Comparisons of link-adaptation-based scheduling algorithms for the WCDMA system with high-speed downlink packet access

Comparaisons des algorithmes d'établissement d'un programme basés sur l'adaptation de lien pour le système WCDMA avec l'accès à grande vitesse de paquet de downlink

Li-Chun Wang and Ming-Chi Chen*

The wideband code division multiple access (WCDMA) system with high-speed downlink packet access (HSDPA) is an important next-generation wireless system. By adopting adaptive modulation, efficient scheduling, and hybrid automatic repeat request technologies, it can support data rates of up to 10 Mb/s in the mobile cellular environment. Among these techniques, the scheduling algorithm plays a key role in realizing the HSDPA concept. A good scheduling algorithm should consider all the important factors, including channel impact, delay issues, and fairness. In this paper, a fairness index is adopted to examine the fairness performance of current link-adaptation-based scheduling algorithms, including the maximum carrier-to-interference (C/I), round-robin, proportional fair, and exponential rule schedulers. It is found that when multi-type services are supported, the fairness performance of current scheduling algorithms, including the round-robin scheduler, can be further improved even though the round-robin scheduler is viewed as the scheduler of the greatest fairness. Thus, a new scheduling algorithm, namely the queue-based exponential rule scheduler, is developed. Through simulations, it is shown that in the context of multi-type services the fairness performance of the queue-based exponential rule scheduler can surpass that of all the other schedulers in the time-multiplexing fashion, while maintaining good throughput and delay performance.

Le système de division de code d'accès multiple à large bande (WCDMA) avec l'accès à grande vitesse de paquet de downlink (*high-speed downlink packet access: HSDPA*) est un système important de radio de la prochaine génération. En adoptant la modulation adaptative, l'établissement d'un programme efficace, et les technologies automatiques hybrides de demande à répétition, le système peut supporter des taux d'informations supplémentaires jusqu'à 10 Mb/s dans l'environnement cellulaire mobile. Parmi ces techniques, l'algorithme d'établissement du programme joue un rôle principal en réalisant le concept de HSDPA. Un bon algorithme d'établissement d'un programme devrait considérer tous les facteurs importants comprenant l'impact de canal, le retard accusé, et l'équitabilité. Dans cet article, on adopte un index d'équitabilité afin d'examiner l'exécution d'équitabilité des algorithmes courants d'établissement d'un programme basés sur l'adaptation de lien, y compris le maximum C/I, le round-robin (la pétition revêtue de signatures), l'équité proportionnelle, et les programmateurs exponentiels de règle. En soutenant les services multi-types, on constate que l'exécution d'équitabilité des algorithmes d'établissement du programme courants, y compris le programmateur à pétition ou round-robin, peut encore être améliorée bien que le programmateur round-robin soit vu comme le programmateur de plus grande équitabilité. Ainsi, on est motivé pour développer un nouvel algorithme d'établissement du programme, à savoir le programmateur exponentiel basé sur la règle de file d'attente. À l'aide des simulations, on prouve que dans le contexte des services multi-types l'exécution d'équitabilité du programmateur exponentiel basée sur la règle de file d'attente peut surpasser tous les programmateurs de mode temps-multiplexage, tout en maintenant la bonne sortie et le bon délai d'exécution.

Keywords: HSDPA, scheduling, WCDMA systems

I. Introduction

In order to satisfy the fast-growing demand for wireless packet data services, the concept of high-speed downlink packet access (HSDPA) has been proposed as an evolution for the wideband code division multiple access (WCDMA) system [1]. The goal of the WCDMA system with HSDPA is to support peak data rates ranging from 120 kb/s to 10 Mb/s by adopting many advanced techniques, such as fast link adaptation, fast physical-layer retransmission, and efficient scheduling techniques [2]. A fast link-adaptation mechanism can enhance throughput performance by adapting modulation and coding schemes in the rapidly changing radio channel. The hybrid automatic repeat request (HARQ) technique can improve the radio link performance by combining retransmitted packets with previous erroneous packets. Scheduling is the key to achieving fairness in a shared channel for multiple users. Basically, a scheduling algorithm selects the most suitable user to access the channel in order to optimize throughput, fairness, and delay performance.

Recently, scheduling has attracted much attention for wireless data networks because it can exploit the multi-user diversity [3]–[4]. In the traditional voice-oriented cellular network, the fluctuation of fast fading is viewed as a drawback. However, channel variations can also be beneficial for the wireless *data* network. Because data services can tolerate some delay, a scheduling mechanism can be designed to select the user with the highest channel peak and serve one user at a time in a time-multiplexing fashion. With a higher channel peak, a more efficient modulation/coding scheme can be applied to enhance data rates. In general, a larger dynamic range of channel variations can yield higher channel peaks, thereby delivering larger multi-user diversity gain.

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In addition to throughput optimization, service delay and fairness are two additional important aspects that need to be taken into account in designing a good scheduling algorithm. The reason why wireless scheduling can improve system throughput lies in the fact that data services can tolerate a certain level of delay. Nevertheless, a constraint on the maximum service delay is still necessary. In wireless systems, mobile users are located at different locations with different channel conditions. If a scheduler always selects the user with the best channel condition, some users at the cell boundary, for instance, may never have a chance to access the system. Hence, how to design a scheduling algorithm to achieve high throughput subject to delay and fairness constraints becomes a crucial and challenging issue for the wireless data network.

In the literature, wireless scheduling algorithms can be categorized into two major types according to the considered channel models. First, the wireless scheduling algorithms in [5], [6] and [7] consider a two-state on-off Markov channel model. Because of its simplicity, the two-state Markov channel model is suitable for examining the fairness performance of scheduling algorithms. However, using the simple two-state Markov channel has limitations in capturing actual radio channel characteristics. Second, some wireless scheduling algorithms like those in [1], [8], [9] and [10] consider a more practical radio channel model with the emphasis on exploiting the multi-user diversity. In [1], the maximum carrier-to-interference ratio (C/I) scheduler is designed to assign the channel to the user with the best C/I. Obviously, the maximum C/I scheduler fully utilizes the multi-user diversity, but employs an unfair scheduling policy. In contrast to the maximum C/I scheduler, a fair time scheduler (also called round-robin scheduling algorithm [8]) allocates the channel to users in sequence with equal service time. Clearly, the fair time scheduler does not consider the channel effect. In [2], [8], [9] and [11], the proportional fair scheduler was proposed for the IS-856 system and the WCDMA system. The proportional fair scheduler improves the fairness performance of the maximum C/I scheduler at the cost of lowering system throughput. However, in [10] it was pointed out that the proportional fair scheduling algorithm does not account for service delays. Thus, the authors in [10] proposed the exponential rule scheduler to improve the delay performance of the proportional fair scheduler. It was proved that the exponential rule scheduler is throughput-optimal in the sense of making a service queue stable [12]. In [13], it was concluded that the exponential rule scheduler is superior to the proportional fair scheduler since it provides excellent latency performance even with a slightly lower system throughput. Nevertheless, the factor of queue length is still not explicitly considered in the exponential rule scheduling policy.

To our knowledge, a wireless scheduling policy that considers all the factors, namely channel variation, service delay, and queue length, is still lacking in the literature. Consequently, we are motivated to develop such a wireless scheduling algorithm. The contributions of this work are twofold. The first contribution of this work is to propose a queue-based exponential rule scheduler to explicitly take into account all the factors, namely queue length, service delay, and channel variation. We find that the queue-based exponential rule scheduler can further improve the fairness performance as compared to the original exponential rule scheduler, while maintaining the same throughput and delay performance.

Second, in the context of multi-type services, we suggest a fairness index to evaluate the fairness performance of the link-adaptation-based wireless scheduling algorithms, i.e., the maximum C/I, proportional fair, and exponential rule schedulers. This fairness index is modified from the one used in the two-state Markov-channel-based wireless scheduling algorithms [5]–[7], [14]. Interestingly, we find that the fairness of current link-adaptation-based wireless scheduling algorithms [1], [8]–[9], [10] is not clearly specified. Thus, we are motivated to adopt a formal fairness index to evaluate the fairness performance of these link-adaptation-based wireless scheduling algorithms. Using this fairness index to compare scheduling algorithms is important, especially in the case of multi-type services. For example, the fair time (or round-robin) scheduler is viewed as the performance upper bound in terms of fairness for most link-adaptation-based wireless scheduling algorithms. However, this upper bound is valid only under the assumption that all users subscribe to the same type of service in any particular duration. In the case of multi-type services, the fair time scheduler can only guarantee equal access time for multiple users, but cannot ensure satisfaction of the different requirements for different users. Thus, even the fair time scheduler may not be the fairest scheduling algorithm in supporting multi-type services. Hence, to support multi-type services, it is important to re-evaluate the fairness of these link-adaptation-based wireless scheduling algorithms based on a formal fairness index. Our simulation results show that in the time-multiplexing fashion, the fairness performance of the exponential rule scheduler is very close to that of the fair time scheduler and both schemes are superior to the proportional fair scheduler. On the other hand, in the code-multiplexing fashion, we find that the exponential rule scheduler is only slightly better than the proportional fair rule, and both schemes are worse than the fair time scheduler.

Table 1
Modulation and coding schemes in HSDPA

Modulation and coding schemes (MCS)	Modulation	Effective code rate
MCS 1	QPSK	1/4
MCS 2	QPSK	1/2
MCS 3	QPSK	3/4
MCS 4	16-QAM	1/2
MCS 5	16-QAM	3/4

The rest of this paper is organized as follows. Section II briefly introduces the background of the HSDPA concept in the WCDMA system. Section III describes existing link-adaptation-based scheduling algorithms. We discuss our proposed new queue-based exponential rule scheduling algorithm in Section IV. Simulation results are presented in Section V. Finally, we give our concluding remarks in Section VI.

II. High-speed downlink packet access

In this section, we introduce three key technologies in implementing the HSDPA concept, including adaptive modulation and coding, fast scheduling, and multi-code assignment.

A. Adaptive modulation and coding

Adaptive modulation and coding is a link-adaptation technique to adapt transmission parameters to the time-varying channel conditions. The basic principle in applying adaptive modulation and coding is to assign higher-order modulation and higher code rate to the users in favourable channel conditions, whereas lower-order modulation and lower code rate are allocated to the users in unfavourable channel conditions. To obtain the channel conditions, the receiver is required to measure the channel conditions and feedback to the transmitter periodically, e.g., 2 ms of every transmission time interval (TTI) in HSDPA. The major benefit of adaptive modulation and coding is the delivery of a higher data rate to the user with better channel conditions, resulting in increased average throughput of the cell. Table 1 lists the modulation and coding schemes used in HSDPA.

B. Fair scheduling

In the downlink shared channel, scheduling techniques can be used to exploit multi-user diversity by taking advantage of short-term channel variations of each user terminal. With scheduling, the selected user is always served in the high channel peak or a constructive fade. When combined with adaptive modulation and coding, the scheduled user therefore has a better chance of transmitting at a higher rate with higher-order modulation and higher code rate.

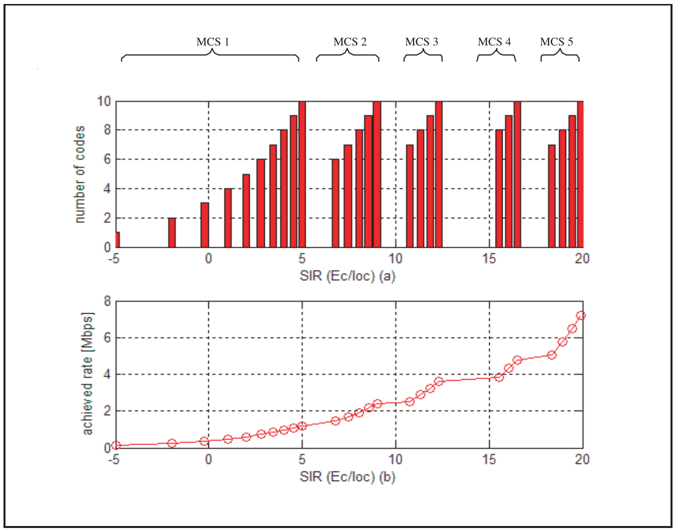

Figure 1: *The hull curve with five modulation and coding schemes and the multi-code operation of maximum* 10 *codes [1].*

C. Multi-code assignment

To achieve a higher data rate in HSDPA, adaptive modulation and coding technique needs to function together with multi-code assignment. Because the number of modulation and coding schemes is limited (e.g., only five formats in HSDPA), the dynamic range of selecting an adaptive modulation and coding scheme may not be enough; e.g., 15 dB of dynamic range in an example from Fig. 51 in [1]. To increase the dynamic range of adapting transmission parameters to channel variations, selecting both the modulation/coding scheme and the number of codes is an effective method. Fig. 1 shows the *hull* curve of five modulation/coding schemes combined with the multi-code operation of 10 codes. As shown in the figure, the dynamic range of selecting transmission parameters for different E_c/I_{oc} (i.e., signal-to-interference ratio (SIR)) values becomes -5 to 20 dB, which is 10 dB larger than the single-code case of [1]. Generally speaking, it is better to increase the number of multi-codes first before transiting to the next higher order of modulation/coding scheme from a spectral-efficiency viewpoint. Note that Fig. 1 in this paper is produced by referring to Fig. 51 of [1]; neither figure considers HARQ. If ARQ is considered, we can straightforwardly use the hull curve of adaptive modulation and coding with ARQ in the single-code operation (e.g., Fig. 50 of [1]) to produce a hull curve of the adaptive modulation/coding scheme with HARQ for the multi-code operation.

III. Current link-adaptation-based scheduling algorithms

As mentioned, the key factor in determining the performance of the WCDMA system with HSDPA is the link-adaptation-based scheduling algorithm [1], [8]–[9], [10]. We will evaluate these scheduling algorithms in terms of three performance metrics: system throughput, delay, and fairness. In order to achieve multi-user diversity, a good scheduling algorithm should take into account channel variations. The greater the multi-user diversity, the higher is the system throughput. However, for some delay-sensitive services, such as streaming video, a good scheduler also needs to pay attention to the latency performance. Furthermore, from the standpoint of an individual user, it is desirable to be treated as fairly as other users in terms of receiving service. Thus, to design a good scheduling algorithm, we need to develop a better tradeoff design among these three performance metrics.

Before we detail the scheduling algorithms, let us first define the following notations:

- k: the index of the k-th transmission time interval (TTI);
- $\gamma_i(k)$: the short-term SIR of user i averaged in the $(k-1)$-th TTI;
- $\overline{\gamma_i(k)}$: the long-term average SIR of user i observed in $[(k-T),k]$, where T is the length of the sliding window in terms of the number of TTIs;
- $d_i(k)$: the delay time for the packet waiting in the head-of-line (HOL) TTI before receiving service for user i;
- $q_i(k)$: the queue length of user i at the beginning of the k-th TTI.

A. Maximum C/I scheduler

The maximum C/I scheduler always selects the user with the best carrier-to-interference ratio. At the beginning of each TTI, the scheduler compares the C/I levels of all active users and grants the channel access to the user with the highest C/I level. Specifically, the maximum C/I scheduler will select user j in the k-th TTI if

$$j = \arg\{\max_i \gamma_i(k)\}. \tag{1}$$

Obviously, the maximum C/I scheduler represents the upper bound in terms of system throughput because it can achieve the maximum multi-user diversity. However, those who are located far from the base station may feel they are being unfairly treated due to the poor radio link condition. This unfairness phenomenon makes the maximum C/I scheduler impractical.

B. Fair time scheduler

At any scheduling instant, the fair time scheduler serves all non-empty source queues in a round-robin fashion; that is, the fair time scheduler will schedule user j in the k-th TTI if

$$j = \bmod\,((k-1), N) + 1, \tag{2}$$

where $\bmod(\cdot)$ denotes the modulus operator and N is the number of active users in the system. One can easily find that this fair time scheduling algorithm is independent of the channel characteristics and thus does not exploit the multi-user diversity at all. However, this scheduler has the best delay performance and is much fairer than the maximum C/I scheduler. Note that the fairness here is defined from the viewpoint of equal access probability. In this paper, we will adopt another fairness index used in the two-state Markov-channel-based wireless scheduling algorithms [14] to examine the fairness performance of the scheduling algorithms.

C. Proportional fair scheduler

The proportional fair algorithm was proposed for the high-data-rate (HDR) system [9]. The basic idea of this algorithm is to select a scheduled user based on the ratio of the short-term SIR over the long-term averaged SIR value with respect to each active user. The proportional fair scheduler takes advantage of the temporal variations of the channel to increase system throughput, while maintaining a certain level of fairness among all active users. Specifically, the proportional fair scheduler will schedule user j in the k-th TTI if

$$j = \arg\left\{\max_i \frac{\gamma_i(k)}{\overline{\gamma_i(k)}}\right\}. \tag{3}$$

Based on the above criterion, $\overline{\gamma_i(k)}$ is the average SIR measured over a sliding window as follows:

$$\overline{\gamma_i(k+1)} = \begin{cases} (1-\frac{1}{T})\overline{\gamma_i(k)} + \frac{1}{T}\gamma_i(k) & \text{if user } i \text{ is scheduled,} \\ (1-\frac{1}{T})\overline{\gamma_i(k)} & \text{if user } i \text{ is not scheduled.} \end{cases}$$

Note that the proportional fair scheduler does not consider the delay issue in each user's service queue and thus has poor delay performance.

D. Exponential rule scheduler

The exponential rule is a modified version of proportional fair. This scheduler further takes delay issues into consideration [10], [13]. This policy tries to balance the weighted delay of all active users when the differences of weighted queue delay among users become significant. For the k-th TTI, the exponential rule scheduler will choose user j if

$$j = \arg\left\{\max_i a_i \frac{\gamma_i(k)}{\overline{\gamma_i(k)}} \exp\left(\frac{a_i d_i(k) - \overline{ad(k)}}{1+\sqrt{\overline{ad(k)}}}\right)\right\}, \qquad (4)$$

where

$$\overline{ad(k)} = \frac{1}{N}\sum_{i=1}^{N} a_i d_i(k) \qquad (5)$$

and $a_i > 0,\ i = 1, \ldots, N$, are selected weights to characterize the desired quality of service.

To understand the idea behind the exponential rule scheduler, let us focus on the exponent term of (4). If an active user has a larger weighted delay than others by more than $\sqrt{\overline{ad(t)}}$, then the exponent term will become dominant and even exceed the impact of channel effect. In such a case, this user will get a higher-priority access opportunity. On the other hand, for small differences in the weighted delay, the exponent term will approach 1, and the exponential rule scheduler will be exactly the same as the original proportional fair rule scheduler. Note that the factor 1 in the denominator of (4) is included to prevent the exponent term from increasing dramatically when $\sqrt{\overline{ad(t)}}$ is too small. In brief, the exponential rule scheduler incorporates the effect of both channel variations and service delay and aims to further improve performance compared to the proportional fair scheduler.

IV. Proposed queue-based exponential rule scheduler

In this section, we will first define fairness and then propose an improved version of the exponential rule scheduler.

A. Definition of fairness

Based on the traditional fluid fair queueing in wireline networks, backlogged flows are served in proportion to their weighted rate. Mathematically, for any time interval $[t_1, t_2]$, the channel capacity allocated to flow i, denoted as $W_i(t_1, t_2)$, should satisfy the following condition [14]–[15]:

$$\left|\frac{W_i(t_1,t_2)}{r_i} - \frac{W_j(t_1,t_2)}{r_j}\right| = 0, \quad \forall i, j \in B(t_1, t_2), \qquad (6)$$

where r_i and r_j are the weights of flows i and j, respectively, and $B(t_1, t_2)$ is the set of backlogged flows during (t_1, t_2).

However, this condition in terms of bits cannot be maintained in a practical packet-switched network. The goal of the packetized fair queueing algorithm is to minimize the difference of $|W_i(t_1,t_2)/r_i - W_j(t_1,t_2)/r_j|$. Therefore, we define a fairness index as follows:

$$\mathrm{FI} = \frac{1}{l}\left|\frac{W_i(t_1,t_2)}{r_i} - \frac{W_j(t_1,t_2)}{r_j}\right|, \qquad (7)$$

where l is a normalization factor of the packet size. In wireless networks, many wireless scheduling algorithms, such as idealized wireless fair queueing (IWFQ) [5], channel-condition-independent fair queueing (CIF-Q) [6], and wireless fair service (WFS) [7], have been proposed to minimize the value of FI during a long period, i.e., to achieve long-term fairness. Here, we define the packet size as the number of data bits that can be transmitted at the minimum data rate during one transmission time interval.

B. Queue-based exponential rule scheduler

The exponential rule scheduler considers the effect of the delay time in the head-of-line TTI. However, it does not *explicitly* incorporate the factor of queue length into the scheduling policy. By observing (7), we note that to achieve fairness, we need to consider not only the HOL delay, but also the queue length. Consequently, we are motivated to propose a queue-based exponential rule scheduler as follows. In the k-th TTI, the proposed scheduler will choose user j if

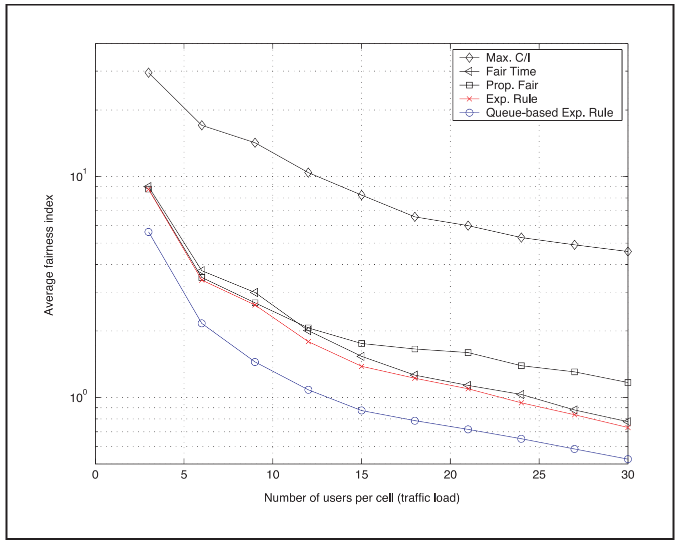

Figure 2: *The average fairness index value for all schedulers without multi-code operation in a time-multiplexing fashion.*

$$j = \arg\left\{\max_i a_i \frac{\gamma_i(k)}{\overline{\gamma_i(k)}} \exp\left(\frac{a_i d_i(k) - \overline{ad(k)}}{1+\sqrt{\overline{ad(k)}}}\right) \cdot \exp\left(\frac{q_i(k) - \overline{q(k)}}{1+\overline{q(k)}}\right)\right\}, \qquad (8)$$

where

$$\overline{ad(k)} = \frac{1}{N}\sum_{i=1}^{N} a_i d_i(k) \qquad (9)$$

and

$$\overline{q(k)} = \frac{1}{N}\sum_{i=1}^{N} q_i(k). \qquad (10)$$

The basic idea of the second exponent term in (8) is to balance the service queue length among multiple users. Moreover, in order to prevent the magnitude of the second exponent term from exceeding that of the first exponent term, the denominator of the second exponent term does not take the square root as does that of the first exponent term.

C. Time-multiplexing fashion versus code-multiplexing fashion

In HSDPA, there are five available modulation and coding schemes and 16 orthogonal variable spreading factor (OVSF) codes [8]. There are two methods for implementing the multi-code operation. One is to assign all available multi-codes to one user at a time in a pure time-multiplexing fashion. The other is to assign different active users to each code in a code-multiplexing fashion. For the code-multiplexing multi-code assignment, we can treat each code as a server, and scheduling algorithms will select suitable users for multiple servers simultaneously. Note that the total power budget in each base station is equally shared by all codes for both methods. The performance comparison of these two methods will be discussed in Section V.

V. Simulation results

Through simulation, we compare the performances of different scheduling algorithms. Three types of simulation configuration are

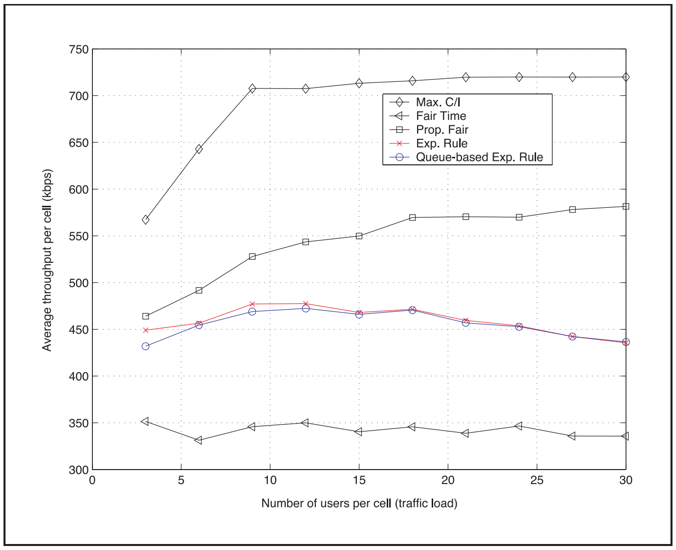

Figure 3: *System throughput performance of all schedulers without multi-code operation in a time-multiplexing fashion.*

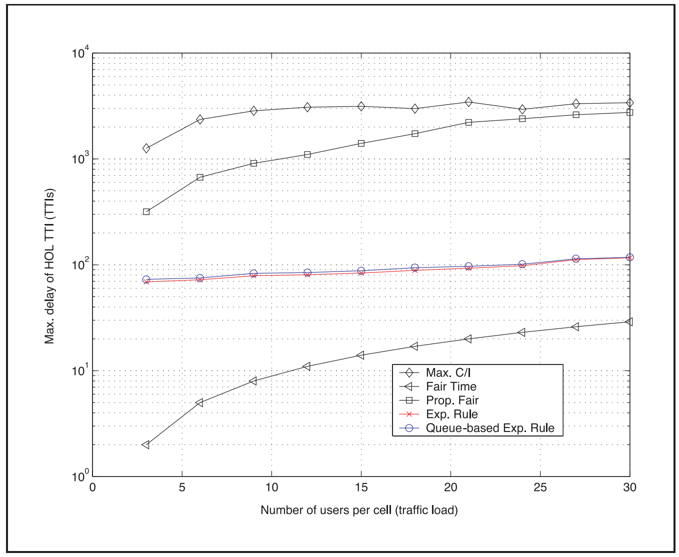

Figure 4: *Maximum delay performance of all schedulers without multi-code operation in a time-multiplexing fashion.*

Table 2
Simulation parameters

Parameters	Explanation/Assumption
Cell layout	7 hexagonal cells
Cell radius	1.6 km
User location	Uniform distribution
Antenna pattern	Omni-direction
Propagation model	$L = 128.1 + 37.6 \log 10(R)$
HS-DSCH power/ Total node-B power	60%
Shadowing standard deviation	8 dB
Correlation distance of shadowing fading	50 m
Carrier frequency	2 GHz
Base station total transmit power	44 dBm
Fast fading model	Jakes spectrum
Number of HS-DSCH multi-codes	10
Transmission time interval (TTI)	2 ms
Simulation duration	5000 TTIs

considered. First, we focus on the performance with single-code operation in the time-multiplexing fashion. In this case, the maximum data rate for each scheduled mobile user is 720 kb/s. In the second simulation configuration, we focus on the performance with multi-code operation in the time-multiplexing fashion. With maximum 10 codes, the maximum achieved data rate in this configuration becomes 7.2 Mb/s. For the third simulation configuration, we investigate the performance with multi-code operation in the code-multiplexing fashion.

A. Simulation model

We consider a cell layout with a centre cell surrounded by six neighbouring cells. We focus only on the performance of the centre cell and treat other cells as the sources causing the downlink interference. The mobile users are uniformly located in the centre cell. We assume that 60% of the total base station transmitted power is allocated in supporting the HSDPA services. In HSDPA, there are 16 orthogonal codes with processing gain of 12 dB. Nevertheless, many other dedicated, shared and common channels may also need to use some codes. Thus, for the multi-code operation in HSDPA, the suggested maximum number of codes that can be assigned to a user is 10 [8]. Table 2 lists other parameters used in our simulations [1].

We apply the *hull* curve of the link-level simulation results obtained from [1] to our system-level simulation. For each randomly located mobile user, the system will first calculate the corresponding received signal-to-interference ratio. It is assumed that the measured SIR in each mobile can be correctly sent back to the base station in time. We consider a mobile at a speed of 3 km/hr in a flat Rayleigh fading channel, or equivalently the maximum Doppler frequency $f_d = 5.5$ Hz.

B. Single-code operation in the time-multiplexing fashion

Fig. 2 compares the fairness performance according to the fairness definition of (7) for all the considered schedulers. Based on (7), the smaller the fairness index, the fairer is the system. Obviously, the scheduler with the least fairness is the maximum C/I scheduler. The fair time scheduler, proportional fair scheduler and exponential rule scheduler have almost equal fairness performance. It is noteworthy that the proposed queue-based exponential rule scheduler is fairer than all the other schedulers. Specifically, the proposed new scheduling algorithm improves the fairness index values by 31% to 50% as compared to the original exponential rule scheduler.

Fig. 3 compares the throughput performance of the proposed scheduling algorithm with that of four existing scheduling algorithms. For the maximum C/I scheduler, we find that when the number of users in the system increases, the system throughput improves because more multi-user diversity gain is achieved. The fair time scheduler exhibits the lowest throughput, whereas the throughput of the proportional fair scheduler is between that of the maximum C/I scheduler and that of the fair time scheduler. Our proposed queue-based exponential rule scheduler performs as well as the original exponential rule scheduler, but has lower throughput than the proportional fair scheduler. Note that when the number of users per cell increases, the achieved average throughput of both the exponential rule scheduler and queue-based exponential rule scheduler decreases slightly because the effect of the exponent term becomes dominant for the case with a large number of users in the system. Although the proportional fair scheduler has better throughput, the exponential rule scheduler has better delay performance, as will be discussed next.

Fig. 4 shows the delay performance of the considered schedulers in terms of maximum delay for the packet waiting in the HOL TTI. In general, higher traffic load causes longer delay due to the presence of more contenders. One can find that both the maximum C/I and proportional fair schedulers have very poor delay performance. As expected, the fair time scheduler has the best performance. Note that both the proposed queue-based exponential rule scheduler and the original exponential rule scheduler perform well and have the same delay perfor-

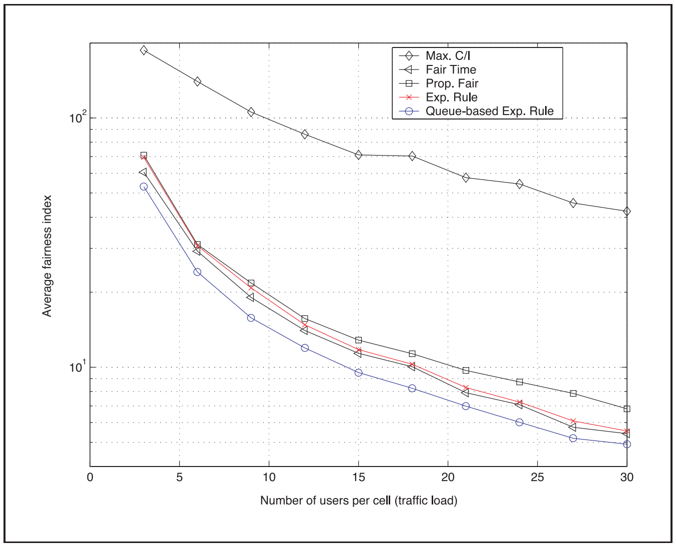

Figure 5: *The average fairness index value for all schedulers with multi-code operation in a time-multiplexing fashion.*

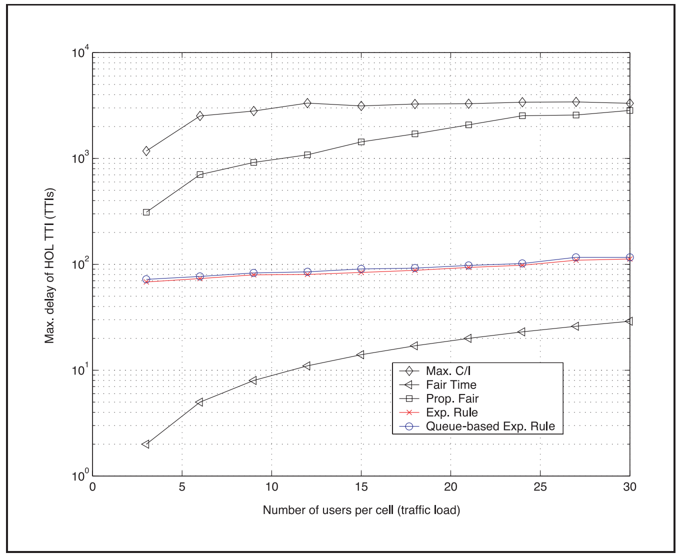

Figure 7: *Maximum delay performance of all schedulers with multi-code operation in a time-multiplexing fashion.*

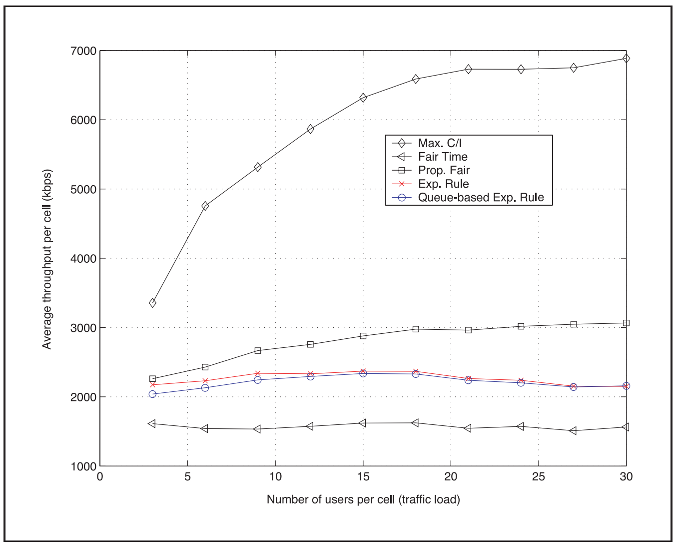

Figure 6: *System throughput performance of all schedulers with multi-code operation in a time-multiplexing fashion.*

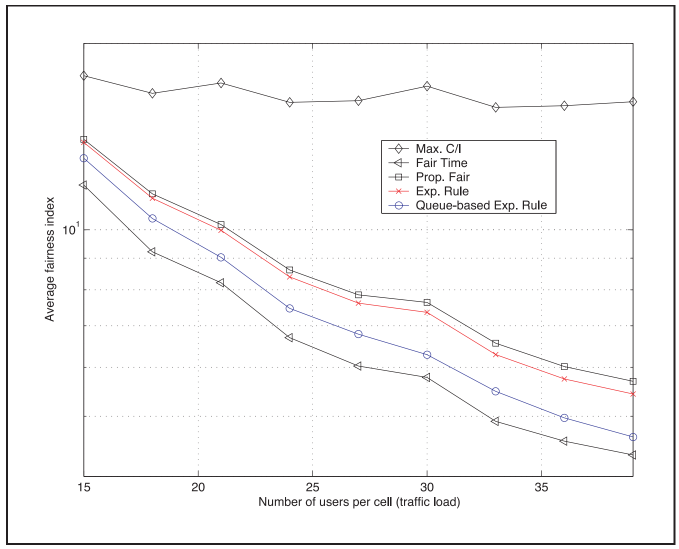

Figure 8: *The average fairness index value for all schedulers with multi-code operation in a code-multiplexing fashion.*

mance, while the proposed queue-based exponential rule scheduler has better fairness performance, as shown in Fig. 2 previously.

C. Multi-code operation in the time-multiplexing fashion

Figs. 5, 6 and 7 show the performance of fairness, system throughput and delay, respectively, for different schedulers with multi-code operation in the time-multiplexing fashion. Basically, the trends of these performance curves are the same as in the single-code case except that for the multi-code operation, the maximum achievable system throughput becomes 7.2 Mb/s. Again, the fairness index of the proposed new algorithm shows improvement ranging from 15% to 30% as compared to the original exponential rule scheduler, even while the algorithm maintains the same throughput and delay performance.

D. Multi-code operation in the code-multiplexing fashion

Fig. 8 shows the fairness performance of all schedulers in the case of the code-multiplexing model. Interestingly, we find that the exponential rule scheduler is only slightly better than the proportional fair scheduler, and both schemes are worse than the fair time scheduler. Nevertheless, when we further evaluate the variance of the fairness index for different schedulers, as shown in Fig. 9, we find that the variation of the fairness index of the queue-based exponential rule scheduler is much smaller than that of the fair time scheduler. This phenomenon implies that the proposed queue-based exponential rule scheduler still has a high possibility of being fairer than the fair time scheduler even in the code-multiplexing case. In addition, the proposed new algorithm improves the fairness index value by 5% to 15% as compared to the original exponential rule scheduler.

Fig. 10 shows the system throughput performance of all schedulers with multi-code operation in the code-multiplexing fashion. We consider more than 10 users in this simulation. We find that the code-multiplexing fashion cannot fully take advantage of the multi-user diversity even for the maximum C/I method. This observation shows that assigning only one user at a time can achieve the maximum system throughput, as was also mentioned in [4]. Specifically, comparing Fig. 6 with Fig. 10 for the case of system load equal to 15 users, we observe that the proposed scheduling algorithm can provide 2.3 Mb/s of system throughput in the time-multiplexing scheme, while in the code-multiplexing scheme the throughput decreases to 1.8 Mb/s.

Fig. 11 compares the corresponding delay performance of all schedulers in the code-multiplexing case. Because there are more servers during each scheduling instant, the delay performance in code-

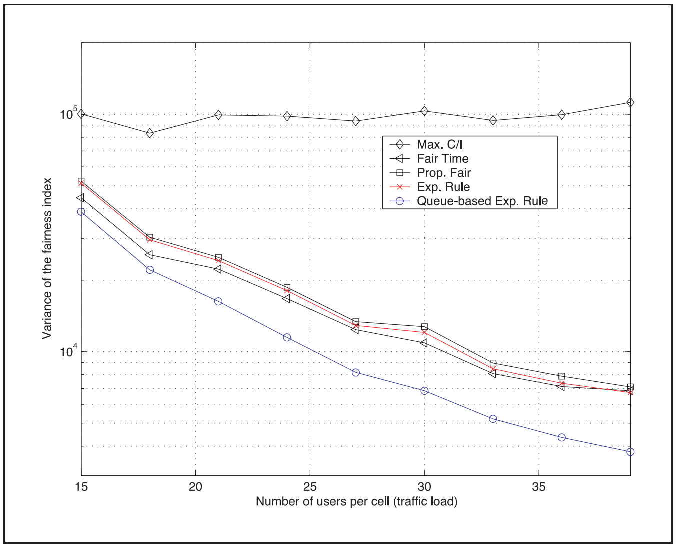

Figure 9: *The variance of fairness index value for all schedulers with multi-code operation in a code-multiplexing fashion.*

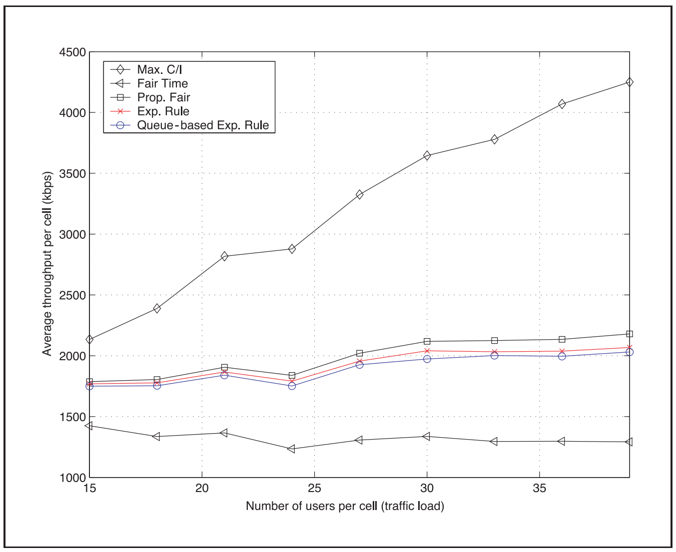

Figure 10: *System throughput performance of all schedulers with multi-code operation in a code-multiplexing fashion.*

multiplexing is much better than that in the time-multiplexing fashion. For example, in the case of 30 users, the maximum delay of the queue-based exponential rule scheduler in the code-multiplexing fashion is reduced to 80 TTIs, as compared to 100 TTIs in the time-multiplexing fashion. Thus, when comparing the performance between the second and third simulation configurations, we conclude that the delay performance of the code-multiplexing scheme is better than that of the time-multiplexing scheme at the expense of lower system throughput compared to the time-multiplexing scheme.

VI. Conclusion

In this paper, we adopted a fairness index to examine the fairness performance of current link-adaptation-based scheduling algorithms, including the maximum C/I, fair time, proportional fair, and exponential rule schedulers. Moreover, we proposed a new queue-based exponential rule scheduler for the HSDPA system. As summarized in Table 3, the proposed scheduling algorithm outperforms all the existing scheduling algorithms in terms of fairness for the time-multiplexing fashion. In the time-multiplexing case, the proposed queue-based exponential rule scheduler improves the fairness index by 15% to 50%

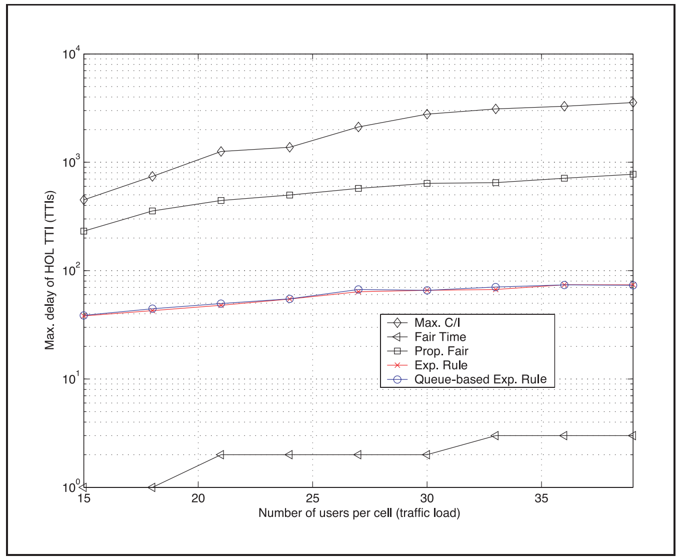

Figure 11: *Maximum delay performance of all schedulers with multi-code operation in a code-multiplexing fashion.*

Table 3
Comparison of link-adaptation-based scheduling algorithms in terms of fairness, throughput, and delay in the time-multiplexing fashion

Scheduling policy	Fairness	Delay	Throughput
Maximum C/I	Poor	Poor	Excellent
Fair time	Good	Excellent	Poor
Proportional fair	Acceptable	Poor	Good
Exponential rule	Good	Good	Acceptable
Queue-based exponential rule	Excellent	Good	Acceptable

Comparison level: excellent > good > acceptable > poor

compared to the original exponential rule algorithm, while in the code-multiplexing case the improvement is in the range of 5% to 15%. For the code-multiplexing configuration, Table 4 compares the schedulers with respect to fairness, delay, and throughput. Note that although the fairness performance of the proposed queue-based exponential rule scheduler is slightly worse than that of the fair time scheduler in terms of the average fairness index value, the variation in the fairness index value of the proposed scheduler is smaller than that of the fair time scheduler, demonstrating that it retains the possibility of being fairer than the fair time scheduler. It is noteworthy that in both the time-multiplexing and code-multiplexing cases, the proposed queue-based exponential rule scheduler and the original exponential rule scheduler improve the fairness and delay performance compared with the proportional fair scheduler at the cost of slightly degraded throughput. In terms of the comparison between code-multiplexing scheduling and time-multiplexing scheduling, we find that the time-multiplexing method is a better choice when all the factors of system throughput, service delay, and fairness are taken into consideration.

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Table 4
Comparison of link-adaptation-based scheduling algorithms in terms of fairness, throughput, and delay in the code-multiplexing fashion

Scheduling policy	Fairness	Delay	Throughput
Maximum C/I	Poor	Poor	Excellent
Fair time	Excellent	Excellent	Poor
Proportional fair	Acceptable	Poor	Acceptable
Exponential rule	Acceptable	Good	Acceptable
Queue-based exponential rule	Good	Good	Acceptable

Comparison level: excellent > good > acceptable > poor

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