Multiuser Scheduling and Power Sharing for CDMA Packet Data Systems

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Abstract

Most existing scheduling algorithms for Code Division Multiple Access (CDMA) packet data systems select *one* user to service with *full transmit power* in each time slot. However, this is not optimal when the traffic is bursty and there are delay constraints. In this paper, we propose scheduling algorithms which split the transmit power and code resources among multiple users. First, we propose a new two-user scheduling rule that provides significantly better delay performance and supports larger stable arrival traffic compared to single user scheduling. Then, we propose a simplified version of this rule that achieves similar gains with significantly lower complexity. Simulation results are shown for the High Speed Downlink Packet Access (HSDPA) system.

1. Introduction

Most scheduling algorithms proposed for CDMA systems [1–4] choose a single user to service in each time slot. This strategy is not optimal for delay-constrained bursty traffic. When traffic is bursty, no single user may be able to fully use the available capacity. Furthermore, packet data systems based on code-division multi-access (CDMA) like High Speed Downlink Packet Access (HSDPA) allow for simultaneous transmission to multiple users using appropriate spreading code and power allocation. We show that, in such situations, splitting the available transmit power amongst multiple users in each time slot leads to a larger stable traffic load region and tighter QoS guarantees.

Gradient-based multiuser scheduling based on a weighted proportionally fair scheduler has been proposed in [5]. However, objective functions that depend on throughput and queue information perform significantly better than the proportionally fair scheduler, especially when the data is bursty [1,2]. In [6], multiuser scheduling is proposed to maximize the weighted sum of rates. By appropriate choice of the weights, various objective functions that incorporate queue information can be obtained. Although the token queue values are used in the simulation example, the design of appropriate weights for the rates is not the focus of [6]. Furthermore, the gain from multi-user scheduling over single-user scheduling is not studied in [5, 6].

The Modified Largest Weighted Delay First (MLWDF) rule [1] has been shown to be throughput-optimal for single-user dynamic time slot allocation, i. e., it is able to keep all the queues stable if at all this is feasible to do with any algorithm. In this paper, we propose a new two-user scheduling rule by defining a generalized utility function based on the MLWDF rule. This two-user MLWDF rule provides significantly better delay performance and supports larger stable arrival traffic compared to MLWDF-based single user scheduling. Furthermore, we propose a simplified version of this two-user MLWDF which has lower complexity without suffering a significant performance penalty. Simulation results based on the HSDPA system are used to demonstrate the performance gains. The proposed idea can also be applied to scheduling more than two users, although the benefits may diminish with increasing number of users.

The paper is organized as follows. Section 2 describes the system model. Section 3 presents the proposed multiuser scheduling algorithms. Section 4 presents the simulation results and the conclusions are presented in 5.

2. System model

Consider the downlink of a CDMA packet data system such as HSDPA in Wideband CDMA (WCDMA) as shown in Figure 1. The basestation schedules transmissions to the users based on feedback about the channel state information for each user and the rate requirements. The available transmit power and spreading codes can be shared among multiple users using various coding and modulation format combinations. The power and code allocation can be updated every time slot (usually of the order of a millisecond).

Assuming an infinite backlog of data to be sent to each user, the throughput can be maximized by transmitting to the user with the best channel condition in each time slot,

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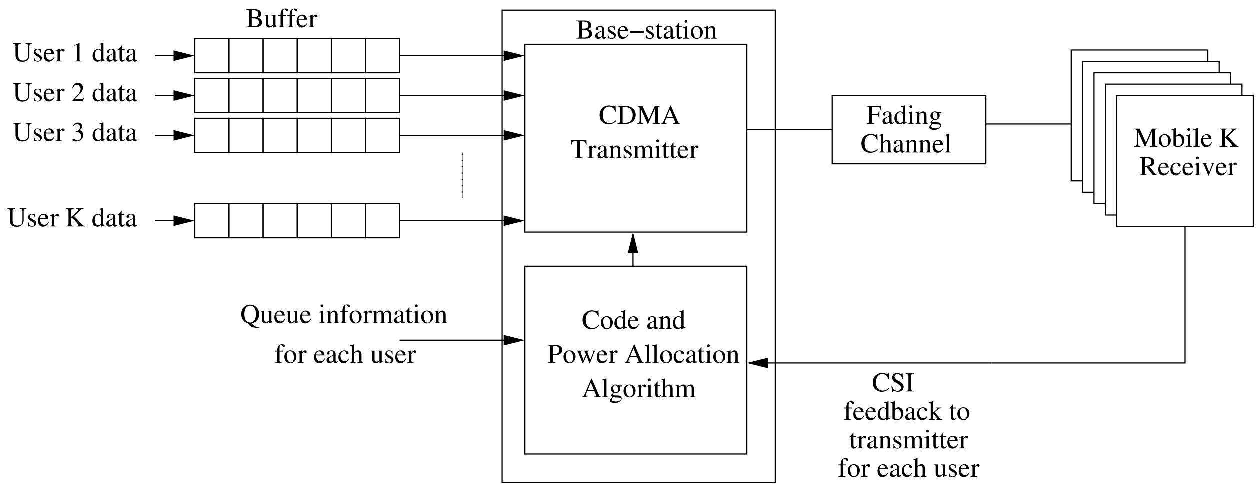

Figure 1: Downlink CDMA Packet Data System Model

i.e., single-user scheduling is sufficient to exploit multiuser diversity in this case. However, no fairness guarantee can be provided for any user in this case. When packet arrivals are considered (i.e., infinite backlog of data is not assumed), and delay guarantees have to be met, multiuser scheduling can provide significant improvement in performance.

A separate first-in-first-out queue is maintained for each user. The channel feedback information is assumed to be accurate in this paper to develop the scheduling algorithms. Practical imperfections like channel estimation error and feedback delay can be considered separately and will affect all the algorithms discussed in this paper.

3. Proposed Scheduling Algorithms

In each time slot, the MLWDF rule in [1] selects the user k with the maximum MLWDF parameter $\Gamma_k = \gamma_k D_k r_k$ as

$$k = \arg \max_{1 \leq i \leq K} \gamma_i D_i r_i,$$

where γ_i is the weight assigned to user i based on QoS requirements, D_i is the delay of the head-of-line (HoL) packet in user i's queue and r_i is the supportable rate on user i's channel in the current time slot assuming that the full power is allocated to user i. The γ_i for each user may be chosen as a function of that user's QoS delay condition of the form $Pr[D_i > W_i] \leq \delta_i$ as

$$\gamma_i = -\frac{\ln \delta_i}{W_i \overline{r_i}}. \quad (1)$$

3.1. Two-User MLWDF Scheduling

The two-user MLWDF rule extends the above MLWDF rule such that two users can be scheduled in each time slot (in CDMA systems like WCDMA-HSDPA). It chooses the users i_1 and i_2 and the fraction of power p allocated to user i_1 as follows:

$$(i_1, i_2, p) = \arg \max_{i_1, i_2, p} \Gamma_{i_1}(p) + \Gamma_{i_2}(1-p), \quad (2)$$

where $\Gamma_k(p) = \gamma_k D_k r_k(p)$, γ_k is the weight assigned to user k based on QoS requirements, D_k is the delay of the head-of-line (HoL) packet in user k's queue and $r_k(p)$ is the supportable rate on user k's channel in the current time slot when a fraction p of the power is allocated to user k.

The above two-user scheduling rule provides gains compared to single-user scheduling mainly because the supportable rate for each user $r_k(p)$ is a concave function of p. Therefore, the improvement in rate achieved for the same increase in p diminishes as p increases. Therefore, it is better to allocate the power to two users rather than a single user.

The optimal p is determined for all possible pairs of users i_1 and i_2 and the best among all the pairs is chosen. For the transmission scheme in HSDPA, the optimal p for a given pair of users i_1 and i_2, is determined by approximating $r_i(p)$ as

$$r_i(p) = \alpha \log_2(1 + \beta p e_i), \quad (3)$$

where e_i is the instantaneous SNR available on the i^{th} user's channel, $\alpha = 5\ MHz$ (WCDMA bandwidth), and $\beta = 0.25$. This approximation for $r_i(p)$ has been proposed in [7,8]. Therefore, the optimal value of p given i_1 and i_2 is

$$p = \frac{\gamma_{i_1} D_{i_1}}{\gamma_{i_1} D_{i_1} + \gamma_{i_2} D_{i_2}} + \frac{\gamma_{i_1} D_{i_1} e_{i_1} - \gamma_{i_2} D_{i_2} e_{i_2}}{\beta e_{i_1} e_{i_2} (\gamma_{i_1} D_{i_1} + \gamma_{i_2} D_{i_2})}. \quad (4)$$

If the above p is less than 0 or greater than 1, p is chosen to be 0 or 1 respectively. For a n user system, this p has to be computed for $n(n-1)/2$ pairs of users.

3.2. Simplified Two-User MLWDF Scheduling

The above two-user MLWDF rule can be simplified by selecting the two users with the two largest MLWDF parameters Γ_{i_1} and Γ_{i_2} calculated by assuming that all the power is allocated to the user for whom the parameter is being calculated, i. e.,

$$\Gamma_{i_1} = \gamma_{i_1} D_{i_1} r_{i_1}(1) \text{ and } \Gamma_{i_2} = \gamma_{i_2} D_{i_2} r_{i_2}(1).$$

In this case, for an n user system, i_1 and i_2 are identified by simply finding the two largest values out of n MLWDF parameters. Therefore, the optimal p needs to be calculated only for this pair of users. The fraction p of power allocated to user i_1 is chosen as in equation (4). In the two-user MLWDF scheduling proposed in the previous subsection, the optimal p is determined for all possible pairs of users i_1 and i_2 and the best among all the pairs needs to be chosen. Therefore, the simplified two-user scheduling rule is significantly less complex than the two-user MLWDF rule proposed in the previous subsection.

4. Simulation Results and Discussion

4.1. Simulation Set-up

The performance of the various algorithms are compared based upon a simulation with a single base station and 14 users. Each user has an average channel SNR in the range of 0-12 dB with independent 8 Hz Rayleigh fading using Jakes' model. The scheduling interval is 2ms, as in HSDPA. The packet sizes and the queue buffer length are 10 kbits and 100 packets respectively. The traffic model used is that of an independent Bernoulli packet generation process for each user, with probability of packet generation in each time slot λ. The rate-SNR table for HSDPA [7, 8] is used and a code constraint of 15 codes is also enforced. The table in [7] gives the possible rates for each user, and the code constraint excludes all the rate combinations for two users that exceed a total of 15 codes.

The rate supportable is shown in Figure 2 as a function of the SNR. The rate is a concave function of SNR. The function is approximately linear for SNR up to 15 (for all QPSK schemes). For higher SNR, it is more concave. In the linear region there is no gain in the overall rate by splitting the power amongst two users.

4.2. Maximum Admissible Load

Figure 3 shows the fraction of packets dropped as a function of average arrival traffic for the following scheduling algorithms: MLWDF, proposed two-user MLWDF and simplified two-user MLWDF, and MLWDF+EPA. The MLWDF+EPA (MLWDF + Excess Power Allocation) algorithm is a simple greedy two-user scheduling algorithm that allocates power to the user with the largest MLWDF parameter first and then allocates any excess available

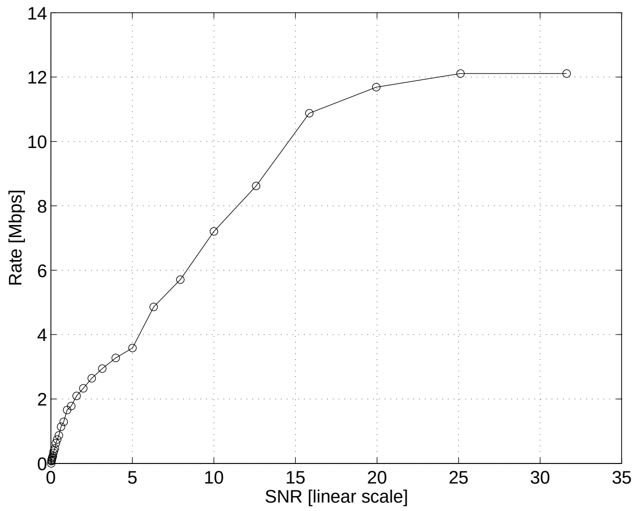

Figure 2: Rate vs. SNR for HSDPA

power (if the first user's queue can be emptied with less than the full power) to the user the with second largest MLWDF parameter. This plot is useful in identifying the maximum load that can be supported on the downlink using the various scheduling algorithms. It is evident that the proposed two-user scheduling algorithms keep the traffic queues stable for larger loads than the MLWDF rule or the simple greedy MLWDF+EPA rule. The simplified two-user MLWDF rule performs very close to the two-user MLWDF rule, while the performance of the MLWDF+EPA is almost identical to MLWDF. For larger average arrival traffic, there is no excess power to be allocated to the second user in the MLWDF+EPA algorithm. Therefore, only a single user is scheduled in almost all the slots. However, the proposed 2-user MLWDF and simplified 2-user MLWDF rules can appropriately share the available power and codes among two users and increase the maximum admissible arrival traffic.

4.3. Delay Performance

Figure 4 shows the probability of packet delay exceeding any specified value d as a function of d. The probabilities are shown for the best (solid lines) and worst users (dashed lines). It can be seen that the proposed algorithms which schedule multiple users in each time slot have significantly lower delays when compared to the MLWDF or the MLWDF+EPA rules.

4.4. Number of Users Scheduled

In this subsection, we present results showing the number of users scheduled by the various algorithms as a function of arrival traffic. There are two main reasons to schedule two users in each time slot instead of one. Firstly, one single user may not have enough traffic to use all the resources (codes and power). This will be observed for low

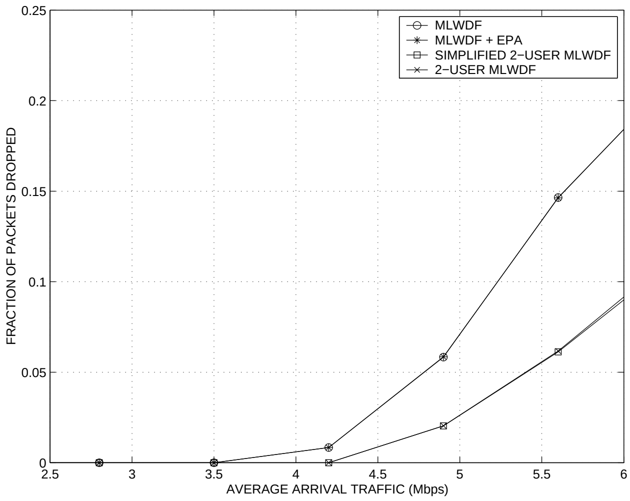

Figure 3: Outage performance

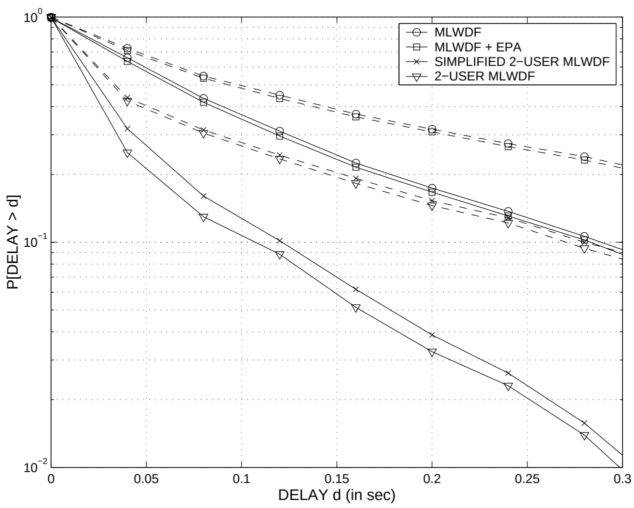

Figure 4: Delay distribution, λ=0.04

arrival traffic compared to the average supported rate of the channel. Secondly, the achievable rate for each user is a concave function of the power allocated. Therefore, in this case, it will be better (in terms of overall rate) if the power us split among two users. This will be observed when the arrival traffic is high.

In the table below, we show the number of slots in which two users are scheduled (out of 100000 slots) for the proposed two-user MLWDF rules and the simple MLWDF+EPA rule.

λ	MLWDF + EPA	2-user MLWDF	Simplified 2-user MLWDF
0.01	1806	3171	3084
0.02	3415	16746	16146
0.03	4277	42679	40503
0.04	2445	74143	70335
0.05	337	92270	87990
0.06	21	98848	94785
0.07	3	99647	96712
0.08	12	99660	97133
0.09	7	99663	97384
0.10	4	99414	97266

It can be seen that the MLWDF+EPA schedules two users only for low arrival traffic and there is no excess power available for the second user once the traffic increases. However, the proposed two-user rules share the power across the two users and support larger arrival traffic load by taking advantage of the concave nature of $r_k(p)$. The proposed rule can also be extended to schedule more than 2 users in a given slot. Further gains could be achieved by extending it to the multiuser case and optimally determining the number of users to be scheduled in each slot.

5. Conclusions

In this paper, scheduling algorithms which split the transmit power and code resources among multiple users are proposed. First, a new two-user scheduling rule that provides significantly better delay performance and supports larger stable arrival traffic compared to single user scheduling is proposed. Then, a simplified version of this rule that achieves similar gains with significantly lower complexity is described. Simulation results are shown for the High Speed Downlink Packet Access (HSDPA) system to illustrate the performance gains. The main reasons for the improvement from two-user scheduling are also illustrated for various arrival loads using simulation examples.

6. References

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