold and delay requirements are different.

Computer data traffic: the transmission interval is exponentially distributed and the mean bit rate is 30 kbps.

The BER and timeout requirements of these traffics are listed in Table 3. In the simulation, adaptive modulation is applied. To simplify the simulation complexity, only BPSK and QPSK modulations are considered. By (11) and (12), the SINR threshold values with different modulations can be calculated by the BER requirements of different traffic classes.

5.3.2. Numerical results

In this section, we give the simulation results. We evaluate the performance of the BER-classified Best-Fit scheduler, and compare with the Best-Fit scheduler. The new mobile terminal arrival rates for different traffic classes are maintained constant throughout the simulations. The percentage of different traffic classes in the total traffic used in the simulation is listed in Table 4.

Figure 7 gives the system throughput of the schedulers of Best-Fit, BER-classified Best-Fit, and BER-classified Best-Fit with adaptive modulation. At light cell load, the system throughputs of all schedulers are the same. As cell load increases, the performance gap becomes more pronounced. It is obvious that BER-classified algorithm is better than Best-Fit. Adaptive modulation also contributes to the system throughput.

In Figure 8, the average packet loss rates of different schedulers are compared. The simulation results show that

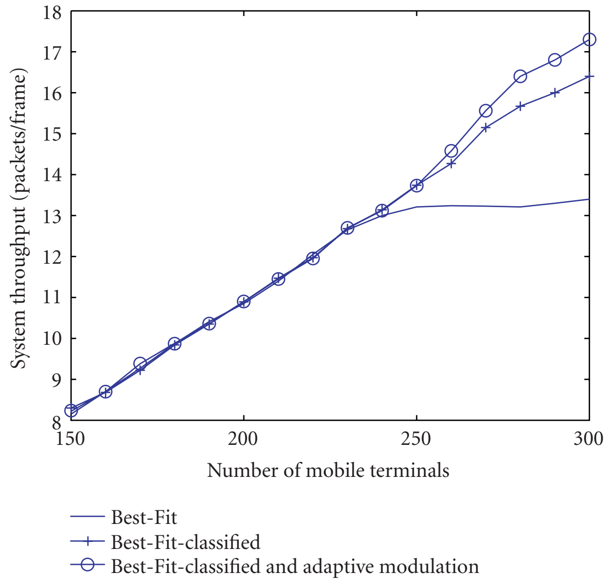

Figure 7: Multimedia system throughput comparison.

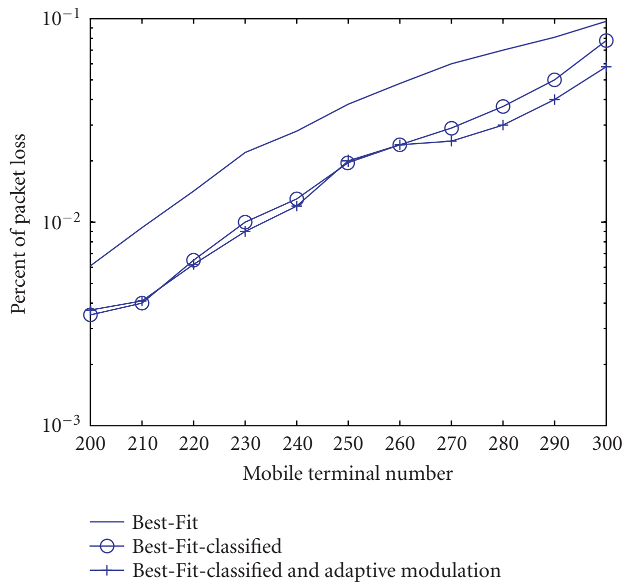

Figure 8: Packet loss rate comparison.

the average packet loss rate of Best-Fit is always larger than the other two schedulers. Adaptive modulation with Best-Fit also reduces the packet loss rate.

The average packet delay performance of the three packet schedulers are shown in Figure 9. In the simulation, it is found that the delay performance is related to the packet loss rate. In order to have a fair comparison, the delay performance of different schedulers, when we evaluate the average delay performance, the lost packets are also included, and the time delay is set to be the same as the timeout value. By comparison, we find that the delay of the Best-Fit scheduler is always larger than that of other schedulers. BER-classified

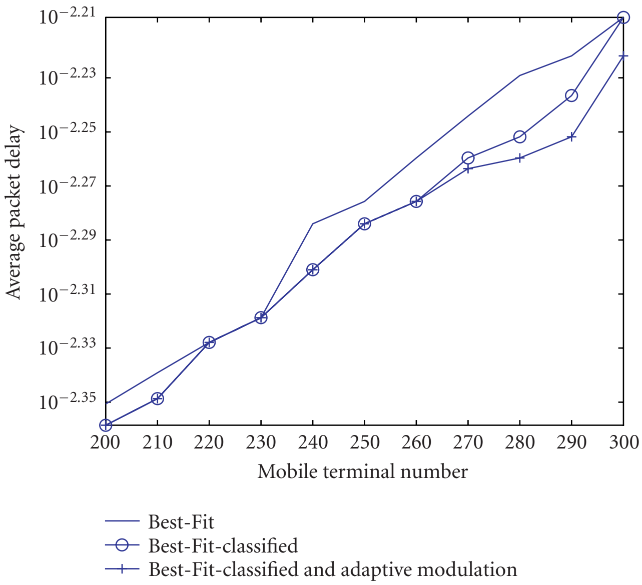

FIGURE 9: Packet delay comparison.

Best-Fit scheduler, with adaptive modulation, also reduces the average packet delay.

6. CONCLUSIONS

In this paper, we propose a dynamic packet allocation scheme with BER scheduling for OFDM/SDMA systems. All traffics are classified by the BER requirement. The algorithm tries to allocate the packets with the same BER class in a frequency subband. In this way, the system throughput is improved, and the complexity is also reduced when compared with the Best-Fit algorithm. Adaptive modulation is applied to improve the system performance. We simulate multimedia traffic with different QoS requirements. Comparing the throughput, delay, and packet loss rate, the BER-classified Best-Fit scheduler is always better than the Best-Fit scheduler, and adaptive modulation further enhances system performance. The number of subchannels in each subband will impact the system performance, and should be decided by the statistical channel quality. In frequency selective channel, the variations of the number of neighboring subchannels are correlated. Thus, scheduling with adaptive subband length will more effectively improve the system performance. We plan to study this in the future.

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REFERENCES

[1] IEEE 802.11 WG—Part 11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHz Band," Supplement to 802.11 standard, September 1999.

[2] ETSI, "Broadband radio access networks (BRAN); HIPERLAN Type 2 technical specification—Part I, Physical layer," October 1999.

[3] J. Litva and T. K. Lo, *Digital Beamforming in Wireless Communicaitons*, Artech, Norwood, Mass, USA, 1996.

[4] F. Shad, T. D. Todd, V. Kezys, and J. Litva, "Dynamic slot allocation (DSA) in indoor SDMA/TDMA using a smart antenna basestation," *IEEE/ACM Transactions on Networking*, vol. 9, no. 1, pp. 69–81, 2001.

[5] F. Piolini and A. Rolando, "Smart channel-assignment algorithm for SDMA systems," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 6, part 1, pp. 693–699, 1999.

[6] J. C. Liberti and T. S. Rappaport, *Smart Antennas for Wireless Communications: IS-95 and Third Generation CDMA Applications*, Prentice Hall, Upper Saddle River, NJ, USA, 1999.

[7] Z. Diao, D. Shen, and V. O. K. Li, "CPLD-PGPS scheduler in wireless OFDM systems," *IEEE Transactions on Wireless Communications*, vol. 5, no. 10, pp. 2923–2931, 2006.

[8] J. Chuang, L. J. Cimini Jr., G. Y. Li, et al., "High-speed wireless data access based on combining EDGE with wideband OFDM," *IEEE Communications Magazine*, vol. 37, no. 11, pp. 92–98, 1999.

[9] J. C.-I. Chuang and N. Sollenberger, "Beyond 3G: wideband wireless data access based on OFDM and dynamic packet assignment," *IEEE Communications Magazine*, vol. 38, no. 7, pp. 78–87, 2000.

[10] P. Vandenameele, L. Van Der Perre, M. G. E. Engels, B. Gyselinckx, and H. J. De Man, "Combined OFDM/SDMA approach," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 11, pp. 2312–2321, 2000.

[11] I. Koutsopoulos and L. Tassiulas, "Adaptive resource allocation in SDMA-based wireless broadband networks with OFDM signaling," in *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '02)*, vol. 3, pp. 1376–1385, New York, NY, USA, June 2002.

[12] D. Shen, Z. Diao, K.-K. Wong, and V. O. K. Li, "Analysis of pilot-assisted channel estimators for OFDM systems with transmit diversity," *IEEE Transactions on Broadcasting*, vol. 52, no. 2, pp. 193–202, 2006.

[13] A. Goldsmith, *Wireless Communications*, Cambridge University Press, Cambridge, UK, 2003.

[14] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, 1999.

[15] A. Goldsmith and S.-G. Chua, "Variable-rate variable-power MQAM for fading channels," *IEEE Transactions on Communications*, vol. 45, no. 10, pp. 1218–1230, 1997.

[16] H. Yin and H. Liu, "Performance of space-division multiple-access (SDMA) with scheduling," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 611–618, 2002.

[17] S. Choi and K. G. Shin, "Cellular wireless local area network with QoS guarantees for heterogeneous traffic," in *Proceedings of the 16th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '97)*, vol. 3, pp. 1030–1037, Kobe, Japan, April 1997.

[18] I. F. Akyildiz, D. A. Levine, and I. Joe, "A slotted CDMA protocol with BER scheduling for wireless multimedia networks," *IEEE/ACM Transactions on Networking*, vol. 7, no. 2, pp. 146–158, 1999.

[19] W. Anchun, X. Liang, Z. Shidong, X. Xibin, and Y. Yan, "Dynamic resource management in the fourth generation wireless systems," in *Proceedings of International Conference on Communication Technology (ICCT '03)*, vol. 2, pp. 1095–1098, Beijing, China, April 2003.

[20] K. B. Johnsson and D. C. Cox, "QoS scheduling of mixed priority non real-time traffic," in *Proceedings of IEEE Vehicular Technology Conference (VTC '01)*, vol. 4, pp. 2645–2649, Rhodes, Greece, May 2001.

[21] D. J. Goodman and S. X. Wei, "Efficiency of packet reservation multiple access," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 1, part 2, pp. 170–176, 1991.

[22] R. R. Roy, "Networking constraints in multimedia conferencing and the role of ATM networks," *AT&T Technical Journal*, vol. 73, no. 4, pp. 97–108, 1994.