Transmission Rate Scheduling with Fairness Constraints in Downlink of CDMA Data Networks

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Abstract - In this paper, we focus on the throughput maximization problem in the downlink of CDMA data networks. Proper transmission rate scheduling of data service in downlink can reduce the intra-cell interference; hence maximize the throughput of the downlink. Various works have been done for the transmission rate scheduling to maximize total throughput in a CDMA network. Among these works, only the best effort method can be applied as a practical scheduling scheme. However, in this method some users may have no chance to receive their data at all during the whole scheduling time horizon since this method considers only throughput maximization. In this paper, we consider the fairness among users while maximizing total throughput of the system. Since the interference from neighboring cells of a certain cell to each user in the cell is stochastic, this problem becomes a stochastic optimization problem. The fairness among users is modeled in two different ways, a hard minimum requirement constraint and a soft minimum requirement constraint for each user. Transmission rate scheduling methods for the two models have been suggested and tested through numerical simulation. Our simulation test showed that the method for the model with soft constraint has excellent performance in both throughput and fairness.

Index Terms - CDMA, fairness, throughout maximization problem, transmission rate scheduling.

I. INTRODUCTION

In the 2nd generation wireless systems, CDMA system has been one of efficient multiple access methods for voice transmission. Power control of a CDMA system can increase the capacity and communication quality of the system. On the other hand, in the 3rd generation wireless systems data service such as Internet access has more important role than voice service. One of the features of data service different from voice service is its asymmetric traffic. A much higher rate is required in downlink than uplink of the system. Therefore, efficient data transmission in downlink of CDMA systems becomes more important problem than in uplink.

In a CDMA downlink, data rate of a particular user depends on the transmission power to the user, which is controllable resource, and his received interference. The power resource for downlink transmission is limited and the transmission power to a certain user causes interference to other users, therefore power assignment is an important problem to maximize the total throughput of the system. A user in a cell receives two kinds of interference. One is the intra-cell interference which is originating from the simultaneous transmission to other users in the same cell and the other is the inter-cell interference which is caused by transmission in other cells.

Various studies have been performed to reduce the intra-cell interference using transmission rate scheduling. The first work was performed for uplink transmission [1], [2]. They introduced a throughput maximization model and transmission rate scheduling in which only one user transmits his data at a certain time instance. And they showed that one-by-one scheduling minimizes the intra-cell interference and can maximize the total throughput of the system, but they did not suggest a practical scheduling method for their throughput maximization model. Another approach in uplink transmission has been shown in [3]. Instead of maximizing the throughput, they considered time span minimization and showed that time span can be minimized by successively maximizing throughput at each time slot, thus the best effort method which assigns a time slot to a user with the highest throughput is optimal.

Similar studies also have been performed in CDMA downlink. The study of [4] has proposed optimality properties of throughput maximization in CDMA downlink. Their first optimality property implies that the optimal transmission rate scheduling is the one-by-one transmission which means that a particular base station transmits to at most one user at a certain time instance. The second one is that if a base station transmits to a certain single user in the cell, the transmission power should be as high as possible. In [5], the best effort method was suggested to maximize the total throughput of system. From these works, we can conclude that the total throughput of the downlink in a CDMA system can be maximized by choosing the user with the best signal-to-interference ratio at each time instance and assign the largest possible power to him. In this case, at each time instance the user with the highest signal-to-interference ratio uses the whole transmission resource in the optimal solution. Hence, some users may have no transmission time assigned at all during the total time duration. To be a more practical transmission rate scheduling, fairness among users should be considered. If we consider the fairness among users then the solution in [5] are not valid any more. Hence it is needed to develop a practical transmission rate scheduling method for throughput maximization with fairness among users.

In this paper, we suggest one-by-one transmission rate scheduling methods for the throughput maximization problem with fairness among users in the downlink of a CDMA system. In order to consider the fairness among users we introduce a minimum throughput requirement constraint for each user. At a time instance, the transmission rate for a user in a certain cell depends on the amount of interference from other cell to the user. We assume that the amount of interference from other cells to each user is random and this problem becomes a stochastic optimization problem. We model this problem in two different ways. We first regard the constraint as a hard constraint, i.e., the constraint for each user should be strictly satisfied during the scheduling time horizon. A transmission rate scheduling method based on the time span minimization and the best effort method is suggested for this model.

Since we do not have prior knowledge about the amount of future inter-cell interference at a certain time instance, our second model regards the minimum throughput requirement constraint as a soft constraint, i.e., the scheduling algorithm for the model tries to satisfy the minimum throughput requirements but it is allowed that constraints for some users may not be satisfied. If the amount of unsatisfied minimum requirements is small, then this amount could be covered in the next scheduling time horizon. A transmission rate scheduling method based on the forecasting of future throughput of each user and the best effort method is suggested for this model. Simulation tests for these two methods have been performed. The method for the model with soft constraints showed excellent performance in the simulation test.

The organization of this paper is as follows. In section II the system model is described and the transmission rate scheduling which maximizes the throughput of the system is introduced in section III. In section IV, the transmission rate scheduling with hard fairness constraints is formulated and a simple transmission rate scheduling method is proposed. And its performance is evaluated using numerical simulations. In section V, we present the transmission rate scheduling with soft fairness constraints and propose another scheduling method for this problem. Its performance is also evaluated using numerical simulations. Concluding remarks are contained in section VI.

II. SYSTEM MODEL

We will consider a cellular CDMA network in which each cell contains one base station and we are interested in downlink transmission rate scheduling in a particular cell in the CDMA network. In downlink, the base station of the cell transmits to each user in the cell simultaneously with the same frequency but with different orthogonal codes. All users in the cell share the power resource of their base station.

Let E be the set of active users in the cell. For a user i in E, let P_i^r be the power received from the base station and I_i be the received interference. If the Gaussian noise model is assumed and the noise is denoted by η, the Signal-to-Interference Ratio (SIR) for the user is given by

$$SIR_i = \frac{P_i^r}{I_i + \eta}$$

Let P_i be the power transmitted by the base station to user i and G_i be the link gain between the base station and user i, then $P_i^r = P_i G_i$. When the transmission rate of user i is r_i and the bandwidth is given by W, the bit energy to noise density ratio for user i is given by [4]

$$\gamma_i = \left(\frac{E_b}{N_o}\right)_i = \frac{W}{r_i} \cdot \frac{P_i G_i}{I_i + \eta}$$

Let $\bar{\gamma}$ be the bit energy to noise density ratio which provides the minimum acceptable bit error rate that is common to all users. If we assume that transmission rates are adapted by varying the processing gain, and then the maximum achievable transmission rate for user i can be written as

$$r_i = \frac{W}{\bar{\gamma}} \cdot \frac{P_i G_i}{I_i + \eta} \tag{1}$$

Since the spreading bandwidth W is constant, equation (1) is valid only when the transmission rate for each user can be adjusted to his SIR. In the 3rd generation system, this can be achieved by adaptive modulation and coding (AMC) technique [6], [7]. If AMC is employed, then system chooses a level of modulation and coding according to the SIR of the user. A higher modulation and coding scheme can be used for a user who has higher SIR. Therefore a higher rate can be achieved. For instance, in [8] eight kinds of data rate are defined for HDR system based on potential channel variation. At a time instance, the data rate of each user is appropriately chosen from the defined data rates according to his SIR. But, although transmission rate can be adjusted to the measured SIR, data rate does not have linear relation to SIR. Hence the assumption on equation (1) has limitation in a practical system. However, if one-by-one scheduling scheme is adopted in the system, then this limitation may not be important.

For a particular user i in the cell, $P - P_i$ is the transmitting power to other users in the cell, where $P = \sum_j P_j$ is the total transmitting power of the base station, which is constrained due to hardware limitation. In a CDMA system, if the orthogonality of the received signals to different users is perfectly maintained the transmitting power to other users does not cause any interference. However, because of the multi-path fading the received signals usually do not have perfect orthogonality and this introduces interference [4], [9]. This kind of interference is called intra-cell interference and can be written as

$$I_i^{intra} = (P - P_i) G_i f_i \tag{2}$$

where f_i is the orthogonality factor for user i. If the base station uses orthogonal codes to transmit to distinct users and there is no multi-path fading, then $f_i = 0$ and there is no intra-cell interference. When there is multi-path fading, the factor is a value in [0, 1] depending on the wireless transmission environment.

User i also receives interference from the base stations of neighboring cells. Let S be the set of neighboring cells of the considered cell and G_{ki} be the link gain from the base station in a neighboring cell k to user i. When P^k is the total transmission power of the base station in a neighboring cell k, the inter-cell interference to user i is

$$I_i^{inter} = \sum_{k \in S} P^k G_{ki} \tag{3}$$

Using equations (1), (2) and (3), the maximum transmission rate of user i can be written as

$$r_i = \frac{W}{\bar{\gamma}} \cdot \frac{P_i G_i}{I_i^{inter} + I_i^{intra} + \eta} \tag{4}$$

III. Transmission Rate Scheduling

Let us first consider the transmission rate scheduling problem which maximizes the total throughput in the cell over a certain time duration T. Bedekar and Yeh [4] have shown that the optimal scheduling of this problem is the one-by-one scheduling in which the base station transmits to a single user in the cell with the maximum transmission power at a given time instance. That is, $P_s = P_{\max}$ for a certain user s and $P_i = 0$ for all $i \neq s$. In this case, there is no intra-cell interference and from (4) the transmission rate of the user s at the time instance is

$$r_s = \frac{W}{\bar{\gamma}} \cdot \frac{P_{\max} G_s}{I_s^{inter} + \eta} \tag{5}$$

and the transmission rates of all other users are zero. Then, the throughput of the cell during short time interval Δt is

$$R = \Delta t \cdot \frac{W}{\bar{\gamma}} \cdot \frac{P_{\max} G_s}{I_s^{inter} + \eta}$$

where s is the user who is assigned to receive data from the base station during the time interval Δt.

To decide which user will use the maximum downlink power at each time instance, we will use a discrete time model where the total time duration T is divided into small time units, called time slot. Let Δt be the length of a time slot and N be the number of time slots. At each time slot t ($t = 1, \ldots, N$), we decide which user the base station will transmit to. Let us introduce binary decision variable x_i^t which indicates whether the base station transmits to user i or not at time slot t. If the time slot t is assigned to user i then x_i^t is 1, and x_i^t is 0 otherwise. Let I_i^t be the inter-cell interference received by user i at time slot t. Then the throughput of user i during time slot t is

$$R_i^t = x_i^t \cdot \Delta t \cdot \frac{W}{\bar{\gamma}} \cdot \frac{P_{\max} G_i}{I_i^t + \eta}$$

And the total throughput of user i during the whole time duration T is

$$R_i = \sum_{t=1}^{N} R_i^t = \sum_{t=1}^{N} x_i^t \cdot \Delta t \cdot \frac{W}{\bar{\gamma}} \frac{P_{\max} G_i}{I_i^t + \eta}$$

We assume all users want data rates as high as possible. Then the downlink throughput maximization problem for the cell can be formulated as the following integer programming problem:

(P1)

$$\begin{aligned} \max \quad & \sum_{i \in E} R_i \\ s.t. \quad & \sum_{i \in E} x_i^t \le 1, \quad t = 1, \dots, N \\ & x_i^t \in \{0,1\}, \quad t = 1, \dots, N, \; i \in E \end{aligned}$$

In this problem, all parameter except the inter-cell interference I_i^t are known assuming the background noise density can be estimated. This problem can be easily solved by using the best effort method which has been shown in [5]. According to the best effort method, the throughput can be maximized by the assignment such that at each time slot the user with the largest value of $SIR_i^t = \frac{P_{\max} G_i}{I_i^t + \eta}$ uses the full power resource.

IV. Transmission Rate Scheduling with Hard Fairness Constraints

The problem (P1) simply maximizes the throughput of the cell. In the optimal solution of the model, the user with the highest SIR uses the whole transmission resource at each time slot. Hence some users may have no time slots assigned at all during the total time duration. To be a more practical transmission rate scheduling model, fairness among users should be considered. In this paper, we model the fairness by introducing a minimum throughput requirement constraint for each user as follows:

$$R_i \ge A_i, \quad \forall i \in E$$

where A_i is the minimum throughput requirement for user i during the whole time duration T. Then, the throughput maximization problem with fairness constraints can be formulated as follows:

(P2)

$$
\begin{aligned}
\max \quad & \sum_{i\in E} R_i \\
s.t. \quad & R_i \geq A_i, && \forall i \in E \\
& \sum_{i\in E} x_i^t \leq 1, && t = 1,\dots,N \\
& x_i^t \in \{0,1\}, && t = 1,\dots,N,\ i \in E
\end{aligned}
$$

To simplify the problem (P2), let $D_i^t = \Delta t \cdot \frac{W}{\bar{\gamma}} \cdot \frac{P_{\max} G_i}{I_i^t + \eta}$. Then problem (P2) can be written as follows:

(P3)

$$
\begin{aligned}
\max \quad & \sum_{i\in E} \sum_{t=1}^{N} D_i^t x_i^t \\
s.t. \quad & \sum_{t=1}^{N} D_i^t x_i^t \geq A_i, && \forall i \in E \\
& \sum_{i\in E} x_i^t \leq 1, && t = 1,\dots,N \\
& x_i^t \in \{1,0\}, && t = 1,\dots,N,\ i \in E
\end{aligned}
$$

In this problem, the inter-cell interference I_i^t is a random variable and its future value cannot easily be estimated.

A. Time Span Minimization And Best Effort

In this section, we suggest a heuristic method to find a good feasible solution of (P3). In this method, we first assign the minimum throughput requirements of all users based on the minimum time span method [3]. And then we use the best effort method to maximize the total throughput during rest of time slots.

Suppose the number of time slots is sufficiently large enough to satisfy minimum throughput requirements of all users. Let F be the set of the users who need more time slots to satisfy their minimum throughput requirement at a certain time instance. At the first time slot, F is equal to E. At each time slot, if $F \neq \phi$, the time slot is assigned to the user who has the highest SIR among the users in F at that time slot. If the minimum throughput requirement for a user is satisfied, then the user is removed from F. Each time slot is assigned until the minimum throughput requirements of all users are satisfied. Once the minimum throughput requirements of all users are satisfied at a certain time slot, then each time slot after the time slot is assigned to the user who has the highest SIR.

This Time Span Minimization And Best Effort (TSMABE) procedure is as follows:

(TSMABE)

Step1 If $F \neq \phi$, go to Step2.

Otherwise, go to Step 3.

Step2 Let $k = \arg\max_{i \in F}\{SIR_i^t\}$.

Then $x_i^t = \begin{cases} 1, & for \quad i = k \\ 0, & for \quad i \in E - \{k\} \end{cases}$

Let $A_k = A_k - R_k^t$. If $A_k \leq 0$, then $F = F - \{k\}$. Stop.

Step3 (Best effort method for remaining time slots)

Let $s = \arg\max_{i \in E}\{SIR_i^t\}$ and

$$x_i^t = \begin{cases} 1, & \textit{for } \ i = s \\ 0, & \textit{for } i \in E - \{s\} \end{cases},$$

and stop.

B. Opportunity Cost Method And Best Effort

Even though TSMABE looks like a good method, its resulting solution is not quite efficient because this method always generates a solution such that all time slots for minimum throughput requirements are allocated in the front part the time duration. This may degrade the optimality of the solution.

In this section, we consider a hypothetical model to estimate the efficiency of TSMABE. We will assume that the inter-cell interferences in (P3) are known in advance. Hence, this model shows what would have been a good schedule when we consider the scheduling problem backward at the end of the time duration. The optimal throughput of this problem provides an upper bound of the optimal throughput of the problem (P3) with random inter-cell interference.

Unfortunately, the problem (P3) with known inter-cell interference is NP-complete, because (P3) is reduced to the 2-partition problem which is known to be NP-complete [10]. Hence, instead of finding exact optimal solution of the problem, we suggest an efficient heuristic method.

In this method, we first assign the minimum throughput requirements of users based on the concept of opportunity cost and then use the best effort method to maximize the throughput. The opportunity cost of a user is defined as the expected decrease of the user's throughput that is occurred when the best time slot for the user is not assigned to the user. At a certain iteration of the method, let R_i^1 and R_i^2 be, respectively, the throughputs of the best and second best remaining time slots for user i. Then, the opportunity cost used in this method is

$$C_i = R_i^1 - R_i^2$$

If user i is not assigned with the best remaining time slot, then maximum amount of throughput he can expect from the assignment of a time slot in the next iterations is R_i^2. Hence, C_i is a measure of the expected decrease of the user's throughput which is occurred when the best time slot for the user is not assigned to the user. At each iteration of the method, we compute C_i for each user who needs additional time slots to satisfy the minimum throughput requirements. Then we find the user with the largest value of C_i and assign the user's best time slot to the user. If this time slot is not assigned to that user, a large amount of loss in throughput is expected. Hence, the assignment of the time slot to that user is a good decision. This procedure is continued until the minimum throughput requirements of all users are satisfied. And then we apply the best effort method for the remaining time slots to maximize the total throughput.

This Opportunity Cost Method And Best Effort (OCMABE) is as follows.

(OCMABE)

Step0 Let $F = E$ be the set of active users and $T = \{1, \dots, N\}$ be the set of time slots.

Step1 For each user $i \in F$, let $u_i = \arg\max_{t \in T}\{D_i^t\}$, $v_i = \arg\max_{t \in T - \{u_i\}}\{D_i^t\}$ and $C_i = D_i^{u_i} - D_i^{v_i}$.

Let $k = \arg\max_{i \in F}\{C_i\}$ and $x_i^{u_k} = \begin{cases} 1, & for \quad i = k \\ 0, & for \quad i \in E - \{k\} \end{cases}$.

Step2 Let $T = T - \{u_k\}$ and $A_k = A_k - D_k^{u_k}$.

If $A_k \le 0$, let $F = F - \{k\}$.

If $F = \phi$, go to Step 3.

If $T = \phi$, Stop. This problem is infeasible.

Otherwise, go to Step 1.

Step3 (Best effort method for remaining time slots)

For each $t \in T$, let $k = \arg\max_{i \in E}\{D_i^t\}$ and

$$x_i^t = \begin{cases} 1, & for \;\; i = k \\ 0, & for \;\; i \in E - \{k\} \end{cases}.$$

Stop.

We can easily show that the computational complexity of OCMABE is $O(|E| \times N^2)$.

C. Numerical Simulations

Numerical simulations with different number of users and different number of time slots are performed to test the efficiency of TSMABE. The downlink transmission of a hexagonal cell surrounded by two tiers of neighboring cells is scheduled optimally using our methods. The considered time duration is 2 seconds and the size of time slot Δt is determined by the time duration divided by the total number of time slots. During the time duration T , we assumed that the location of each user is fixed. The position of each user is randomly generated assuming that users are probabilistically uniformly distributed in the cell. At each time slot, we assumed that the base station of each neighboring cell transmits with random power. We assumed the path loss parameter is 4, the cell radius is 1km and the noise level is -150dBW. The spreading bandwidth is set to $W = 1.229$ MHz and the required bit energy to noise density ratio $\bar{\gamma} = 8\text{dB}$ for all users. The maximum power is set to $P_{\max} = 5\text{W}$ and the transmitted power for control is 0.5W.

For each scenario with a given numbers of users and time slots, random numbers are generated to determine the position of each users and the power of neighboring cells. Then we calculated D_i^t for $\forall i \in E,\ t = 1, \cdots N$. The minimum throughput requirements of users can be any values. However, to have more realistic simulation environment, we generated minimum throughput requirement for each user as follows. We first calculate the maximum possible throughput, R_m, of the cell without any minimum throughput requirement. Then we assume that the sum of the minimum throughput requirements of all users is equal to αR_m, where α is a number between 0 and 1. A large value of α implies that there are heavy minimum throughput requirements in the cell. We simulate for different values of α. In our simulation, we assumed that the user with better link gain has higher minimum throughput requirement. If the minimum throughput requirements of all users are equal, then a user who has worse SIR is guaranteed more chance to transmission. Hence, the total of the minimum throughput requirements, αR_m, is distributed to each user in proportion to link gain.

Table 1 shows the simulation results of 36 cases with different numbers of users and time slots and different values of α. For each case, the position of users and the power level of neighboring cells are randomly generated. Then we applied the two methods to find the optimal throughput of the cell. These results are represented as a percentage to R_m, the maximum possible throughput of the cell when there are no minimum throughput requirements. We performed this simulation 300 times for each case. The numbers in Table 1 are the averages of the 300 results. The numbers in parentheses are the ratios of the throughput of TSMABE to that of OCMABE.

In all 36 cases the throughput of TSMABE achieves about 67%~99% to that of OCMABE. When α is large, the performance of TSMABE shows much worse than that of OCMABE. Especially, when α is 0.4, the throughput of TSMABE achieves only about 67%~80% to that of OCMABE. This difference came from two sources. One is the fact that we assumed the future inter-cell interferences are known in OCMABE and this information provides better performance to OCMABE. Another is that the solution of TSMABE may have been degraded as we discussed in section 4.A. In any case, the simulation results in Table 1 show that there may be some room to improve the performance of transmission rate scheduling over TSMABE.

To test the performance of OCMABE, we calculated the true optimal value using a known general- purpose optimization package, ILOG CPLEX 7.0 [11]. Table 2 shows the throughput of OCMABE and the true optimal value. The numbers in parentheses are the ratios of the throughput of OCMABE to the true optimal value. In this table, we can see that the throughput of OCMABE achieves about 78%~96% of the optimal value.

V. TRANSMISSION RATE SCHEDULING WITH SOFT FAIRNESS CONSTRAINTS

A. Transmission rate scheduling with soft fairness constraints

One problem of TSMABE is that inefficiency is occurred in the assignments of the minimum throughput requirements because minimum requirements are always assigned in the front part the time duration. In this section, we suggest a new practical transmission rate scheduling method which has better performance than TSMABE.

In our new method, at each time slot there is a step to decide whether the time slot is assigned to the user with the highest SIR or not. If we decide that the time slot is not assigned to the user, then the second step decides which user is assigned with the time slot. Unlike TSMABE, time slots for minimum throughput requirements will be distributed over the whole time duration in this new method and the performance of the solution is expected to be better. But since the future inter-cell interference is random and unknown, the minimum throughput requirements for some users may not be satisfied at the end of the time duration in the solution of this method. However, if the amount of unsatisfied minimum throughput requirements is quite small, this amount could be covered for the next scheduling time duration and may not cause any significant problem in the practical application. Hence, we will employ the concept of soft fairness constraints. In the model with soft fairness constraints, the constraints are not regarded as strict requirements thus a solution that does not strictly satisfy the constraint for each user is also valid if the amount of unsatisfied requirements is small. In the method for the model, we only require the amount of unsatisfied minimum throughput requirements during the time duration to be small instead of requiring the realized throughput of a user i during the time duration to be strictly greater than or equal to A_i.

Let D_i^t be the throughput of user i at time slot t. For $t > 1$, let

$$\bar{D}_i^t = \frac{1}{t-1} \sum_{s=1}^{t-1} D_i^s$$

be the average throughput of user i during previous time slots. In our method $\bar{D}_i^t$ will be used as an estimator of the throughput of user i at a future time slot.

At time slot t, we choose the user k who has the highest SIR or D_k^t. If his throughput D_k^t is sufficiently larger than $\bar{D}_k^t$, then we assign this time slot to user k since this slot has high throughput for user k compared to his expected future throughputs. Otherwise, we can expect that the throughput of user k in some future time slots will be quite large enough compared to his current throughput. Hence, there is no urgent need to allocate the current time slot to user k. This is the first step of our new method.

Suppose that we decided not to allocate the current time slot to the user k. Then we allocate this time slot to a user who has minimum throughput requirement left to satisfy. Among these users, the user with the largest value of $D_i^t / \bar{D}_i^t$ is allocated with the time slot since this user's throughout at this time slot is much higher than his expected future throughput. This is the second step of our method.

Our Transmission Rate Scheduling with Soft Fairness Constraints (TRSSFC) is as follows:

(TRSSFC)

Let β be a parameter which is greater than 1. Then the procedure of this method at each time slot $t \in T$ is as follows.

Step*0* Let $F = E$, $A_i^r = A_i$ for all $i \in E$. Let $t = 1$.

Let $k = \arg\max_{i \in E}\{D_i^1\}$

Go to Step 2.

Step1 Let $k = \arg\max_{i \in E}\{D_i^t\}$.

If $\frac{D_k^t}{\bar{D}_k^t} \geq \beta$ or $F = \phi$, then go to Step 2.

Otherwise, let $k = \arg\max_{i \in F}\{\frac{D_i^t}{\bar{D}_i^t}\}$ and go to Step 2.

Step*2* Assign time slot t to user k.

If $A_k^r > 0$, then let $A_k^r = A_k^r - R_k^t$ and if $A_k^r < 0$ then let $F = F - \{k\}$.

Let $t = t + 1$. Go to Step 1.

B. Numerical Simulations

In this section, the simulation environment is identical as that in section 4.C. We first choose the parameter β *as 1.5. Since TSMABE has poor performance when the minimum throughput requirements are heavy, our simulation has been performed for three large values of* α. *Tables 3 and 4 show the performances of TSMABE, TRSSFC and OCMABE with* $\alpha = 0.4$ *and* $\alpha = 0.5$, *respectively and Tables 5 and 6 show the performances of those methods with* $\alpha = 1$. *Notice that when* $\alpha = 1$ *the problem is infeasible since the total minimum throughput requirement of users exceeds the capacity of the network. Each case is tested 300 times and each number in all Tables is the average of the 300 results. Each number in the tables is the throughput measured as the percentage to* R_m *as in section 4.C.*

We first consider the feasible cases. Tables 3 and 4 show that the throughput of TRSSFC is much better than that of TSMABE and very close to that of OCMABE in all cases. The throughput of TRSSFC is about 14%~29% better than that of TSMABE when α is 0.4 and about 21%~39% better than that of TSMABE when α is 0.5.

There is no guarantee that the solution of TRSSFC satisfies the minimum throughput requirements of all users strictly. However, it turned out that all solutions of TRSSFC satisfies the minimum throughput requirements of all users when α is 0.4 as shown in Table 3. When α is 0.5, the minimum throughput requirements of some users are not satisfied as shown in Table 4. This is due to the randomness of the inter-cell interference. But Table 4 shows that the number of unsatisfied users is very small. For example, when there are 10 users and 100 time slots, the number of unsatisfied users is 0.004 in average in the simulation process. This means that only one out of the 300 simulation trials had one unsatisfied user and the solutions of 299 simulation trials had no unsatisfied users. In the trial with an unsatisfied user, the amount of the unsatisfied requirement of the unsatisfied user was only 0.21% of his total minimum requirement. Even though there is no guarantee that the solution of TRSSFC satisfies the minimum requirements of all users, TRSSFC generates a solution which satisfies the requirements in most simulation tests.

Tables 5 and 6 show the results of the infeasible case with $\alpha = 1$. *All three methods were not able to find a solution with no unsatisfied users. Table 5 shows the results of fairness performance we obtained from those three methods. As we expected, solutions of TSMABE and OCMABE have less unsatisfied users than solutions of TRSSFC but solutions of TRSSFC have higher throughputs than those of TSMABE and OCMABE as shown in Table 6.*

To evaluate the sensitivity of TRSSFC on the parameter β, we plot the variation of the throughput of TRSSFC for different values of β in Figure 1 when α is 0.5, the number of users are 40 users and the number of time slots are 300 slots. Also, Figures 2 and 3 show, respectively, the fraction of unsatisfied requirement of the most unsatisfied user and the number of unsatisfied users for different values of β. These Figures indicate that TRSSFC has stable and proper performance for β larger than or equal to 1.2.

VI. CONCLUSIONS

In this paper, we deal with the transmission rate scheduling problem to maximize the throughput while considering fairness among users in the downlink of a CDMA system. Since inter-cell interference is assumed to be random, this problem becomes a stochastic optimization problem. We modeled this problem in two different ways, a model with hard minimum requirement constraints and a model with soft minimum requirement constraints. In the model with soft minimum requirement constraints, the constraints do not considered to be strict. And we suggested two practical scheduling methods, one for each of the models. The method for the model with soft constraints shows very excellent performance in the numerical simulations.

In addition, the proposed scheduling methods require the information about only the current SIR. This information can be easily obtained because in the 3rd generation system such as HDR each base station measures the SIR of each user using the pilot channel. Therefore the proposed methods can be implemented to on-line scheduler in downlink of a CDMA data network.

REFERENCES

[1] S. Ramakrishna and J. M. Holtzman, “A Scheme for Throughput Maximization in a Dual-Class CDMA system”, *IEEE Journal on Selected Areas in Communications*, Vol. 16, No. 6, August 1998, pp830~844.

[2] A. Sampath, P.S. Kumar and J. M. Holtzman, “Power Control and Resource Management for a Multimedia CDMA Wireless System”, in *Proceeding PIMRC’95*, September 1995, pp21 ~ 25.

[3] R. Jantti and S-L. Kim, “Transmission Rate Scheduling for the Non-Real-Time Data in a Cellular CDMA System”, *IEEE Communications letters*, Vol. 5, No. 5, May 2001, pp.200~202.

[4] A. Bedekar and E. Yeh, “Downlink Scheduling In CDMA Data Networks”, *IEEE Global Telecommunications Conference* ’99, pp2653~2657.

[5] J. Zender, “Performance Bounds for Joint Power Control and Link Adapatation for NRT bearers in Centralized (Bunched) Wireless Networks”, in *Proceeding PIMRC ’99*, September 1999, pp890~894.

[6] S. Tateesh, S. Atungsiri and A.M. Kondoz, “Link adaptation to channel interference using multi-rate source and channel coding for CDMA mobile communications”, *IEEE International Comference on Acoustics, Speech and Signal Processing*, 1997, pp2485~2488.

[7] D. D. N. Bevan, C.R. Ward and K. M. Kelly, “Aggregate throughput gains due to downlink CIR enhancement in an HDR-type network”, *IEEE Vehicular Technology Conference*, 2001, pp2670~2671.

[8] P. Bender, P. Black, M. Grob, R. Padovani, N. Sindhushayana and A. Viterbi, “CDMA/HDR:A Bandwidth-Efficient High-Speed Wireless Data Service for Nomadic Users”, *IEEE Communication Magazines*, July 2000, pp 70~76.

[9] F. Berggren, S-L. Kim, R. Jantti and J.Zender, “Joint Power Control and Intracell Scheduling of DS-CDMA Nonreal Time Data”, *IEEE Journal on Selected Areas in Communications*, Vol. 19, No. 10, October 2001, pp 1860~1870.

[10] M. L. Fisher, R.Jaikumar and L.N. Van Wassenhove, “A Multiplier Adjustment Method For the Generalized Assignment Problem”, *Management Science*, Vol. 32, No. 9, September 1986, pp1095~1103.

[11] ILOG CPLEX, http://www.ilog.com/products/cplex

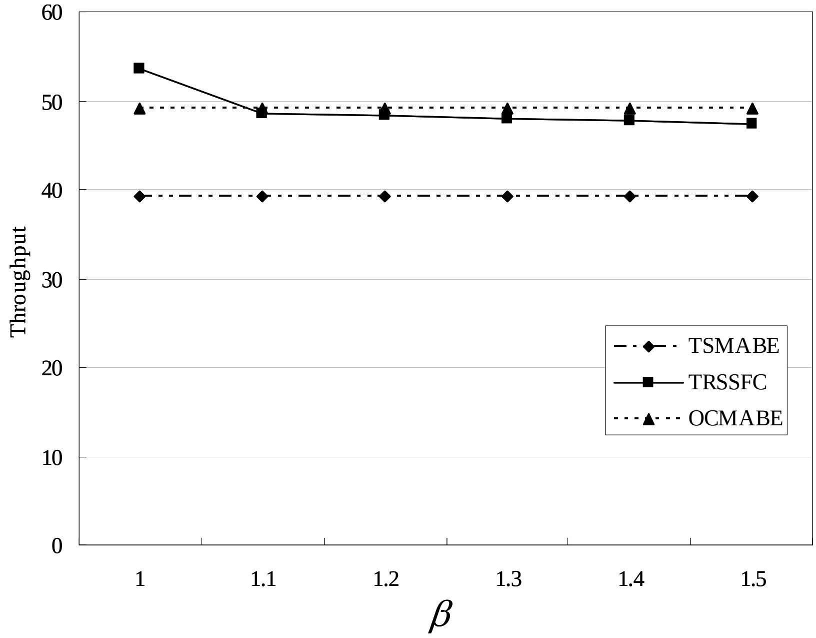

Figure 1. Throughput for different values of β .

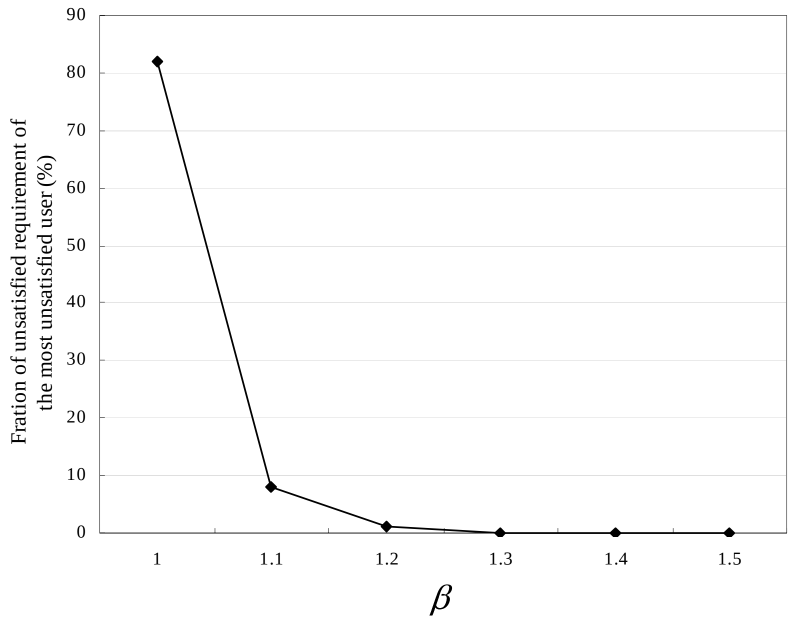

Figure 2. Fraction of unsatisfied requirement of the most unsatisfied user for different values of β .

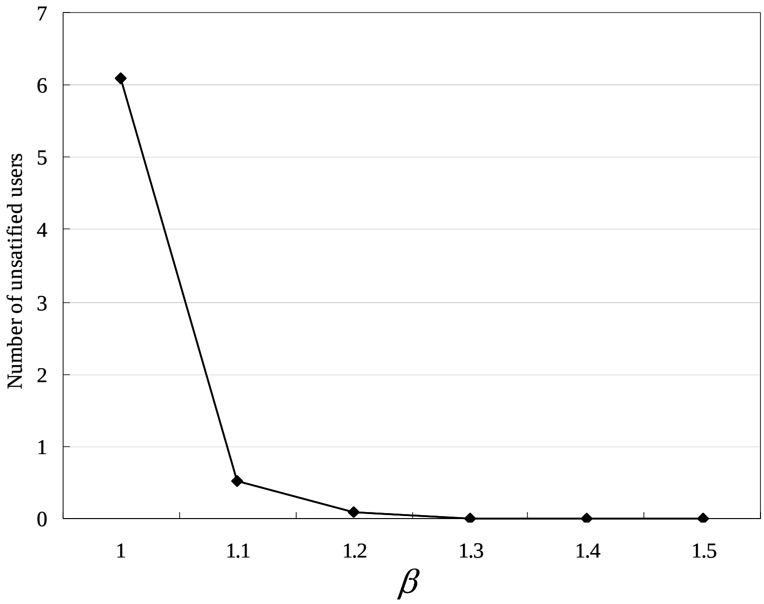

Figure 3. Number of unsatisfied users for different values of β .

Number of users	Number of slots	$\alpha = 0.2$		$\alpha = 0.3$		$\alpha = 0.4$	
		TSMABE	OCMABE	TSMABE	OCMABE	TSMABE	OCMABE
10	100	71.85(0.91)	79.18	61.94(0.84)	73.38	49.85(0.78)	63.68
	200	74.89(0.90)	83.07	63.69(0.84)	75.82	53.28(0.79)	67.82
	300	75.87(0.90)	84.07	64.87(0.84)	76.78	54.41(0.79)	69.06
20	100	65.18(0.86)	75.55	53.66(0.83)	64.93	42.78(0.80)	53.55
	200	71.09(0.92)	77.67	59.79(0.85)	70.57	48.53(0.80)	61.04
	300	73.31(0.91)	80.64	61.50(0.85)	72.04	50.30(0.80)	62.90
30	100	60.98(0.94))	64.83	47.05(0.77)	60.90	37.13(0.74)	50.23
	200	68.21(0.89)	76.83	56.77(0.87)	65.04	45.69(0.81)	56.70
	300	71.09(0.92)	76.96	59.96(0.86)	69.41	48.70(0.81)	60.04
40	100	54.75(0.99)	55.03	43.41(0.83)	51.68	30.91(0.67)	46.42
	200	65.33(0.87)	74.34	53.77(0.84)	63.95	42.51(0.83)	51.23
	300	69.31(0.90)	77.00	57.92(0.88)	65.91	46.51(0.82)	57.21

Table 1. Throughput of TSMABE and OCMABE.

Number of users	Number of slots	OCMABE	Optimal Solution
10	100	75.05(0.94)	80.03
	200	76.13(0.95)	80.33
	300	78.79(0.96)	82.06
20	100	65.53(0.90)	72.66
	200	69.95(0.92)	76.30
	300	71.52(0.93)	76.54
300	100	62.45(0.89)	70.23
	200	66.20(0.89)	74.39
	300	69.02(0.91)	75.56
400	100	50.54(0.78)	64.50
	200	62.50(0.88)	71.21

Table 2. Comparison of the throughput of OCMABE and optimal value when $\alpha = 0.3$.

Number of users	Number of slots	Throughput			Number of unsatisfied users	Fraction of unsatisfied requirement of the most unsatisfied user (%)
		TSMABE	TRSSFC	OCMABE		
10	100	53.75	62.16	64.91	0	0
	200	56.97	64.93	67.39	0	0
	300	57.72	65.69	68.06	0	0
20	100	46.40	55.27	55.55	0	0
	200	52.03	59.72	61.09	0	0
	300	54.30	61.67	63.03	0	0
30	100	39.67	47.72	51.17	0	0
	200	48.72	55.98	56.13	0	0
	300	51.58	58.61	59.53	0	0
40	100	35.04	44.78	47.51	0	0
	200	46.06	53.65	5317	0	0
	300	49.71	56.57	56.60	0	0

Table 3. Performance of TSMABE, TRSSFC and OCMABE when $\alpha = 0.4$ and $\beta = 1.5$.

Number of users	Number of slots	Throughput			Number of unsatisfied users	Fraction of unsatisfied requirement of the most unsatisfied user (%)
		TSMABE	TRSSFC	OCMABE		
10	100	43.91	54.32	57.94	0.004	0.21
	200	46.47	56.44	60.14	0	0
	300	47.78	57.87	61.33	0.008	0.20
20	100	35.81	45.50	47.36	0.002	0.03
	200	41.28	50.80	53.11	0	0
	300	43.43	52.40	54.94	0	0
30	100	29.12	39.55	41.57	0	0
	200	38.39	47.30	49.06	0.002	0.03
	300	41.23	49.65	51.41	0	0
40	100	23.60	32.86	37.82	0.036	1.47
	200	35.25	44.04	44.31	0	0
	300	39.34	47.37	48.98	0	0

Table 4. Performance of TSMABE, TRSSFC and OCMABE when $\alpha = 0.5$ and $\beta = 1.5$.

Number of users	Number of slots	Number of unsatisfied users			Fraction of unsatisfied requirement of the most unsatisfied user (%)	
		TSMABE	TRSSFC	OCMABE	TRSSFC	OCMABE
10	100	2.72	7.14	2.74	45.23	68.78
	200	2.59	7.36	2.65	42.49	63.83
	300	2.52	7.35	2.67	41.61	60.19
20	100	5.29	14.96	5.38	56.34	94.59
	200	4.51	14.97	4.62	51.25	85.90
	300	4.39	15.00	4.66	49.09	83.16
30	100	8.00	22.34	8.32	64.05	99.13
	200	6.59	22.61	7.04	56.58	95.78
	300	6.13	22.48	6.80	53.81	93.23
40	100	11.01	29.63	11.30	71.73	100.00
	200	8.77	29.58	9.46	59.74	99.22
	300	7.87	29.81	8.77	56.77	97.45

Table 5. Fairness Performance of TSMABE, TRSSFC and OCMABE when $\alpha = 1.0$ and $\beta = 1.5$

Number of users	Number of slots	Throughput		
		TSMABE	TRSSFC	OCMABE
10	100	18.90	31.73	19.28
	200	18.64	31.83	19.01
	300	18.52	32.17	18.76
20	100	10.45	26.14	10.78
	200	10.08	26.34	10.29
	300	9.63	26.03	9.76
30	100	7.79	24.26	8.16
	200	6.81	23.79	7.06
	300	6.26	23.51	6.42
40	100	6.01	22.78	6.84
	200	5.68	23.46	6.01
	300	5.38	23.43	5.58

Table 6. Throughput of TSMABE, TRSSFC and OCMABE when $\alpha = 1.0$ and $\beta = 1.5$