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Scheduling with base station diversity and fairness analysis for the downlink of CDMA cellular networks

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Summary

Efficient packet scheduling in CDMA cellular networks is a challenging problem due to the time variant and stochastic nature of the channel fading process. Selection diversity is one of the most effective techniques utilizing random and independent variations of diverse channels to improve the performance of communication over fading channels. In this paper, we propose two packet scheduling schemes exploiting base station selection diversity in the downlink of CDMA cellular networks. The proposed schemes rely on the limited instantaneous channel state information (CSI) to select the best user from the best serving base station at each time slot. This technique increases the system throughput by increasing multiuser diversity gain and reducing the effective interference among adjacent base stations. Results of Monte Carlo simulations are given to demonstrate the improvement of system throughput using the proposed scheduling schemes. In addition, we investigate fairness issue of wireless scheduling schemes. Due to different characteristics of wireless scheduling schemes, the existing fairness indexes may result in misleading comparison among different schemes. We propose a new fairness index to compare the overall satisfaction of the network users for different scheduling schemes. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: cellular networks; diversity; fairness index; downlink scheduling

1. Introduction

Communication networks are designed to satisfy user needs while maximizing the revenue for network operators. Thus, efficient resource management is of paramount importance. Dynamic resource allocation is the major component of a resource management policy to share channel bandwidth among multiple users. For delay-tolerant user applications (i.e., non-realtime data traffic), scheduling is a widely used technique for efficient dynamic resource allocation. For a wireline channel, where a *work conserving* scheduling scheme [1] can utilize the whole channel bandwidth, the challenge is to maintain fairness among users. However, for wireless channels, besides fair bandwidth sharing, proper scheduling can increase spectrum utilization as well. Thus, efficient scheduling becomes more crucial in wireless networks. Due to the significant random and location-dependent variations of wireless channels, designing

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an efficient wireless scheduling scheme is a challenging problem. Furthermore, since wireless spectrum is more expensive than wireline channel bandwidth, low efficiency is less affordable in wireless networks.

The existing wireless scheduling schemes can be categorized into two distinct groups: (1) scheduling schemes for networks with *fixed* transmission rates; and (2) scheduling schemes for networks with *dynamic* transmission rates. The schemes from the first group are traditionally adopted from the wireline scheduling schemes. A good survey of those scheduling schemes can be found in Reference [2]. The schemes for the modern dynamic rate systems employ radically different service disciplines. The widely used service discipline for dynamic transmission rate scheduling schemes has been motivated by the information theoretic results of Reference [3]. It has been shown that for the uplink of a cellular network, given the partial channel state information (CSI) at the transmitter side, the scheduling strategy to maximize the total information-theoretic capacity of the system is to transmit to only one user with the best channel quality at each time slot. Similar results have been reported for the downlink transmission from a single base station to multiple users in Reference [4]. This can be thought of as an *opportunistic service discipline* that exploits an existing dimension of spatial diversity in cellular systems, known as *multi-user* diversity. A variant of the opportunistic service discipline has been employed by several existing scheduling schemes, such as the proportional fair scheduling (PFS) scheme [5,7,8] and packet scheduling for wireless ad hoc networks [6].

In cellular networks, existence of multiple base stations provides another significant dimension of spatial diversity for improving quality of communication. Soft handoff is an example of using base station diversity in order to improve reliability of communication to the users with good signal strength from several base stations. Another possibility is to use base station diversity to increase the system throughput by selecting the best serving base station at each scheduling time slot. Inspired by this fact, in this paper we propose a PFS scheme with base station diversity (PFS-BDIV) and a round robin scheduling scheme [12] with base station diversity (RR-BDIV). In the proposed schemes, the partial CSI is used by the scheduler to choose the best serving base station of the selected user at each time slot. For the PFS-BDIV scheme, the core service discipline is from the PFS scheme to utilize multiuser diversity. On the other hand, a simple round robin (RR) scheme is used as the core service discipline in the RR-BDIV scheme. For base station diversity, each scheduler controls three most interfering sector antennas from three adjacent base stations, and each user is associated with one scheduler during call admission process. Once a user is selected for transmission by the scheduler, the best serving sector antenna will be used for transmission, and the other two sector antennas will remain silent for the entire time slot. This technique reduces intercell interference in CDMA networks. Furthermore, base station selection diversity increases multiuser diversity by increasing the effective number of users for each scheduler. The Monte Carlo simulation results are given to demonstrate the superiority of scheduling with base station diversity in terms of total system throughput.

Fairness is an important performance metric of scheduling schemes. Comparison of fairness is a difficult problem. It is desirable to define a fairness index to quantify and compare fairness of different scheduling schemes. The existing fairness indexes, such as *Variance, Variance coefficient*, and *Jain* indexes [15], are not directly applicable in wireless networks. For the existing fairness indexes, it is assumed that if the system settings do not change, different scheduling schemes can achieve equal throughput. However, this assumption does not apply for wireless scheduling schemes. In other words, total system throughput cannot be known without specifying the scheduling scheme. Thus, the existing fairness indexes may produce misleading results. We propose a new fairness index, namely the capitalistic fairness index (CFI). The proposed fairness index compares the overall satisfaction of the users for two given scheduling schemes. The CFI does not assume equal total throughput for the scheduling schemes. Thus, it can be used to compare two arbitrary scheduling schemes, regardless of their total achieved throughput.

In summary, the contributions of this paper are as follows:

- Two novel scheduling schemes using base station selection diversity among adjacent interfering base stations.
- A new fairness index for meaningful comparison of fairness among different wireless scheduling schemes.

The rest of this paper is organized as follows. In Section 2, we present the proposed scheduling schemes. The fairness issue is investigate in Section 3.

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Simulation results are given in Section 4, followed by the concluding remarks in Section 5.

2. The Proposed Scheduling Schemes

We consider the downlink of a CDMA cellular network. The coverage area of the network is divided into many hexagonal cells. There is a single base station with three directional sector antennas at the center of each cell. A sector antenna in a cell is directed to cover a 120-degree angle of the cell. A group of base stations is controlled by a central controller, which is called a base station controller system (BSC). The resource management modules run on the BSCs. Each BSC contains a number of schedulers, depending on its coverage area. A single scheduler controls a group of three most interfering sector antennas. As shown in Figure 1, the sector antennas controlled by a single scheduler belong to three adjacent base stations. Simultaneous transmission of the sector antennas is separated using different quasi-orthogonal spreading codes. We assume that inside a single cell, each sector antenna can only transmit to a single user at each scheduling time slot. In other words, a TDMA scheme is employed for each sector antenna. Depending on its location, each mobile station is associated with one of the schedulers, and is allocated a separate data queue. At each time slot, mobile users report back their estimated channel quality from three serving sector antennas from three adjacent base stations. The scheduler may use any of the three sector antennas under its control for transmission at each time slot. To enable selection of the best serving base station, the cellular system should support *fast cell selection*. The transmission rate to each mobile user at each time slot will be dynamically adjusted according to its channel quality. To support dynamic transmission rates, the physical layers are assumed to support adaptive modulation and coding (AMC). These features are parts of the air interface specifications of the next generation cellular networks, such as cdma2000 $1 \times$ EV-DV [10] and the high-speed downlink packet access (HSDPA) [11].

In the aforementioned system model with many sector antennas and mobile users, there are two important dimensions of spatial diversity: (1) multiuser diversity; and (2) base station diversity. The concept of multiuser diversity can be explained in Figure 2, where a single base station serves several users simultaneously. Since the channels from the base station to the users fluctuate independently, the base station can take advantage of the fluctuations to transmit to a single user with the best channel condition at each scheduling time slot. This can be thought of as a random and

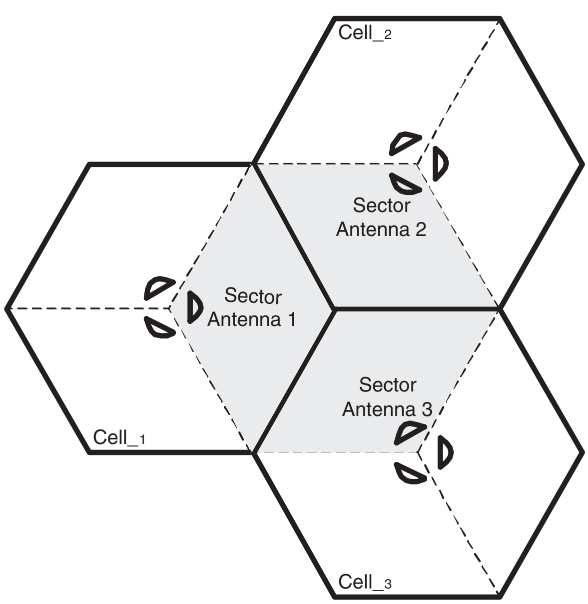

Fig. 1. Three most interfering sector antennas controlled by a single scheduler.

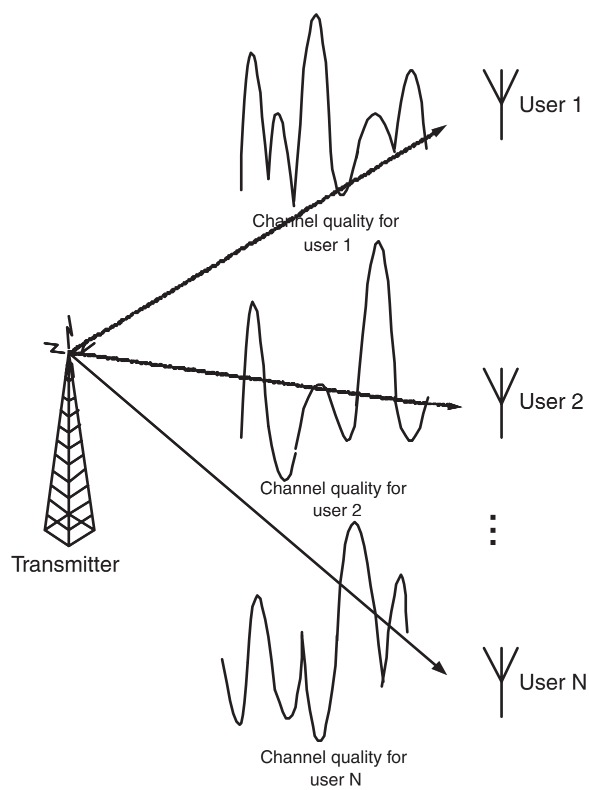

Fig. 2. Multi-user diversity.

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opportunistic service discipline, and can significantly improve the total system throughput. The larger the number of users, the higher is the multiuser diversity gain.

A group of sector antennas can be used to implement another form of space diversity. Soft handoff is a good example of such techniques that has been already implemented in IS-95 CDMA networks to provide robust communication with the users near cell boundaries. In an alternative approach, we can coordinate transmissions from a group of most interfering sector antennas. At each time slot, the selected user can be served by the best serving sector antenna. During each time slot, only one sector antenna is allowed to transmit. However, the transmission power of the selected sector antenna can be increased up to the total allowed transmission power of three sector antennas controlled by the corresponding scheduler. This technique can be considered as selection diversity that can improve the total system throughput by: (1) reducing interference among the most interfering sector antennas; and (2) improving multiuser diversity gain by increasing the effective number of users for each scheduler.

Next, we apply the aforementioned diversity techniques to downlink scheduling. Each scheduler can be illustrated by an abstract model shown in Figure 3. A single scheduler in a BSC serves a group of users through three sector antennas. The incoming data packets for different users are buffered in different queues. The scheduler fragments and transmits the head of line packet of a user when the user is chosen for transmission. A general framework of the proposed scheduling schemes has been illustrated in Figure 4. In this procedure, each mobile station continuously monitors its channel conditions by receiving the pilot signals from three serving sector antennas, computes the maximum achievable rates, and reports a *Data rate control (DRC)* message to the scheduler. The DRC message includes the maximum achievable rates from the three serving sector antennas. Based on the DRC information, the scheduler selects only one user and one sector antenna for transmission at each time slot. The combination of a selected user and a sector antenna is the one that maximizes the instantaneous transmission rate, and satisfies the fairness criteria. The fairness support mechanism is usually a part of the core service discipline. The proposed framework can be integrated with different core service disciplines. In the following, we explain the integration of the proposed framework with the RR and an opportunistic service discipline.

The first scheduling scheme, called the RR-BDIV scheme, extends a RR service discipline with base station selection diversity. In this scheme, packet scheduling is done as follows.

1. Each active mobile user measures the signal-to-interference and noise ratio (SINR) from the pilot signals of the three serving sector antennas, and reports the corresponding DRC to the BSC.
2. A user is selected for transmission according to the RR service discipline [12].
3. The scheduler selects the best serving sector antenna for the selected user in the next time slot.
4. A data frame is transmitted to the intended user.

The PFS scheme with base station diversity, called the PFS-BDIV scheme, customizes the general framework in Figure 4 with an opportunistic service discipline as used in the PFS scheme. To explain this scheme, first, we define four notations in Table I. In this scheme, packet scheduling is done as follows:

1. All users report their DRCs from the three serving sector antennas back to the scheduler.
2. The scheduler selects the best serving sector antenna for each user.

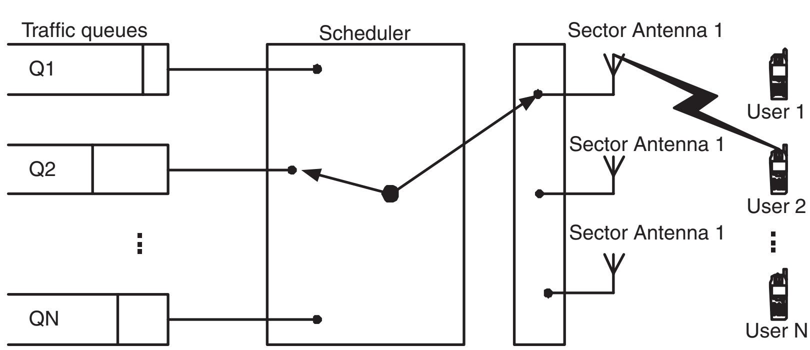

Fig. 3. The scheduling model of down-link.

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Table I. The notations used in the PFS-BDIV scheme.

$\mathrm{DRC}_{i,j}(t)$	The DRC of user i from sector antenna j in time slot t
$\mathrm{DRC}_i(t)$	$\max_j[\mathrm{DRC}_{i,j}(t)],\ j = 1, 2, 3$
$r_i(t)$	The allocated rate of user i in time slot t
$R_i(t)$	The average allocated rate of user i up to time slot t

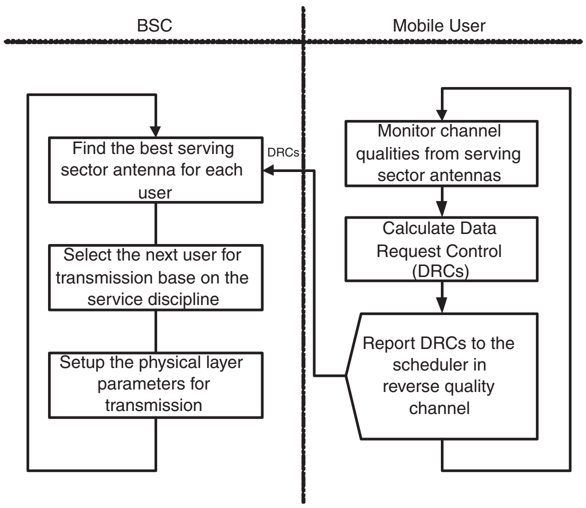

Fig. 4. General framework.

3. A user with the highest $\mathrm{DRC}_i(t)/R_i(t)$ is selected for transmission in time slot t.
4. A data frame is transmitted to the intended user.
5. Estimation of the average transmission rate for each user is updated as follows:

$$R_i(t) = \left(1 - \frac{1}{T_c}\right)R_i(t-1) + \frac{1}{T_c}r_i(t) \qquad (1)$$

where $r_i(t)$ is the transmission rate of user i at time slot t and T_c is a constant parameter.

T_c determines significance of the history of R_i on the new estimation at time slot t. The larger the value of T_c, the stronger is the influence of the previous estimation, and the weaker is the influence of the recent allocated rate (i.e., $r_i(t)$). A typical value of $T_c = 1000$ is proposed for implementing the PFS scheme in Reference [19].

The probability of transmission to each user in time slot t is balanced by its average transmission rate up to time slot t. Users with relatively small average transmission rate will be given higher chance than the users with relatively large average transmission rate. This mechanism maintains some degree of fairness among users, which is known as the *proportional fairness* [13].

3. A New Fairness Index

It is important to define the concept, and preferably, quantify the degree of fairness for a specific resource allocation scheme using a fairness index. The concept of fairness index can be explained as follows. Let $\boldsymbol{s} = (s_1, \ldots, s_n)$ be an allocation vector, where s_i is the amount of a shared resource allocated to user i, and n is the total number of users. A fairness index is a function $f : R^n \to R$, which associates a real number with an allocation vector. By comparing the value of fairness indexes for different allocation policies, one should be able to determine and compare fairness of different allocation schemes.

A definition of fairness depends on the application domain. For communication networks, the widely referred definition of fairness is the *max–min* fairness [14]. Scheme A is considered to be fairer than scheme B if the poorest user can receive more in scheme A than in scheme B. To quantify fairness, there are several fairness indexes appeared in the literature [15]. Some widely used fairness indexes are defined in the following:

Variance index

$$F = \frac{1}{n-1}\sum_{i=1}^{n}(s_i - \mu)^2, \quad \text{where } \mu = \frac{1}{n}\sum_{i=1}^{n} s_i \qquad (2)$$

Variance coefficient index

$$F = \frac{\frac{1}{n-1}\sum_{i=1}^{n}(s_i - \mu)^2}{\mu} \qquad (3)$$

where μ is defined in Equation (2)

Min–max ratio

$$F = \frac{\min\{s_i\}}{\max\{s_i\}} \qquad (4)$$

Jain fairness index

$$F = \frac{|\sum_{i=1}^{n} s_i|^2}{n\sum_{i=1}^{n} {s_i}^2} \qquad (5)$$

For the *variance* and the *variance coefficient*, the higher the value of the fairness index, the higher is the degree of unfairness. For the *min*–max ratio and

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the *Jain index*, the smaller the value of the fairness index, the higher is the degree of unfairness. The above fairness indexes can be used to quantify the degree of fairness for a variety of resource allocation schemes. However, for meaningful comparison, the total system throughput of the scheduling schemes must be equal. Furthermore, in the above fairness indexes, a fair allocation vector is considered to be an even allocation vector, that is, all users receive equal amount of the shared resource in a fair allocation scheme. In wireless domain: (1) different scheduling schemes may achieve different total throughput; and (2) the fair allocation vector may not be an even vector due to channel discrepancies. Indeed, the network will have to spend an unfair amount of effort to achieve equal transmission rates. Thus, equal rate allocation may not be considered a fair allocation scheme. Typically, a fair allocation scheme is an uneven allocation scheme. Therefore, the results of the above fairness indexes may be misleading as explained in the following examples. In the first example, the rate allocation vectors for schemes A and B are assumed to be (1, 3, 5) and (1, 4, 6), respectively. In the second example, the allocation vectors are (1, 2, 3) and (1, 3, 5) for schemes A and B, respectively. We assume that the system settings for A and B are identical in both examples. However, scheme B has achieved better system throughput than scheme A due to better resource allocation policy in both examples. As it can be seen, all users have received higher transmission rates in A than in B for both the examples. This cannot happen in a wireline resource allocation scheme, where the total system throughput is known and fixed. However, different wireless resource allocation schemes usually achieve different total throughput. Thus, all users can receive higher transmission rates in one wireless scheduling scheme than in other scheme. According to the definition of *max–min fairness*, in the above examples, scheme B is fairer than scheme A. However, as it can be seen in Table II, the fairness indexes as defined in Equations (2)–(5) can produce results that contradict with the definition of *max–min fairness*. In the first example, the *variance* and *variance coefficient* indexes have given worse evaluations for scheme B than scheme A. In the second example, *min–max ratio* and *Jain fairness* indexes have marked scheme B worse than scheme A. To the best of our knowledge, this problem has not been addressed by the existing fairness indexes in the literature. In the rest of this section, we propose a new fairness index that gives meaningful results of fairness analysis in wireless networks.

Table II. The fairness index values.

Fairness index	Example 1		Example 2	
	A	B	A	B
Variance	4.00	6.33	4.00	2.33
Variance coefficient	1.33	1.77	1.33	0.64
Min–max ratio	0.20	0.16	0.20	0.40
Jain	0.77	0.76	0.71	0.89

Let $\{s_{A,i}\}$ and $\{s_{B,i}\}$ denote the amount of resources allocated to user i by schemes A and B, respectively. We define the *CFI* of scheme A in comparison with scheme B as

$$F_A(B) = \frac{\sum_{i=1}^{n} U(s_{A,i} - s_{B,i})}{1 + \sum_{i=1}^{n} U(s_{B,i} - s_{A,i})} \tag{6}$$

where $i = 1, 2, \ldots, n$ and $U(\cdot)$ is the unit step function given by

$$U(x) = \begin{cases} 1, & \text{if } x \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

In fact, $F_A(B)$ represents the ratio of the number of users who receive more or at least the same amount of the shared resource in scheme A than in scheme B to the number of users that receive less or the same amount of the shared resource in scheme A than in scheme B. If $F_A(B)$ is zero, then scheme B is absolutely fairer than scheme A. If $F_A(B)$ is equal to n, scheme A is absolutely fairer than scheme B. In general, for $F_A(B) \geq n/(n+2)$, scheme A is fairer than scheme B, and for $F_A(B) \leq n/(n+2)$, scheme B is fairer than scheme A. This can be thought of as being similar to the concept of fairness in capitalistic societies, where system A is fairer than system B if system A can provide the majority of the population with better fortune than scheme B.

4. Numerical Results

In this section, we use Monte Carlo simulation to investigate the impacts of base station diversity on the performance of the two wireless scheduling schemes. For the simulation studies, we have considered a 19-cell system with one center cell and 18 interfering cells in two surrounding tiers, as illustrated in Figure 5. Each cell has three sector antennas. Mobile users are uniformly distributed in the center

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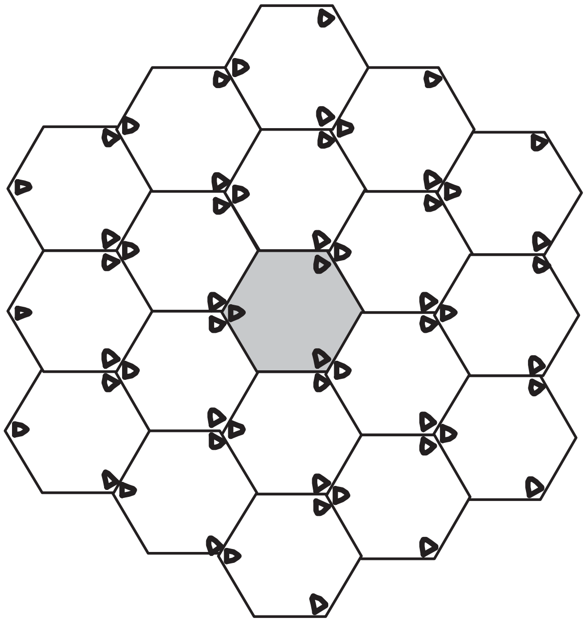

Fig. 5. The simulation system configuration.

cell, and scheduling is simulated in the center cell alone.

The channels from the sector antennas within the center cell to the mobile users in the center cell are modeled by a flat Rayleigh fading process including the impacts of path loss and shadowing. However, the channels from the sector antennas in the neighboring cells to the mobile users are modeled by path loss only. For the Rayleigh fading channels, the received power of user i from sector antenna j, denoted $P_{\mathrm{R}_{i,j}}$, is modeled by a random process with an exponential ensemble distribution [16] as follows:

$$f_{P_{\mathrm{R}_{i,j}}}(p) = \frac{1}{\Omega_P}\exp\left\{-\frac{p}{\Omega_P}\right\} \tag{8}$$

where Ω_P is the average signal power. $\Omega_P(\mathrm{d}B)$ is modeled by a random variable with a normal distribution as follows.

$$f_{\Omega_P(\mathrm{d}B)}(\omega) = \frac{1}{\sqrt{2\pi}\sigma_\Omega}\exp\left\{-\frac{(\omega-\mu_{\Omega_P(\mathrm{d}B)})^2}{2\sigma_\Omega^2}\right\} \tag{9}$$

where $\sigma_\Omega = 8(\mathrm{d}B)$ is a typical value for macro-cellular environments [16]. μ_{Ω_P} is the area mean caused by path loss, and has been modeled in Reference [16] as

$$\mu_{\Omega_P} = P_\mathrm{T}G_\mathrm{T}G_\mathrm{R}\left(\frac{h_m h_b}{d^2}\right)^2 \tag{10}$$

Table III. Maximum achievable rates versus SINR for FER = 0.01.

SINR(dB)	9.5	7.2	3.0	1.3	−6.5	−9.5
Achievable rate (kbps)	2457	1628	921	614	76	38

where P_T is the transmitted power, G_T is the transmitter antenna gain, G_R is the receiver antenna gain, h_m is the mobile station antenna height, h_b is the sector antenna height, and d is the distance between the antenna and the mobile station. For a typical cellular system, path loss has been modeled in Reference [17] as

$$\mu_{\Omega_P(\mathrm{d}B)} = 30\log_{10}(f_c) + 49 + 40\log_{10}(d) \tag{11}$$

where f_c is the carrier frequency in MHz and d is the distance in Km.

The value of SINR is mapped to the maximum achievable rate using Table III. These values are obtained by exact bit simulations for frame error rate (FER) of 0.01 in Reference [17]. The other parameters used in our channel simulator are given in Table IV.

For throughput analysis, we have simulated the RR, the RR-BDIV, the PFS, and the PFS-BDIV scheduling schemes. Each simulation run lasted for 15 s (12 000 time slots of 1.25 ms each) and independent simulations have been performed for 100 times. Figure 6 shows the cumulative distribution function (CDF) of the average per-user throughput for 21 simultaneous mobile users (i.e., seven users per sector). It can be seen BS diversity significantly improves the per-user throughput for both the PFS and the RR schemes.

For fairness analysis, we compare the CFI for different scheduling schemes. The results of fairness analysis are shown in Figure 7. It can be seen that: (1) the RR-BDIV scheme is absolutely fairer than the RR scheme in 99% of the iterations; (2) in 60% of the iterations, the PFS-BDIV scheme is absolutely fairer than the PFS scheme, and in 40% of the iterations the PFS-BDIV scheme is relatively fairer than the PFS scheme; and (3) the PFS-BDIV scheme

Table IV. Simulation parameters for the fading channel.

Parameter	Value
Carrier frequency	1800 Mhz
Speed of mobile nodes	5 Km/h
Sampling frequency	8000 samples/s

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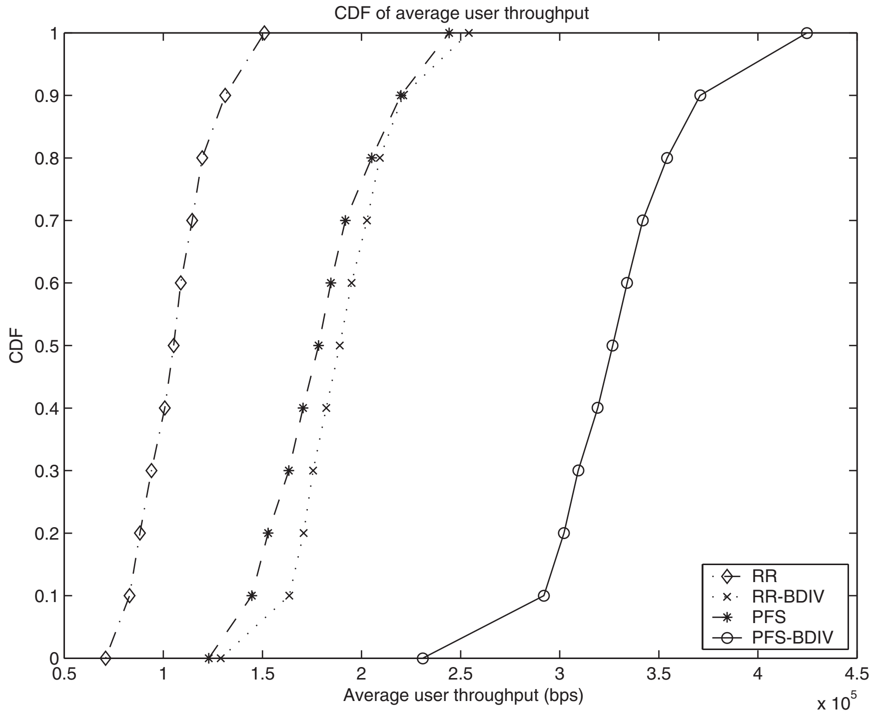

Fig. 6. Cumulative distribution function (CDF) of average user throughput.

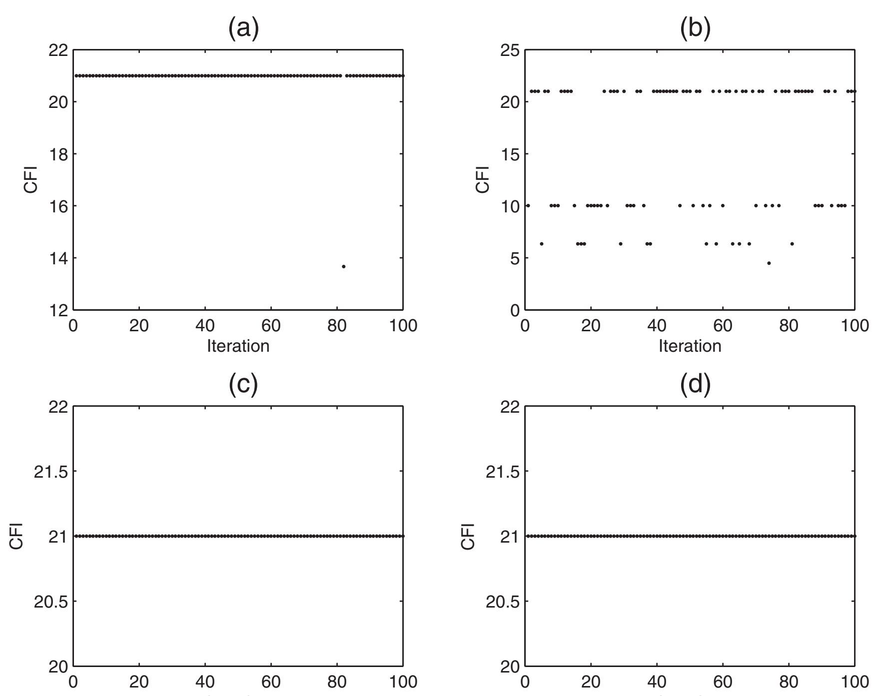

Fig. 7. Comparison of fairness (a) RR-BDIV with RR; (b) PFS-BDIV with PFS; (c) PFS-BDIV with RR; (d) PFS-BDIV with RR-BDIV.

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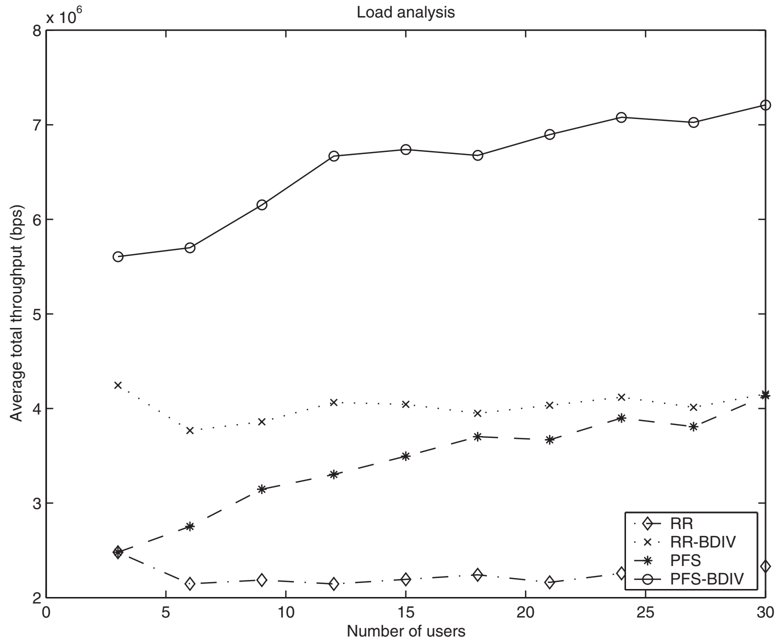

Fig. 8. Total throughput versus number of users.

is always absolutely fairer than the RR and RR-BDIV schemes.

Next, we investigate the impact of system load on the total throughput of the scheduling schemes. We use the number of active users as the system load. We have performed simulation studies for different number of users starting from 3 users up to 30 users in the center cell. Figure 8 shows the average total throughput versus the system load for different scheduling schemes. It can be seen that for the PFS and the PFS-BDIV schemes, the total system throughput increases as a result of increasing the number of users. This is an expected result as both the scheduling schemes implement an opportunistic service discipline which produces higher scheduling gain for higher number of users. However, the throughput of the RR and the RR-BDIV schemes remain almost constant as they do not employ an opportunistic service discipline.

5. Conclusion

In this paper, we have investigated the integration of base station selection diversity with packet scheduling for the downlink of cellular CDMA networks. We have proposed two scheduling schemes, namely the PFS-BDIV and RR-BDIV. The RR-BDIV scheme extends a RR scheduling scheme with base station selection diversity. On the other hand, the PFS-BDIV scheme integrates the PFS scheme with base station selection diversity. We have demonstrated that base station diversity can improve the performance of wireless scheduling schemes by reducing inter-cell interference and increasing multiuser diversity gain. We have also investigated fairness analysis of wireless scheduling schemes. We have shown that the existing fairness indexes can result in meaningless comparison. To address this problem, we have proposed a new fairness index for comparison of fairness among different wireless scheduling schemes. The proposed fairness index is more appropriate for the wireless networks than the existing fairness indexes.

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