Multi-user Fair Scheduling in the Downlink of CDMA Packet Systems

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***Abstract*— A fair scheduling algorithm is proposed to improve the system throughput while maintaining the fairness in the downlink of a code-division multiple access (CDMA) system employing AMC and multicodes. R. Kwan and C. Leung [1] suggested an optimal scheduling to maximize the total throughput based on simultaneous transmissions strategy. In this letter, we extend the optimal scheduling so that some degree of fairness can be maintained. We formulate a mixed-integer nonlinear programming problem to assign the radio resources such as the transmit power and codes to several users effectively. The result shows that the proposed algorithm provides a significant throughput gain over PF scheduling with one-by-one transmission at the same level of fairness.**

***Index Terms*— CDMA, downlink, scheduling, radio resource management, fairness.**

I. Introduction

IN THIRD generation (3G) code-division multiple access (CDMA) systems, packet scheduling algorithms are used to support the Internet services with high data rate transmissions. Previous studies for packet scheduling have focused on the tradeoff between throughput and fairness in the downlink of 3G CDMA packet systems [2]–[6]. Well-known proportional fair (PF) scheduling attempts to maximize throughput while maintaining some degree of fairness [3]. In order to maintain the fairness, the PF scheduler selects the next MS to be served based on the amount of data that has already transmitted to each MS as well as the reported data rate requests from MSs. In [4], a transmission rate scheduling that guarantees a minimum throughput for each user during a time duration was suggested. Reference [5] proposed a fast channel adaptive scheduler taking into account the instantaneous and average channel condition, where the user with the relatively best channel state is selected for transmission. It is shown that the same asymptotic fairness as in RR scheduling can be maintained, but all users will experience higher throughput.

However, the studies were performed on one-by-one transmission, which means that a particular base station transmits data to one user at a time. Therefore, at a time of data transmission, all radio resources are utilized for one user selected. For example, PF scheduler applied in cdma2000 EV-DO system allocates all transmission power in BS to one user at a time. The reason that the studies consider one-by-one transmission for scheduling is presented in [5]–[6]. This result is based on a simplified model which assumes that a linear relationship exists between the bit rate and the transmission power for a fixed modulation scheme and error rate. Such an assumption is not valid when adaptive modulation and coding (AMC) is employed. R. Kwan and C. Leung [1] proved that the optimal strategy for downlink scheduling involves simultaneous transmissions to several users rather than one user even through such transmissions may yield increased intra cell interference. The goal of the optimal scheduling proposed in [1] is only to maximize of the system throughput. In this letter, we extend the optimal scheduling so that some degree of fairness can be maintained. We perform simultaneous transmissions to several users to improve the system throughput while maintaining the degree of fairness. The proposed scheduling provides a resource allocation method. Furthermore, the number of MSs to be served simultaneously and the priority is determined. We formulate a mixed-integer nonlinear programming problem and use it to allocate the radio resources to several users. Performance of the proposed algorithm is compared to PF scheduling which allocates radio resources based on one-by-one transmission strategy.

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II. The Proposed Optimization Model

We focus on downlink high-speed traffic channels which employ AMC and multicodes. For MS *i*, ∀*i*=0, 1, 2,· · ·, *L*, the downlink signal-to-interference ratio (SIR) per multicode, γ_i, is given by

$$\gamma_i = \frac{g_{0i} P_i / n_i}{g_{0i} \alpha P_T + \sum_{k \in B} I_k g_{ki} + N_0 W} \tag{1}$$

where P_T is the total transmit power at Base Station (BS) and I_k is the interference power due to kth BS in the neighboring BS set $\boldsymbol{B}$. We consider the effect of "self-noise" as in [1]. α represents the orthogonality factor which is used to model multiple access interference due to delay spread in the radio channel. $N_0 W$ is the thermal noise power. g_{0i} is the path gain between a target BS 0 and MS *i* and g_{ki} is the path gain between a neighboring BS *k* and MS *i*. Let d_{ki} be the distance from the BS *k* to MS *i*. And then the path gain is expressed as

$$g_{ki} = d_{ki}^{-\mu} \cdot 10^{\xi/10} \cdot \omega \tag{2}$$

where μ is the pathloss exponent, ξ is the Gaussian distributed random variable (RV) with zero mean and the standard deviation of σ representing shadow fading, and ω is the RV for Rayleigh fading.

From (1), the required power for MS *i* which employs MCS *j* with n_i multicodes is given by

$$P_{i,j}(n_i) = n_i \cdot \lambda_{i,j} \cdot \left(\alpha P_T + \sum_{k \in B} I_k g_{ki} / g_{0i} + N_0 W / g_{0i} \right) \tag{3}$$

where $\lambda_{i,j}$ is the minimum SIR required to satisfy a given target block error rate (BLER) for MCS *j* at MS *i*. Assuming that MS i employs MCS j with n_i multicodes, the assigned bit rate to MS i is given by

$$R_i = n_i r_{ij} \tag{4}$$

where

$$r_{ij} = \frac{W}{g} R_c^{(j)} \log_2 M_j. \tag{5}$$

In (5), g is the spreading factor, W is the chip rate, $R_c^{(j)}$ is the code rate for MCS j and M_j is the number of points in the modulation constellation.

We introduce a parameter which originates from PF scheduling algorithm [3]. Let $\phi_i(t)$ be the ratio of the requested bit rate to MS i with n_i multicodes to the average rate received by the MS over a window of appropriate size, i.e., $\phi_i(t) = n_i r_{ij}(t)/\bar{r}_i(t)$, $\forall i$=0, 1,$\cdots$, L. $\phi_i(t)$ is used to determine service priority for each user in PF scheduling. All MSs update $\phi_i(t)$ at every scheduling period. If MS i is served with $n_i r_{ij}(t)$, the average rate is updated as

$$\bar{r}_i(t+1) = (1-\zeta)\cdot \bar{r}_i(t) + \zeta \cdot n_i r_{ij}(t) \tag{6}$$

or else,

$$\bar{r}_i(t+1) = (1-\zeta)\cdot \bar{r}_i(t) \tag{7}$$

where ζ is a parameter used for the update of the average rate and let us call it the fairness factor. The tradeoff between system throughput and fairness is affected by fairness factor $\zeta \in [0,1)$. If ζ=0, system throughput is maximized. On the other hand, as ζ approaches one, a long-term fairness is provided to each MS over the whole service area. t is incremented when scheduling is performed.

In conventional PF scheduling, assuming that a MS uses all radio resources at a time, each MS updates $r_{ij}(t)/\bar{r}_i(t)$ by computing the requested bit rate $r_{ij}(t)$ based on its channel condition. And then, PF scheduler selects a MS with the highest value of $r_{ij}(t)/\bar{r}_i(t)$ among MSs. However, the served MS may not utilize all available radio resources because the requested bit rate of the MS can be limited by its channel condition, and the bit rate and the used channelization codes have discrete values. If the surplus resources are allocated to other MSs, the throughput can be enhanced in spite of increased intra cell interference [1].

Here, we extend the mixed-integer nonlinear programming (MINLP) problem formulated in [1]. The objective of the MINLP problem in [1] is to maximize the sum of the bit rates assigned to all MSs. We formulate a MINLP problem to maximize the sum of the bit rates divided by the average rates for all MSs, i.e. the sum of $\phi_i(t)$, given some constraints such as a maximum allowable traffic channel power, P_{max}, a maximum number of multicodes, N_{max} and certain per-MS constraints. Consequently, taking into account the average rate as well as the channel condition for each MS, the scheduler assigns the radio resources to several MSs. By this algorithm, the employed MCS, numbers of multicodes, and transmit powers used for all MSs are jointly chosen at every scheduling period. If ζ=0 and the initial average data rates $\bar{r}_i(0)$ for all MSs are set to the same value, the scheduler optimally allocates the radio resources to MSs such that the sum of the bit rates assigned to all MSs is maximized. Therefore, the optimal scheduling for throughput optimization shown in [1] is a special case of the proposed algorithm. The proposed MINLP problem is given by

$$T = \max_{\mathbf{a},\mathbf{n}} \left\{ \sum_{i=1}^{L}\sum_{j=1}^{J} \frac{a_{ij} n_i r_{ij}(t)}{\bar{r}_i(t)} - \rho \right\} \tag{8}$$

subject to

$$a_{ij} \in \{0,1\} \quad \forall i,j \tag{9}$$

$$\sum_{j=1}^{j} a_{ij} = 1 \quad \forall i \tag{10}$$

$$n_i \le N_{i,max} \quad \forall i \tag{11}$$

$$\sum_{i=1}^{L} n_i \le N_{max} \tag{12}$$

$$\sum_{i=1}^{L} P_i \le P_{max} \tag{13}$$

$$\sum_{j=1}^{J} a_{ij} P_{i,j}(n_i) = P_i. \quad \forall i \tag{14}$$

In (8), $\mathbf{a} = [a_{ij}]$ is a L-by-J matrix and $\mathbf{n} = [n_1, n_2, \cdots, n_L]$. $N_{i,max}$ is the allowable maximum number of multicodes for MS i. We can numerically solve (8) by using a standard integer programming computer package as in [1]. The integer variable a_{ij} takes on value 1 if and only if MS i employs MCS j. It is assumed that the MS can not use multiple MCSs simultaneously and each code channel employed by a MS has the same transmit power. The term ρ is a factor to minimize the required power and the number of multicodes as follows:

$$\rho = \beta\Big(\sum_{i=1}^{L} P_i/P_{max} + \sum_{i=1}^{L} n_i/N_{max}\Big). \tag{15}$$

Several combinations of $\mathbf{a}$ and $\mathbf{n}$ can yield the same value of $\sum_{i=1}^{l}\sum_{j=1}^{J} a_{ij} n_i r_{ij}(t)/\bar{r}_i(t)$. ρ is introduced to select a combination that requires the minimum power and the number of multicodes. Since we hope that T is mainly determined by the value of $\sum_{i=1}^{l}\sum_{j=1}^{J} a_{ij} n_i r_{ij}(t)/\bar{r}_i(t)$ to enhance the system performance, ρ should have a minor effect on the value of T. Therefore, we use β as a small constant. To decide the value of β, we performed a simulation that shows the system throughput versus the value of β. The result notes that when $\beta < 1$, the system throughput converges on a maximum value. In our analysis, we set β as 10^{-3} which is small enough for our use.

III. Simulation Results

We perform a simulation to evaluate the performance of the proposed algorithm. The simulation model consists of 7 cells of 1-tier and we collect data from the center cell. The cellular system is modeled by locating BSs at the centers of a hexagonal grid pattern. An omni directional antenna pattern is used. Three active MSs a cell are considered. The MSs are located in the positions of the distance *R/4*, *R/2* and *R* away from the BS of center cell, respectively, where, *R* is the cell radius. The MS near to BS has the good channel condition, whereas MS at cell edge has the poor channel condition due

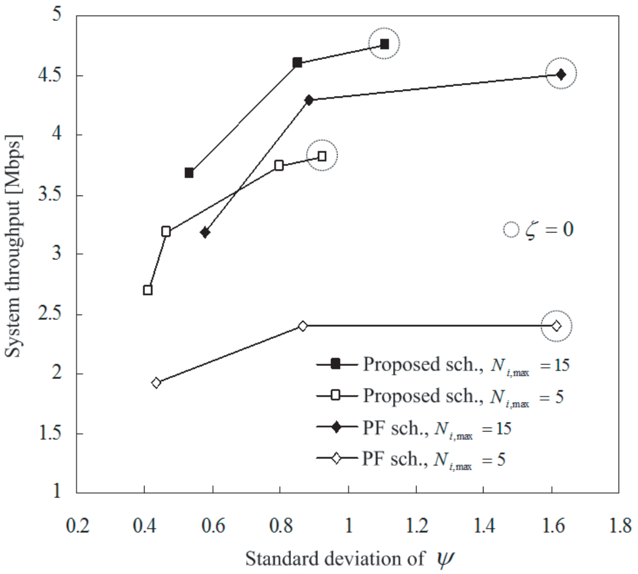

Fig. 1. System throughput versus fairness.

to other cell interference. The values of system parameters used for the analysis are as follows: $W = 3.84$ Mcps, $g = 16$, $N_{max} = 15$, $P_T = I_1 = 20$ W, $P_{max} = 18$ W, $\alpha = 0.4$. Among 16 codes, 15 codes are used for traffic channels. We consider 5 MCS levels with a combination of QPSK and 16 QAM modulation and code rate 1/4, 1/2 and 3/4. Thermal noise power is ignored. We consider the pathloss exponent of 4 and the shadow fading with $\sigma = 8$ dB. Rayleigh fading r.v. is generated by a Jakes filter depending on the velocity of 3 km/h. The performance of PF scheduling is also shown to be compared to the proposed algorithm. The PF scheduler lets BS transmit data to one MS at a time. And then, the allowable power and all multicodes are used to the MS. We perform the proposed algorithm during 10,000 scheduling periods. The initial average data rates $\bar{r}_i(0)$ for all MSs are set to the smallest MCS level.

We consider system throughput and fairness as system performance measures. The user throughput is defined as the average bit rate of each user. The system throughput is the sum of the user throughputs of all MSs. Let ψ_i be the ratio of user throughput for MS i to average user throughput. We define the fairness performance measure as the standard deviation (std) of ψ_i, $\forall i$=0, 1, 2,$\cdots$, L. It means that the less is the value of the fairness measure, the higher is the QoS fairness among users.

Fig. 1 shows the relationship between the system throughput and fairness for the proposed scheduling and PF scheduling according to the fairness factor ζ. For $\zeta = 0$, both schedulers maximize system throughput. The enhanced throughput can be obtained with the proposed scheduling. We also confirmed that this result is identical to that derived in [1]. As ζ approaches one, the std of ψ_i is decreased. It means that long-term fairness is improved, compared to the case with $\zeta = 0$. When a MS can utilizes all codes assigned for traffic channels, i.e., $N_{i,max} = 15$, the proposed scheduling provides the throughput gain of $7 \sim 10\%$ over PF scheduling with one-by-one transmission at the same level of fairness. In real system, the maximum number of multicodes used by a MS can be limited due to MS capability. As an example, we also showed the results for $N_{i,max} = 5$ in Fig. 1. The results show that the constraint yields a decrease in system throughput. Compared to PF scheduling, the proposed scheduling lets the system maintain relatively high throughput.

IV. Conclusion

A fair scheduling algorithm was proposed in the downlink of CDMA system employing AMC and multicodes. We performed the simultaneous transmissions to multiple users in order to improve the system throughput while maintaining the fairness. Moreover, an effective resource allocation method was presented by formulating a mixed-integer nonlinear programming problem. From our results, it is found that simultaneous transmission strategy in packet scheduling can improve the system performance compared to one-by-one transmission. The optimal scheduling in [1], which maximizes the total throughput is a special case of the proposed algorithm. It is shown that the proposed scheduling provides a throughput gain over PF scheduling with one-by-one transmission at the same level of fairness.

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