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A Throughput-Efficient and Channel-Adaptive Scheduling Scheme in Voice/Data DS-CDMA Networks with Transmission Power Constraints∗(Revised Manuscript)

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Abstract: In a practical voice/data CDMA network, the constraint of transmission powers makes it necessary to transmit multiple data users in parallel in order to fully utilize system resource (power). How to choose those data users that should be transmitted simultaneously and allocate appropriate powers among them remains as an open issue. In this paper we prove that it is optimal in the sense of maximum data throughput to select data users and allocate powers according to the descending order of their indexes of received power capability (IRPC). Here, IRPC is defined as the product of the transmission power upper bound and the channel gain. Based on this principle, a channel-adaptive scheduling scheme, Partially Descending IRPC (PDI) scheduling, is proposed to achieve efficient throughput performance for data traffic while maintaining certain fairness among different users. The efficiency and fairness of the PDI scheduling are verified by comparing with the conventional fair-sharing scheme and round-robin scheme through computer simulations. Numerical results also reveal the robustness of the new scheme to the channel estimation errors.

Key Words: CDMA, scheduling, throughput optimization, fading channel

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1 Introduction

At present, with the rapid development of Internet and wireless communication, there is a growing trend toward the convergence of these two major communication technologies, i.e., providing data service in current voice-dominant wireless networks[1]-[3] or providing roaming and handoff capability in current Internet[4]-[6]. Integrated voice/data CDMA network is deemed to be the first step toward such a next generation mobile Internet.

Among the quality-of-service (QoS) parameters, throughput is usually the most critical one for data service. So far, a lot of studies have been dedicated to the integrated voice/data CDMA systems to improve the data throughput while keeping the QoS level of voice service acceptable[7]-[18]. In [7], the authors formulated the throughput maximization as a classical optimization problem to derive the optimal power allocation for the concurrent data users. In [8], a combined power control and rate selection scheme is proposed to enhance system throughput. On the other hand, [9] and [10] proposed physical layer channel adaptation techniques such as adaptive modulation and adaptive coding for the enhancement of system throughput. However, the works in [7]-[10] generally did not consider an employment of scheduling in their system model. In fact, scheduling can further improve throughput by exploiting the delay-tolerance feature of data traffic, e.g., see [11]-[18]. In [11], an “opportunistic” transmission scheduling policy was proposed for best-effort users with varying channel conditions to maximize its wireless utility. In [12], in order to achieve capacity gain, the intercell interference was alleviated through a joint scheduling and power allocation method. In [14], a rate-based grouping transmission was proposed where the transmission rate of each data users was scheduled to be either the maximum rate or the minimum rate, to increase the average throughput of data service. In [17], the data throughput of a multi-code CDMA system is improved by finding the optimal number of simultaneous streams and the queue-length-based allocation of code channels. Transmission scheduling was also investigated in [13] and [15], where it was shown that under target bit-energy-to-interference ratio ($E_b/I_0$) values, permitting only one data user to transmit at a time
maximizes the throughput. This conclusion was most recently reported in [16], where it showed that the maximum throughput may be obtained by time sharing between operating points, at which each user either uses full power or is silent (so called “bang-bang” control). [16] also studied the scheduling so as to meet some pre-specified service curves. A similar study was conducted in [18] for integrated voice/data multi-code CDMA network, where it was proposed that all available codes should be assigned to only one user at each time slot and different users were switched in a round-robin manner to improve the system throughput. From an information theory’s perspective, this result was explained in [19] and [20]: the capacity gain comes from the attenuated multiple-access-interference (MAI) induced from single user transmission. Under the achievement in capacity, this method also requires the data user must be provided with enough transmission power so that its received power at the base station takes up the whole power budget available for data service.

However, in a practical voice/data CDMA system it is usually difficult to completely utilize system resource (power) if only one data user is permitted to transmit at one time. This is because that the transmission power is always limited, especially on the side of mobile station (MS). Take the uplink (from mobile to base station) as an example: due to the channel loss, even if the MS transmits signal by its maximum power, its received power at BS may not occupy the whole power budget available for that data user. The unoccupied portion of power budget leads to throughput loss. Therefore, in an integrated voice/data CDMA system with constrained transmission power, multiple data users should be allowed to transmit in parallel in order to fully utilize system resource. Then, the next question arises: in a time slot, which data users should be selected for transmission and how to allocate powers among the users selected? So far, two commonly proposed scheduling schemes are the fair-sharing[14] scheme and the round-robin[15][18] scheme. However, both of them only focus on the fairness issue but ignore the efficient utilization of system resource (i.e., the throughput).

In this paper, we study the throughput-optimal selection and power allocation of simultaneous data users in an integrated voice/data network with transmission power constraint, while
at the same time we also care about the issue of fairness among different users. In order to take the channel variation and the limit of transmission power into consideration, we suggest a new parameter, *index of received power capability* (IRPC), which is defined as the product of the transmission power upper bound and the channel gain, to represent the maximum received power that a data user can provide in the current time slot. We prove that under a given received power budget and transmission power constraint, the throughput of data service is maximized by selecting data users and allocating received powers according to the descending order of their IRPCs. Based on this principle, a channel-adaptive scheduling scheme, Partially Descending IRPC (PDI) scheduling, is proposed to achieve efficient throughput performance for data traffic while maintaining certain fairness among different users at the same time. The efficiency and fairness of this scheme is verified by numerical examples. It shows that superior performance is achieved by PDI scheduling over the fair-sharing scheme and the round-robin scheme in terms of higher throughput and lower total transmission power consumption. In addition, the throughput-fairness trade-off feature of PDI scheduling is verified. Numerical results also reveal the robustness of the new scheme to the channel estimation errors so that it is suitable for the implementation in a practical system.

The rest of this paper is organized as follows. We describe our system model in Section 2. The throughput analysis is conducted in Section 3. In Section 4, we present the proposed PDI scheduling scheme. Section 5 gives numerical examples and we conclude our work in Section 6.

## 2 System Model

We consider the uplink of a slotted DS-CDMA system with $N_v$ real time voice users and $N_d$ non real-time data users. The voice traffic is of ON-OFF characteristics and its activity factor is $\alpha_v$. A constant bit rate $R_v$ is required during its ON period. The minimum bit-energy-to-interference ratio $E_b/I_0$ required for voice user is $\gamma_v$. The data traffic is of so called *best effort* characteristics and no explicit rate requirement is imposed. The different data rates are achieved by using different spreading gains. The $E_b/I_0$ requirement of data service is $\gamma_d$. We
assume perfect power control for voice users, i.e., in any time slot the received power at BS of an active voice user is kept at $P_v$. We also assume the background Additive White Gaussian Noise (AWGN) is small enough compared to the multiple access interference (MAI) thus can be ignored.

Denoted by $W$ and $P_{total}$ as the total spread spectrum bandwidth of the system and the total received power at the BS in current time slot, respectively. Then the $E_b/I_0$ of an active voice user is given by

$$\left(\frac{E_b}{I_0}\right)_v = \frac{W}{R_v \gamma_v} \frac{P_v}{P_{total} - P_v},$$

(1)

In order to meet the $E_b/I_0$ requirement of voice users, $P_{total}$ must satisfy

$$P_{total} \leq P_v \left(\frac{W}{R_v \gamma_v} + 1\right) \equiv P_{total}^{max}. $$

(2)

where $P_{total}^{max}$ is the maximum total received power that satisfies the SIR requirement of voice service. Denote by $K_v$ the number of active voice users in the current time slot. The maximum total received power available for data service, namely $B_d$, is given by

$$B_d = P_{total}^{max} - K_v P_v = P_v \left(\frac{W}{R_v \gamma_v} + 1 - K_v\right).$$

(3)

In this paper, $B_d$ is also defined as the received power budget of data service. In order to utilize system resource sufficiently, $B_d$ should be completely allocated among data users.

According to [15], data throughput is maximized if $B_d$ is exclusively allocated to only one data user in each time slot. This requires that data user must own enough transmission power so that its received power at BS reaches $B_d$. However, because of the channel loss and the constraint of transmission power, this requirement is usually hard to be satisfied. Specifically, in the current time slot, the maximum received power that data user $i$ can provide is given by

$$P_i^{max} = Q_i^{max} h_i,$$

(4)

where $Q_i^{max}$ is the transmission power constraint of data user $i$ and $h_i$ is the channel loss of user $i$. $h_i$ is related to the distance attenuation, the shadowing, and the fading of the channel,
but is assumed constant during the ongoing time slot. We refer $P_{\text{max}}^i$ to as the index of received power capability of user $i$. When $P_{\text{max}}^i < B_d$, $B_d$ should be allocated to multiple data users.

We further assume there are enough data users in the system so that $\sum_{i=1}^{N_d} P_{\text{max}}^i \geq B_d$.

### 3 Problem Formulation and Solution

The focus of this paper is to find out the proper selection of simultaneous data users and the proper power allocation among them, which provide maximum throughput under the given power budget and the transmission power constraint. More specifically, the problem is formulated as follows:

\[
\begin{aligned}
\text{max} & \sum_{i=1}^{N_d} R_{di}, \\
\text{s.t.} & 0 \leq P_i \leq P_{\text{max}}^i, & i = 1, \ldots, N_d \\
& \sum_{i=1}^{N_d} P_i = B_d,
\end{aligned}
\]

(5)

where $R_{di} = \frac{W}{\gamma_d} P_{\text{total}} P_i - \sum_{i=1}^{N_d} P_{\text{max}}^i \geq B_d$. $R_{di}$ and $P_i$ are the bit rate and the received power of data user $i$ in current time slot, respectively. At the first glance, this formulation is similar to that in [7]. However, it is noted that $P_i$ could be 0 in (5), which corresponds to no transmission for user $i$ in current time slot. In contrast, $P_i$ must be greater than 0 in [7], which corresponds to a case where no scheduling is applied, i.e., all users are transmitted simultaneously. There is no closed-form optimal solution achieved for the problem in [7]. However, under the more specialized formulation in (5), we derive the throughput-optimal scheduling for the voice/data system as follows.

**Proposition 1**: Given the received power budget $B_d$ and the index of received power capability $P_{\text{max}}^i$, where $P_{\text{max}}^1 \geq P_{\text{max}}^2 \geq \ldots \geq P_{\text{max}}^{N_d}$, the following power allocation is optimal in the sense of throughput maximization:

\[
P_i^* = \begin{cases} 
  P_{\text{max}}^i, & 1 \leq i \leq k \\
  B_d - \sum_{j=1}^{k} P_{\text{max}}^j, & i = k + 1 \\
  0, & k + 2 \leq i \leq N_d
\end{cases}
\]

(6)

where $k$ satisfies $\sum_{i=1}^{k} P_{\text{max}}^i \leq B_d$ and $\sum_{i=1}^{k+1} P_{\text{max}}^i > B_d$.

Before proving Proposition 1, we first present and prove the following lemma.
Lemma 1: Given two data users with IRPCs $P_{1}^{\text{max}} > P_{2}^{\text{max}}$, let their received powers be constrained by $P_{1} + P_{2} = B_d$ and $P_{1}^{\text{max}} + P_{2}^{\text{max}} \geq B_d$, then the power allocation $P_{1}^{*} = \min(P_{1}^{\text{max}}, B_d)$ and $P_{2}^{*} = \max(B_d - P_{1}^{*}, 0)$ maximizes $R_{1} + R_{2}$.

Proof: Let $(P_{1}, P_{2})$ be any power allocation scheme for data user 1 and 2, where $0 \leq P_{1} \leq P_{1}^{\text{max}}$, $0 \leq P_{2} \leq P_{2}^{\text{max}}$, and $P_{1} + P_{2} = B_d$. Denote the total (these two plus other users) received power at BS by $P_{\text{total}}$. Then, the bit rates corresponding to this power allocation is given by

$$R_{1} = \frac{W}{\gamma_d} \frac{P_{1}}{P_{\text{total}} - P_{1}}, \quad (7)$$

$$R_{2} = \frac{W}{\gamma_d} \frac{P_{2}}{P_{\text{total}} - P_{2}}. \quad (8)$$

Thus the aggregate throughput of users 1 and 2 is

$$R_{1} + R_{2} = \frac{W}{\gamma_d} \frac{B_d - \frac{P_{1}^{\text{max}} P_{2}}{P_{\text{total}}}}{P_{\text{total}} - B_d + \frac{P_{1} P_{2}}{P_{\text{total}}}}. \quad (9)$$

Depending on the value of $B_d$, we divide our proof in the following two cases:

Case 1: if $B_d \leq P_{1}^{\text{max}}$, then $P_{1}^{*} = B_d$ and $P_{2}^{*} = 0$. Then we derive the corresponding transmission rates as

$$R_{1}^{*} = \frac{W}{\gamma_d} \frac{B_d}{P_{\text{total}} - B_d}, \quad (10)$$

and $R_{2}^{*} = 0$. Comparing (9) with (10), it is obvious that $R_{1}^{*} + R_{2}^{*} \geq R_{1} + R_{2}$.

Case 2: if $B_d > P_{1}^{\text{max}}$, then $P_{1}^{*} = P_{1}^{\text{max}}$ and $P_{2}^{*} = B_d - P_{1}^{\text{max}} = P_{2} - (P_{1}^{\text{max}} - P_{1})$. Then we derive the corresponding transmission rates as

$$R_{1}^{*} = \frac{W}{\gamma_d} \frac{P_{1}^{\text{max}}}{P_{\text{total}} - P_{1}^{\text{max}}}, \quad (11)$$

$$R_{2}^{*} = \frac{W}{\gamma_d} \frac{P_{2} - (P_{1}^{\text{max}} - P_{1})}{P_{\text{total}} - P_{2} + P_{1}^{\text{max}} - P_{1}}. \quad (12)$$

From (11) and (7), we have

$$R_{1}^{*} - R_{1} = \frac{W}{\gamma_d} \frac{P_{\text{total}}(P_{1}^{\text{max}} - P_{1})}{(P_{\text{total}} - P_{1})(P_{\text{total}} - P_{1}^{\text{max}})}, \quad (13)$$

similarly, from (12) and (8), we have

$$R_{2}^{*} - R_{2} = -\frac{W}{\gamma_d} \frac{P_{\text{total}}(P_{1}^{\text{max}} - P_{1})}{(P_{\text{total}} - P_{1} + (P_{1}^{\text{max}} - P_{2}))(P_{\text{total}} - P_{2})}. \quad (14)$$
Because $P_{1}^{\text{max}} \geq P_{2}^{\text{max}} \geq P_2$, from (13) and (14), it can be derived that $(R_1^{*} + R_2^{*}) - (R_1 + R_2) \geq 0$, or $R_1^{*} + R_2^{*} \geq R_1 + R_2$.

Combining the results of cases 1 and 2, it can be concluded that the maximum throughput of $R_1 + R_2$ is achieved by the power allocation $(P_1^{*}, P_2^{*})$. Thus lemma 1 is proved.

Remarks: Lemma 1 indicates that transferring received power as many as possible from a user with lower IRPC to the user with higher IRPC increases the total rates of these two users.

Applying Lemma 1, Proposition 1 can be proved as follows, where all users are denoted according to the descending order of their IRPCs.

Proof of Proposition 1: The power allocation vector $\mathbf{P}^{*} = (P_1^{*}, \ldots, P_{N_d}^{*})$ suggested in Proposition 1 is equivalent to the form of $(P_{1}^{\text{max}}, P_{2}^{\text{max}}, \ldots, P_{k}^{\text{max}}, B_d - \sum_{i=1}^{k} P_{i}^{\text{max}}, 0, \ldots, 0)$, where $k$ satisfies $\sum_{i=1}^{k} P_{i}^{\text{max}} \leq B_d$ and $\sum_{i=1}^{k+1} P_{i}^{\text{max}} > B_d$. We apply proof-contradiction method to prove this power allocation maximizes the throughput of data service. Suppose there exists some power allocation $\mathbf{P}$ for (5), whose total throughput is greater than that achieved under $\mathbf{P}^{*}$, i.e., $\sum_{i=1}^{N_d} R_i > \sum_{i=1}^{N_d} R_i^{*}$. $\mathbf{P} = (P_1, \ldots, P_{N_d})$, where $\sum_{i=1}^{N_d} P_i = B_d$ and $(P_1, \ldots, P_{N_d}) \neq (P_1^{*}, \ldots, P_{N_d}^{*})$.

Because $P_i \leq P_i^{*}$ for $i = 1, \ldots, k$ and $\sum_{i=1}^{N_d} P_i = \sum_{i=1}^{N_d} P_i^{*}$, the relation between $\mathbf{P}^{*}$ and $\mathbf{P}$ could only be either of the following two cases. Accordingly, we proceed our proof separately under these 2 cases:

Case 1: $P_1 = P_1^{*}, \ldots, P_k = P_k^{*}, P_{k+1} < P_{k+1}^{*}, P_i \geq 0$, where $i = k+2, \ldots, N_d$ and at least one inequality strictly holds. We eliminate the difference between $P_{k+1}$ and $P_{k+1}^{*}$ by transferring received powers as many as possible from the $k + 2$nd, $k + 3$rd, \ldots, $N_d$th users to the $k + 1$st user in $\mathbf{P}$, respectively. Because the $k + 1$th user owns the highest IRPC among these users, according to lemma 1, each received power transferring always leads to a larger throughput of the data service. Finally, $\mathbf{P}$ equals to $\mathbf{P}^{*}$ by performing the received power transferring stated above, which leads to a contradiction $\sum_{i=1}^{N_d} R_i^{*} \geq \sum_{i=1}^{N_d} R_i > \sum_{i=1}^{N_d} R_i^{*}$. Thus there must not be such a supposed $\mathbf{P}$ which achieves a larger total throughput than that achieved under $\mathbf{P}^{*}$.

Case 2: $P_1 \leq P_1^{*}, \ldots, P_k \leq P_k^{*}$ and at least one inequality strictly holds. Without loss of generality, let the inequivalent one be $P_j < P_j^{*} = P_{j}^{\text{max}}, 1 \leq j \leq k$. Again, the difference
between \( P_j \) and \( P_j^* \) can be eliminated by transferring received powers as many as possible from the users after \( k \) in \( P \). Because user \( j \) owns the largest received power capability among the users involved in the transferring, according to lemma 1, each received power transferring leads to a larger throughput of the data service. The procedure above is performed respectively to all users whose \( P_j < P_j^* \) and who is before user \( k + 1 \). Finally, \( P \) equals to \( P^* \) by the transferring of received powers, which leads to the contradiction \( \sum_{i=1}^{N_d} R_i^* \geq \sum_{i=1}^{N_d} R_i > \sum_{i=1}^{N_d} R_i^* \). Thus there must not be such a supposed \( P \) which achieves a larger total throughput than that achieved under \( P^* \).

Combining cases 1 and 2, it is concluded that any power allocation different from \( P^* \) cannot achieve a larger total throughput than that achieved under \( P^* \), or equivalently, \( P^* \) achieves the maximum total throughput among all possible power allocations of (5). Thus Proposition 1 is proved.

**Remarks:** In order to maximize the throughput of data service, Proposition 1 suggests that we should select the transmission users and allocate power according to the descending order of their IRPCs, i.e., the data user with larger received power capability owns higher priority to be selected for transmission, and as many received power as its received power capability should be allocated to it unless all received power budget are exhausted.

## 4 Description of Scheduling Schemes

Under a given received power budget and the transmission power constraint, Proposition 1 suggests a simple yet throughput-optimal solution for the selection of transmission users and the allocation of received power in a voice/data CDMA network. However, there is an unfairness problem when applying Proposition 1 directly to the scheduling of data users: those users with the strong IRPCs may monopolize the transmission and powers for a long time so that the users with the weak IRPCs are deprived of the chance of transmission. To relieve this unfairness problem, some slight revision on Proposition 1 is made as follows, which leads to our novel throughput-efficient scheduling scheme, Partially Descending IRPC (PDI) scheduling. In
order to evaluate the performance of the proposed scheme, we also introduce two conventional scheduling schemes, the fair-sharing scheme and the round-robin scheme, for the performance comparison.

A. Proposed scheme: Partially Descending IRPC scheduling

This scheme is basically based on Proposition 1 we proved in Section 3, i.e., the data user with larger IRPC owns higher priority to be selected for transmission. However, in order to prevent from the monopoly of transmission by the strong data users, the application of Proposition 1 is dynamically restricted to only a portion of users instead of all the users. Depending on the application scope of Proposition 1, the proposed PDI scheduling provides a trade-off between the throughput efficiency and the fairness.

We give a pseudo-code description of the PDI scheduling in Fig.1. The selection of transmission data users is composed of two steps: $K$ transmission users are selected in step 1 and the others are selected in step 2. $K$ is a pre-specified system parameter. In step 1, the users are selected according to the descending order of their IRPCs from a candidates set $U$ so that those $K$ users with the largest IRPCs in $U$ are selected for transmission. The initial state of $U$ is all data users. Once a user is selected, it will be deleted from this set so that it will not be eligible for selection again in the first step of the scheduling in the consequent time slots. When $U$ is empty, it is initialized to all data users once again. A selected data user is allocated with the same quantity of received power as its received power capability from $B_d$ if it is possible. By this mechanism, all data users are guaranteed at least one transmission in the successive $\frac{N_d}{K}$ time slots.

Unless $B_d$ is exhausted in step 1, the scheme proceeds to step 2 to select the remaining transmission data users according to Proposition 1 as well. The scope of selection is all data users except those $K$ selected in the step 1. Thus the larger IRPC a user has in current time slot, the higher priority it will be selected with. And the same quantity of received power as its IRPC will be allocated for its transmission unless $B_d$ is exhausted, in which case the selection in current time slot is completed. The data users which are selected are allowed to transmit
with their corresponding received powers allocated.

Because IRPC is jointly determined by channel loss and the limit of transmission power, this scheme in fact takes both factors into consideration in its operation. In order to acquire the channel state in advance, some channel prediction techniques must be applied. Some examples of such techniques are [21][22] and [23]. Because such prediction could not be perfect, we will study the impact of prediction errors on the performance of the proposed scheme in our numerical examples. On the other hand, since the channel state varies with respect to time, it is expected that different data users will be selected for transmission in different time slots, thus the scheduling scheme is a dynamic and channel-adaptive one. By PDI scheduling, the received power budget $B_d$ is prevented from devoting to those users experiencing heavy channel loss or lacking sufficient transmission power, which in turn is translated into a more efficient utilization of system resource to increase throughput.

Remarks: In the proposed PDI scheduling scheme, the number of selected users in step 1, i.e. $K$, is a key parameter which provides throughput-fairness trade-off in the algorithm. Noting that each data user is guaranteed at least one transmission in the successive $\frac{N_d}{K}$ time slots, a larger $K$ will apparently provide a higher minimum rate and better fairness for each data user. At the same time, a larger $K$ will make PDI scheduling deviate from Proposition 1 in a larger degree thus larger throughput loss is resulted. However, because the throughput-optimal Descending IRPC user selection principle is insisted locally (i.e., in step 1 and step 2 of PDI scheduling, respectively), the highest throughput is still guaranteed for such a stepped user selection under the given fairness requirement. In this way we can expect both an enhanced system throughput and a desired fairness at the same time. Therefore, depending on the value of $K$, PDI scheduling provides an efficient trade-off between the throughput and the fairness. When $K$ is large enough so that $P^\text{max}_d$ is exhausted in Step 1, the fairness performance of this scheme will become similar to the Round-Robin scheme introduced below. However, we will show later in numerical example that, a much higher throughput is still provided by PDI scheduling than its counterpart does even at this point where they present equal fairness.
B. Fair-sharing scheme

In the fair-sharing scheme, all data users are allowed to transmit simultaneously in each time slot. Power budget $B_d$ is divided and allocated fairly to each data user without considering the channel loss and the limit of transmission power. So, for data user $i$, its transmission power is given by

$$Q_i = \min\left(\frac{B_d}{N_d h_i}, Q_{i}^{\text{max}}\right)$$  \hspace{1cm} (15)

Thus the bit rate achieved by data user $i$ is given by

$$R_i = \frac{W}{\gamma_d K_v P_v + \sum_{j=1}^{N_d} Q_j h_j - Q_i h_i}$$  \hspace{1cm} (16)

C. Round-robin scheme

In this scheme, users are allowed to transmit in a round-robin style. The difference here from the traditional round-robin is that not single but multiple users are allowed to transmit in a time slot as long as there is received power budget available. For example, suppose that in current time slot the user selection and power allocation starts from user $i$: $P_i = \min(B_d, P_{i}^{\text{max}})$. If the residual power budget after this allocation is larger than 0, i.e., $B_d > P_{i}^{\text{max}}$, then the residual power budget is allocated to user $i + 1$ as $P_{i+1} = \min(B_d - P_{i}^{\text{max}}, P_{i+1}^{\text{max}})$. The allocation process will go on until user $i + K$, where $0 \leq B_d - \sum_{j=i}^{i+K-1} P_{j}^{\text{max}} \leq P_{i+K}^{\text{max}}$ and $P_{i+K} = B_d - \sum_{j=i}^{i+K-1} P_{j}^{\text{max}}$. Thus in this time slot, users $(i, \ldots, i + K)$ are allowed to transmit with the allocated received powers $(P_i, \ldots, P_{i+K})$, respectively. In the next time slot, the user selection and power allocation will start from user $i + K + 1$ and follows the same procedure in a cyclic manner.

5 Numerical Results

A. Simulation setup

In this section, we compare the performance of the three scheduling schemes presented in Section 4 by computer simulations. We consider a voice/data DS-CDMA system which operates on the frequency of 900MHz with the spread-spectrum bandwidth of 5MHz. The required $E_b/I_0$ is 4 for voice service and 6 for data service. The total number of voice users is 20 with the
activity factor of 0.4, and the bit rate requirement of 32kb/s when it is active. The received power of active voice user is assume to be fixed at 10^{-9}W at BS. The length of time slot is 10ms.

In the simulation, all data users are assumed to be of the same transmission power limitation \( Q_{\text{max}} \). In the same time slot, data users experience independently and identically distributed (i.i.d.) shadowing and fading, respectively. The channel gain of user \( i \) is given by

\[
h_i = L(d_0) \left( \frac{d_i}{d_0} \right)^\mu Y_i \left( X_{Ii}^2 + X_{Qi}^2 \right),
\]

where \( L(d_0) = \frac{G_t G_r \lambda^2}{16\pi^2 d_0^2} \) is the path loss of the close-in distance \( d_0 \), with the antenna gain of the transmitter \( G_t \), the antenna gain of the receiver \( G_r \), and the wave-length of carrier \( \lambda \). A close-in distance \( d_0 = 50m \) is considered in the simulation. \( d_i \) is the distance between user \( i \) and BS. We assume a uniform distribution between the distance of 100 meters and 500 meters from BS for all users. \( Y_i \)'s are i.i.d. lognormal shadowing with standard deviation \( \sigma_S \). Moreover, \( X_{Ii} \) and \( X_{Qi} \) are the real and the imaginary part of a Rayleigh fading channel gain and follow normal distributions with zero mean and variance \( \frac{1}{2} \). \( \mu \) is the propagation loss exponent and is assumed to be \(-4\) in the simulation. We also assume the composite antenna gain from the transmitter and the receiver is \( G_t G_r = 10 \). In following simulations, only one user (i.e., \( K = 1 \)) is selected from Step 1 of PDI algorithm in each time slot when we do not explicitly specify this value.

B. Simulation results

We plot the throughput of data service and the total transmission power of data users as functions of number of data users in Figs.2 and 3, respectively. It shows that the highest throughput is achieved but the lowest total transmission power is needed for data service by employing the proposed PDI scheduling scheme. The round-robin scheme performs at the second place and the fair-sharing scheme has the poorest performance. This result is well explained by noting that all powers are intended to be allocated to those users with the best channel gains under PDI scheduling, so that the transmission powers are most effectively utilized which in turn is translated into the improvement of throughput and the decrease of transmission
power consumption under PDI scheduling. Although the round-robin scheduling also focuses powers on a limited number of users, it performs poorer than PDI scheduling because it does not count for the channel information in its operation. Therefore it has a less efficient power allocation than PDI scheme does. At the same time, under fair-sharing scheme, the powers are distributed across all users regardless of their difference on channel conditions, thus it has the most inefficient power utilization and the poorest performance. In addition, it shows that with the increase of data users, the throughput of fair-sharing scheme and round-robin scheme tends to be constants quickly and respectively. However, the throughput of the proposed scheme continues to increase before it is saturated at a relatively large number of users (about 35 in this simulation). Thus the proposed scheme takes more advantage from large number of users in the throughput enhancement. This advantage comes from the fact that the users with larger IRPC (or equivalently, better channel condition when power upper bounds are the same) can be selected from a larger set of candidates by the proposed scheme, therefore higher efficiency of power utilization is achieved. In contrast, the increase of users has no influence on the user selection under round-robin and fair-sharing scheme, thus their throughput is saturated quickly. It is just because of the same reason, under PDI scheduling, for a given received power budget, a smaller number of users, each of which is of relatively larger IRPC, will be selected for transmission when the total number of users is increased. Noting that there is a unified transmission power upper bound for all users, the decrease in the number of simultaneous users reduces the total transmission power. This explains why the total transmission power will decrease with the increase of user population under PDI scheduling in Fig. 3.

We study the throughput and the power consumption as functions of lognormal shadowing depth in Figs.4 and 5, respectively. It shows that with the deterioration of shadowing, throughput degradation is resulted. At the same time, more transmission power is needed for data service. This is because that a shadowing with larger standard variation is more likely to result in deeper fading, i.e., smaller channel gain at this point. Thus the deterioration of shadowing weakens the channel conditions of all users so that lower efficiency of power utilization is re-
sulted, which is translated into throughput loss and the expense of additional powers.

We study the throughput and the power consumption as functions of transmission power constraint in Figs.6 and 7, respectively. Generally speaking, data throughput will increase with a larger transmission power constraint before it is saturated. This indicates that the negative influence on data throughput resulted from the constrains of transmission powers may be neglectable as far as the constrains are above some threshold (e.g. 2.5W in Fig.6). It should also be noted that, under PDI scheme although the throughput is substantially improved by employing a larger power limit, the total transmission power of data users generally remains unchanged. This is because the number of simultaneous users in a time slot is reduced with the increase of transmission power limit, thus the increased transmission power of individual user is balanced by a reduced number of simultaneous transmissions so that the total transmission power remains basically unchanged in Fig.7.

The throughput and the total transmission power of data users are plotted as functions of distance between MS and BS in Figs.8 and 9, respectively. In these figures, all 30 data users are set to be of the same distance from BS. It is shown that the superiority of PDI scheme is much more obvious when the distance is small. This is because that the co-channel interference is high when the distance is small, thus the efficiency of power utilization is more sensitive to the optimum of scheduling schemes employed. It is also shown that the performance of all three schemes deteriorate and converge gradually with the increase of distance. Thus when the distance is large enough, all schemes loss their advantages. This phenomenon is due to the limitation of transmission powers. With the increase of distance, the channel gain of all users decay by an exponent of 4. Considering the constraint of transmission power, the IRPC also decay by an exponent of 4. Thus finally all users are allowed to transmit simultaneously and there is no difference between individual scheduling scheme. Figs.8 and 9 also imply an unequality on the throughput achieved by users with different distance from the BS: under the same transmission power limitation, the users near the BS will acquire more throughput than those far away from the BS. Because throughput increases with the increment
of transmission power constraint, in order to achieve a more fair throughput-sharing among
users, larger transmission power upper bound may be assigned to those users far away from
the BS.

We study the throughput-fairness trade-off comparison between PDI scheduling and round-robin
scheme in Fig.10. As we mentioned in the remarks of PDI scheduling in section 4.A, the number
of users selected (i.e., parameter $K$) in Step 1 of PDI algorithm provides a trade-off between
throughput and fairness. With a larger $K$, PDI scheme will provide better fairness among users
and its fairness performance tends to be similar to that of the round-robin scheduling. This
is clearly demonstrated in Fig.10, where it shows with the increase of $K$, the index of fairness
achieved by PDI scheduling tends to be that of round-robin scheme. Here the index of fairness
is defined as

$$
\delta_F = \frac{\left( \sum_{i=1}^{N_d} \bar{R}_i \right)^2}{N_d \sum_{i=1}^{N_d} \bar{R}_i^2},
$$

(18)

where $\bar{R}_i$ is the average data rate achieved by data user $i$. Clearly, $\delta_F$ is positive and always
less than or equal to 1. A larger $\delta_F$ indicates a better fairness in throughput sharing among
different users. With the increase of $K$, more transmitting users are selected from the exclusive
set of candidate users in Algorithm Step 1, so that the chance that a user is repeatedly selected
in the successive slots are reduced. This results in a better fairness. From Fig.10, it should also
be noted that even if $K$ is large enough, data throughput achieved under PDI scheme is still
much larger than that under round-robin scheme. This is well explained by noting that the
user selection in Algorithm Step 1 in PDI scheme is also according to the descending order of
users’ IRPCs. Therefore, according to Proposition 1 superior power utilization is maintained
by PDI scheduling to that of round-robin scheme even when they present equal fairness.

In the proposed scheduling scheme, prediction algorithm must be employed to estimate the
fast fading experienced by data users in the up-coming time slots. In a practical system, such
estimation could not be perfect, i.e., errors exist in the estimated values. We study the impact
of estimation error on the performance of the proposed scheme in our simulation. Here the
estimation error is modeled as an AWGN $W_\epsilon$ with zero mean and variance $\epsilon_f$. In addition, in order to have a better understanding of the influence of fading estimation error, we will ignore the influence of the distance difference between users, i.e., we assume all users are of the same distance from BS. Thus the predicted channel loss is given by

$$h'_i = L(d_0) \left( \frac{d}{d_0} \right)^\mu Y_i \left( X_i^2 + X_\epsilon^2 + W_\epsilon \right),$$

(19)

where $d = 250m$ is employed in the simulation. Because the average fading gain has been normalized to 1 in (19), $\epsilon_f$ represents both absolute value and relative value of estimation errors. The throughput and the total transmission power of data service as functions of estimation errors under PDI scheduling scheme are plotted in Figs.11 and 12, respectively. It shows that estimation errors lead to throughput loss and the larger the errors, the larger the throughput loss. However, by comparing Fig.11 with the throughput of round-robin scheme, it can be shown that as long as the estimation errors are controlled within 5%, 35%, and 45% for a total number of 5, 30, and 50 data users, respectively, the throughput achieved by the proposed scheme is still larger than that of the round-robin scheme and thus much larger than that of the fair-sharing scheme. The more the data users there are, the larger estimation error the proposed scheme can tolerate to acquire a superior throughput performance to its counterparts. This directly demonstrates that the negative influence of estimation error on PDI scheduling is alleviated with the increase of user population. In other words, PDI scheme achieves its immunity to the estimation error from the enlarged number of users. This advantage is explained by noting that under PDI scheduling throughput tends to increase with a larger number of users (as shown in Fig.2), which counteracts the impact of larger estimation errors. Thus the proposed scheme owns a certain degree of robustness and is of value in practical implementation.

6 Conclusions

In this paper, we have proved that under a given received power budget and constrained transmission powers, the throughput of data service is maximized by focusing all the received powers
on those data users with the largest index of received power capabilities. Based on this principle, we have proposed a Partially Descending Index of Received Power Capability (PDI) scheduling scheme for the data users in a voice/data CDMA network. This scheme provides efficient throughput and guarantees certain fairness by stepped selection of transmission users and allocating received powers according to the descending order of their indexes of received power capability. By numerical examples, the performance of the proposed scheme has been compared with that of the fair-sharing scheme and the round-robin scheme. The results have shown that the best performance is achieved by the proposed scheme in terms of the largest data throughput and the smallest total transmission power consumption. At the same time, the throughput-fairness trade-off feature of PDI scheduling has been examined through simulation. We have also studied the influence of channel estimation errors on the performance of the proposed scheme. It has been found that as long as the channel estimation errors are maintained within certain degree, the performance of the proposed scheme is still the best among the schemes considered. In addition, more data users there are in the network, larger channel estimation error PDI scheme can tolerate to achieve a superior throughput performance. Therefore, the efficiency, fairness and robustness of the proposed scheme have been verified.

References


Initialization: $U = \{1, \ldots, N_d\}$;

# In each time slot, perform the following

Input: $H = \{h_1, \ldots, h_{N_d}\}$

$P_{\text{max}} = \{P_{1,\text{max}}, \ldots, P_{N_d,\text{max}}\}$

$B_d$

Initialization: $P = \{P_1, \ldots, P_{N_d}\} = \{0, \ldots, 0\}$

# Algorithm Step 1:

$\text{number_of_selected}=0$

while ($\text{number_of_selected} < K$)

\[
\begin{align*}
    j &= \text{arg max}_{i \in U \text{ and } P_i = 0} P_{i,\text{max}} \\
    P_j &= \min \{B_d, P_{j,\text{max}}\} \\
    B_d &= B_d - P_j
\end{align*}
\]

delete $j$ from $U$

$\text{number_of_selected}++$

if $\text{sizeof}(U) = 0$

$U = \{1, \ldots, N_d\}$
endif

if $B_d <= 0$

break
endif
end while

# Algorithm Step 2:

while ($B_d > 0$)

\[
\begin{align*}
    j &= \text{arg max}_{i = 1 \ldots N_d \text{ and } P_i = 0} P_{i,\text{max}} \\
    P_j &= \min \{B_d, P_{j,\text{max}}\} \\
    B_d &= B_d - P_j
\end{align*}
\]

$\text{number_of_selected}++$

if $\text{number_of_selected} = N_d$

break
endif
end while

Output: $P = \{P_1, \ldots, P_{N_d}\}$

Figure 1: Pseudocode of PDI algorithm
Throughput of data users (Kb/s)
Number of data users
PDI scheduling
round-robin scheduling
fair-sharing

Figure 2: Data throughput vs. number of data users

Total transmission power of data users (W)
Number of data users
PDI scheduling
round-robin scheduling
fair-sharing

Figure 3: Total transmission power of data users vs. number of data users
$Q^\text{max} = 2W$, $N_d = 10$, $d_i$ is uniformly distributed between 100m and 500m.

Figure 4: Data throughput vs. standard variation of lognormal shadowing

$Q^\text{max} = 2W$, $N_d = 10$, $d_i$ is uniformly distributed between 100m and 500m.

Figure 5: Total transmission power of data users vs. standard variation of lognormal shadowing
Figure 6: Data throughput vs. transmission power limit

Figure 7: Total transmission power of data users vs. transmission power limit
Figure 8: Data throughput vs. distance from the BS

Figure 9: Total transmission power of data users vs. distance from the BS
Figure 10: Trade-off between throughput and fairness under PDI scheduling

Figure 11: Data throughput vs. channel estimation error under PDI scheduling
Figure 12: Total transmission power of data users vs. channel estimation error under PDI scheduling

\[ Q_{\text{max}} = 2W, \sigma_s = 8\text{db}, d = 250\text{m} \]