Uplink Scheduling in CDMA Systems

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Abstract

Uplink scheduling in wireless systems is gaining importance due to arising uplink intensive data services (ftp, image uploads etc.), which could be hampered by the currently in-built asymmetry in favor of the downlink. In this work, we propose and study algorithms for efficient uplink scheduling in a CDMA cell. The algorithms explicitly account for transmit power limitations of the mobiles, which is an important practical issue in most circumstances.

The major observation arising from our analysis is that it is advantageous on the uplink to schedule "strong" users one-at-a-time, and "weak" users in larger groups. This contrasts with the downlink where one-at-a-time transmission for all users has shown to be the preferred mode in much previous work. We obtain throughput optimal scheduling techniques for a single cell when mobile queue content information is available at the base, and propose less complex and more practical approximate methods, both of which offer significant performance improvement compared to one-at-a-time transmission, and the widely acclaimed *Proportional Fair* algorithm, in simulations.

Index Terms

Scheduling, Uplink, Reverse Link, CDMA.

I. Introduction

Data scheduling in wireless networks is a widely studied topic due to the impending explosion of high speed wireless data services in third generation (3G) systems. For natural reasons associated with the expected traffic characteristics, most of the previous research has focused on the forward-link/downlink, i.e. base to mobile communication. The traffic is expected to be dominated by web browsing and file downloads. As a result, current wireless data systems employ highly asymmetric link designs (e.g. HDR) with skinny uplinks and fat downlink pipes [1]. However, it has also often been pointed out that there could be a proportional increase in reverse-link/uplink traffic in the form of acknowledgments, feedback etc. along with the growth of other services like ftp, image/data uploads etc. which require high data rates on the uplink. These considerations have resulted in some research on the subject of uplink scheduling [2], [3], [4], [5], [6], [7], although small compared to the literature on downlink scheduling.

In this work, we consider the problem of optimal scheduling of uplink user transmissions in a single CDMA cell. We assume that the system operates in a TD/CDMA manner, with time-slotted scheduling of transmissions, assisted by periodic feedback of channel and/or congestion information through control channels. While our general goals are similar to those of the prior work on uplink scheduling, we formulate the problem in a different manner that enables efficient computation of throughput optimal schedules. Moreover, we observe that the optimal schedules are reasonably well approximated by some very simple scheduling rules that may be implemented with modest effort in 3G systems. The optimal schedules, as well as our proposed approximations, seem to possess an intuitively appealing property that is consistent with traditional observations about wireless transmission: *it is advantageous for users with weak channels to transmit simultaneously, and for users with strong channels to transmit one-at-a-time*. Hereafter, we refer to users with low recieved power at the base even when transmitting at peak transmit power as "weak" users, and the strongly recieved users at the base as "strong" users. The intuition behind this is that the added interference at the base from simultaneous transmissions of weakly recieved users to each other is small compared to the extraneous interference, and thereby does not affect the user SIRs and data rates significantly. On the contrary, for users recieved strongly at the base, the penalty in terms of SIR and data rate with simultaneous transmission can be quite significant.

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The rest of the presentation begins with the problem formulation, followed by a discussion of solution methods, then by approximate scheduling algorithms derived from the optimal solution and related benchmarks, and finally simulation results.

II. Feasible Rate Region for Single Cell Uplink

Consider the uplink of a single CDMA cell serving N users. Let P_i be the instantaneous received power and γ_i the SIR of the ith user. For simplicity, we express P_i in units of the total interference $I + \sigma$, where σ is thermal noise and I is the total instantaneous interference from other sources, such as other cells in the network. In order to meet the SIR requirement of all users, we must then have for each i

$$\frac{P_i}{\sum_{j\in\{1,\ldots,N\},j\neq i} P_j + 1} \geq \gamma_i \tag{1}$$

The feasible SIR vectors γ specified by (1) above has been derived in many previous papers [2], [5], [3], and we recall it below to point out the specific aspects utilized later in our scheduling algorithm. Given the peak received power of the ith user $\bar{P}_i$, computed using the path gain G_i and peak transmit power $\bar{P}_i^t$ as $\bar{P}_i = \bar{P}_i^t G_i$, we may change variables to $\theta_i = \frac{P_i}{\bar{P}_i}$ to rewrite (1) as

$$\frac{\theta_i \bar{P}_i}{\sum_{j\in\{1,\ldots,N\},j\neq i} \theta_j \bar{P}_j + 1} \geq \gamma_i \tag{2}$$

A given SIR vector γ_i is feasible if (2) can be satisfied with equality with $0 \leq \theta_i \leq 1$ for all i. We hence examine the solution to the set of linear equations

$$\frac{\theta_i \bar{P}_i}{\gamma_i} = \sum_{j\in\{1,\ldots,N\},j\neq i} \theta_j \bar{P}_j + 1 \tag{3}$$

which can be further rewritten as

$$\theta_i \bar{P}_i (1 + \frac{1}{\gamma_i}) = \sum_{j\in\{1,\ldots,N\}} \theta_j \bar{P}_j + 1 \tag{4}$$

It can be seen by inspection that the solution is of the form $\theta_i \bar{P}_i (1 + \frac{1}{\gamma_i}) = C$ where C is a global parameter. The value of C can be obtained by substituting the postulated solution in (4) to obtain $C = C \sum_j \frac{\gamma_j}{\gamma_j + 1} + 1$ which gives the final solution

$$\theta_i = \frac{\gamma_i}{\bar{P}_i(1+\gamma_i)} \frac{1}{\left[1 - \sum_{j\in\{1,\ldots,N\}} \frac{\gamma_j}{1+\gamma_j}\right]} \tag{5}$$

Defining $\alpha_i = \frac{\gamma_i}{1+\gamma_i}$ we see that

$$\theta_i = \frac{\alpha_i / \bar{P}_i}{1 - \sum_j \alpha_j} \tag{6}$$

Clearly, $0 \leq \alpha_i < 1$. Since we require $0 \leq \theta_i \leq 1$, equations (6) result in the following feasibility conditions to meet the required SIRs.

$$\sum_j \alpha_j + \frac{\alpha_i}{\bar{P}_i} \leq 1 \qquad \forall\, i \tag{7}$$

Note the simple linear form of the feasible SIRs (7) in terms of the α_i, about which we make the following observations:

- When there is no power limitation, i.e. $\bar{P}_i$ are arbitrarily large for each i, equations (7) collapse into the single condition $\sum_j \alpha_j \leq 1$, which is the simple, single-cell version of the well-known stability condition for uplink power control. In this case, as we later show, the feasible SIR region has a fully concave boundary which is dominated by its convex hull composed by time-sharing single user transmissions.
- When the power limitations are severe, i.e. $\bar{P}_i$ are small for each i, the constraints (7) approach independent box constraints $0 \leq \alpha_i \leq \bar{P}_i$ for each i, and simultaneous transmission is favored.
- For intermediate cases, where some $\bar{P}_i$ are large and others small, the optimal scheduling strategy involves time-sharing over different subsets of simultaneously transmitting users. An interesting observation regarding the optimal strategy, that we prove below, is that all transmitting users would always transmit at full power, i.e. at $\bar{P}_i$.

In the subsequent section, we analyze the last item above, which is the most likely practical scenario, to determine the optimal transmitting sets.

III. Uplink Scheduling

A large body of work exists on scheduling in wireless networks, see for example [8], [9] and references therein. Substantial work also exists on the subject of this paper, scheduling for CDMA uplink [4], [7], [6]. However, the previous work addresses somewhat different problems, and does not offer the solutions that we do below to maximize uplink scheduling gains while meeting rate/QoS requirements among competing users. The approach of maximizing rate sum or SIR sum, taken in [7], [6] is often a practically poor option, since it mostly benefits users in favorable locations while ignoring the performance seen by the disadvantaged users.

Our own approach involves scheduling uplink transmissions in a manner analogous to the downlink scheduling algorithms proposed in [8], [9]. A version of the algorithm that guarantees *queue stability*, i.e. boundedness of queue lengths when feasible, is specified as the rate choice that satisfies

$$\mathbf{R}^* = \arg\max_{\mathbf{R}\in\mathcal{R}} \mathbf{Q}\cdot\mathbf{R}$$

where $\mathbf{R}$, $\mathbf{Q}$ are rate and queue vectors of the user set respectively, and $\mathcal{R}$ is the *rate region*, or the set of feasible rate vectors. In general, $\mathbf{Q}$ may be replaced by other choices of *weights* [9] $\mathbf{w}$ to satisfy other QoS criteria such as delay violation probability, packet loss probability etc. Minimum instantaneous rate guarantees may be satisfied by restricting the rate region $\mathcal{R}$ appropriately. Thus, the general optimal scheduling problem can be solved if one has a technique to solve for $\mathbf{R}^*$ in

$$\mathbf{R}^* = \arg\max_{\mathbf{R}\in\mathcal{R}} \mathbf{w}\cdot\mathbf{R}. \tag{8}$$

for arbitrary given weights $\mathbf{w}$.

To formulate (8) for uplink CDMA scheduling, we require a relationship between rate and SIR as $R \triangleq f(\gamma)$ for each user. We assume this relationship to be *concave* in the argument γ, as is the case for the Shannon formula for the AWGN Gaussian channel where $R = \beta\log(1+\gamma)$. Since (7) are linear in $\alpha \triangleq \gamma/(1+\gamma)$, it is more convenient to consider the R,α relationship $R = g(\alpha)$ which is now *convex* for the Shannon formula as $g(\alpha) = \beta\log[1/(1-\alpha)]$. (8) then becomes the following optimization problem:

$$\max \sum_{i=1}^{N} w_i g_i(\alpha_i) \tag{9}$$

subject to

$$\sum_{j=1}^{N} \alpha_j + \frac{\alpha_i}{\bar{P}_i} \leq 1 \quad , \quad \alpha_i \geq 0 \qquad \forall i. \tag{10}$$

Typically $g_i(\cdot) = g(\cdot) \ \forall \ i$ are identical functions, as is the case for the Shannon formula, but our results remain unaffected even if they were all different, as long as they stay *convex*. Before discussing methods to solve (9), (10), we observe some useful properties of the optimal solution.

Theorem 1: The optimal schedule has the property that each transmitting user transmits at full power, i.e. $P_i = 0$ for some subset $\mathcal{S}$ of the users and $P_i = \bar{P}_i$ for the complementary set $\bar{\mathcal{S}}$.

Proof: Equations (10) specify $2N$ constraints on the feasible α_i. From standard theorems on convex maximization with linear constraints, it is easy to see that the optimum occurs at *corner point* of (10) due to the joint-convexity of (9) in the α_i. Corner points of (10) have exactly N of the $2N$ constraints binding, i.e., some subset of the α_i are null, while the complementary set saturate their respective constraints in the first equation of (10). Combining this observation with (6) results in $\theta_i = 1$ for the complementary set, thus proving the theorem. ■

Theorem 2: Without power constraints, i.e. $\bar{P}_i = \infty \quad \forall \ i$, the optimal schedule picks a single user at each scheduling interval.

Proof: In this case, the first equation of (10) reduces to the single constraint $\sum_j \alpha_j \leq 1$, reducing the number of constraints to $N + 1$ including the non-negativity constraints. From an argument similar to the proof of Theorem 1, we see that exactly $N - 1$ of the α_i are 0 and only one is set at unity on any corner point. One of these is the optimal solution, namely $i^* \stackrel{\triangle}{=} \arg\max_i w_i g_i(\alpha_i)$. ■

We now present the solution to (9), (10), which determines the subset $\mathcal{S}, \bar{\mathcal{S}}$ for each scheduling interval. Defining $\Lambda \stackrel{\triangle}{=} \sum_{j=1}^{N} \alpha_j$, we rewrite (9), (10) as

$$\max \sum_{i=1}^{N} w_i g_i(\alpha_i) \tag{11}$$

subject to

$$\begin{aligned} \sum_{j=1}^{N} \alpha_j &= \Lambda \\ 0 \leq \ \alpha_i &\leq \bar{P}_i(1 - \Lambda) \qquad \forall i. \end{aligned} \tag{12}$$

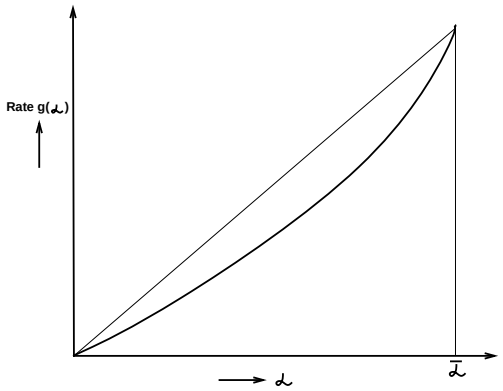


Fig. 1. Rate vs. α for $f \in [0.5, 1]$ for fixed Λ.

For any fixed value of Λ, (11) and (12) have a simple greedy solution for $g(\cdot)$ convex. The idea behind the procedure is illustrated in Figure 1, where the convex rate curve is replaced by a straight line joining the endpoints. This is valid on account of Theorem 1, which implies that the α_i always take one of the bounding values in the constraints of eqs. (12) if Λ is appropriately chosen. The algorithm to construct the solution is outlined below:

1) Let $\bar{\alpha}_i = min\{\Lambda, \bar{P}_i(1 - \Lambda)\}$. Order the users according to decreasing value of the quantity $v_i = \frac{w_i}{\bar{\alpha}_i} g_i(\bar{\alpha}_i)$.

2) Assign $\alpha_i = \bar{\alpha}_i$ for the user with the highest value of v_i.
3) Update as $\Lambda \rightarrow \Lambda - \bar{\alpha}_i$ and repeat with remaining users. The user ordering will not change if $\Lambda \geq \bar{P}_i(1-\Lambda)$ for all remaining users. Else the users must be reordered by recomputing the v_i with the new Λ.
4) Stop if $\Lambda = 0$ and set $\alpha_i = 0$ for all remaining users.

The optimal solution to (9), (10) is then obtained by searching over all $\Lambda \in [0,1]$ with sufficiently fine granularity.

Further, it is also clear from the original problem that $\Lambda^* = \sum_{i \in \mathcal{S}} \bar{P}_i(1-\Lambda^*)$ for the optimal value Λ^*, where $\mathcal{S}$ is the optimal transmitting set. Thus, the role of Λ is mainly in ordering the users in the best manner out of the $N!$ possibilities, and once an ordering is chosen, it is simple to check the N different values $\Lambda_k = \frac{\sum_{i<=k} \bar{P}_i}{1+\sum_{i<=k} \bar{P}_i} \qquad i \in \{1,...,N\}$ for optimality. Further, an ordering change only takes place when $\Lambda = \Lambda_{ij}$ specified by the solution to $v_i = v_j$ for some $i \neq j$. This condition hence specifies atmost $N(N-1)/2$ ordering changes out of the $N!$ possibilities, some of which may not lie in $[0,1]$ and can hence be discarded. From these considerations, the following computationally simpler algorithm can be devised.

1) Compute, and sort in increasing order, the Λ_{ij} satisfying

$$v_i = v_j \quad \text{for some} \quad i,j \in \{1,...,N\}, \qquad \Lambda_{ij} \in (0,1).$$

Denote this list as $\{\Lambda_k : \ m \in \{1,..,M\}\} \stackrel{\triangle}{=} \{0, \Lambda_1, ..., 1\}$.
2) For each interval $[\Lambda_m, \Lambda_{m+1}]$, determine the user ordering in some interior point, say the midpoint, according to decreasing values of v_i.
3) Evaluate the objective (9) for the current ordering by successively including users from the top of the order.
4) Pick the best objective over all the intervals and user sets examined.

The complexity of the above algorithm for N users is $\mathcal{O}(N^3 \log N)$, and is guaranteed to give the optimal solution.

Rate Limits: All of the above can be repeated when there are specified upper and lower bounds on individual user rates, i.e. $R_i^{min} \leq R_i \leq R_i^{max}$. This condition can be transformed to $\alpha_i^{min} \leq \alpha_i \leq \alpha_i^{max}$ using the functions $g_i(\cdot)$. The lower rate limits may arise due to real-time services, and the upper limits may arise from transmitter capabilities or current queue content. These limits further favor simultaneous transmission, and must be included in the formulation for QoS, and power efficiency reasons. Our approach can accommodate rate limits in the optimization by modifying (12) as $\alpha_i^{min} \leq \alpha_i \leq \min\{\bar{P}_i(1-\Lambda)\ ,\ \alpha_i^{max}\}$, but we don't describe the somewhat more elaborate solution procedure here. Simple inspection reveals the changes necessary in the previous algorithms, which entail only a small computational overhead.

IV. Low-Complexity Approximation of Optimal Uplink Scheduling

In this part, we attempt to provide a greedy, low-complexity, approximate solution to the convex maximization discussed before.

A. QRP Algorithm

Recall that the sorting measure used in the optimal solution for fixed Λ was of the form

$$v_i = Q_i g_i(\alpha_i)/\bar{P}_i$$

which suggests a greedy algorithm that ranks users by the same measure without Λ. We hence propose the following simple scheduling scheme that may be more suitable for practical implementation:

QRP algorithm:

1) Sort users in decreasing order of the measure

$$v_i = \frac{Q_i R_i^0}{\bar{P}_i}$$

assuming no interference from other users while computing R_i^0.

2) Add user i, in order starting from the top of the list, while maintaining and updating the value of $\mathcal{O} \triangleq \sum_{j<i} Q_i R_i$, where R_i now takes into account interference from all added users.
3) Stop if adding the next user reduces $\mathcal{O}$, and allow transmission of all added users at their peak powers and rates as computed.

As we will see in our simulations section, this simple algorithm captures most of the benefi ts of optimal uplink scheduling, and has the properties alluded to in the introduction. In other words, the chosen user sets from the above algorithm tend to be one of the following types:

- A single "strong" user with high $\bar{P}_i$.
- A group of "weak" users with low $\bar{P}_i$, and often high Q_i.

This observation is consistent with the common intuition relating to the nature of interference in CDMA systems.

B. Other Sub-optimal Algorithms and Benchmarks

One benchmark algorithm is the optimal algorithm given in previous sections. It gives the best possible performance. Another benchmark algorithm is the MaxQR algorithm. It serves the user (one-at-a-time) with the maximum queue length and data rate product, $argmax_i Q_i R_i$. This algorithm serves as a lower bound. We will compare with this algorithm to evaluate the gains of different sub-optimal algorithms. Round Robin and fully simultaneous transmission are considered too far from optimal and perform very poorly in most of the cases, and are thus ignored here.

We will provide some other sub-optimal algorithms, which perform less well than the above proposed QRP algorithm. However, they offer simplicity in implementation by using less processing and signaling power. One example of such algorithm is the *Average-SIR algorithm*.

Calculate average SIR, γ_{avg}, among all the users (with non-empty queue). There are two ways to compute users SIR at this stage.

A1. Assume users (with non-empty queue) transmit one-at-a-time.

A2. Assume users (with non-empty queue) transmit simultaneously.

We choose the 2nd approach since it gives clearer difference between "strong" users and "weak" users. Another reason is that it takes co-existence (namely, the orthogonalization factor) into consideration. Then apply MaxQR algorithm to the group of users below average SIR and each user above average SIR. The detailed steps are listed below:

Average-SIR algorithm:

Step 1. Denote the group of users below average SIR as a set B. Re-compute the rates of users belonging to B (only users in B will transmit simultaneously). Denote the group of users above average SIR as a set C. Re-compute the rates of users belonging to C (users in C will transmit one-at-a-time).

Step 2. For users in B, let $q_r[0] = \sum_{i \in B} Q_i R_i$; For the ith user (i start at 1) in C, let $q_r[i] = Q_i R_i$.

Step 3. Choose user/users to serve by $argmax_i q_r[i]$, $i = 0, 1, 2, ...$ If $i = 0$, serve all users in B. Otherwise, serve one user in C with maximum queue length and data rate product.

Note that we could also replace the SIR in the above algorithm by other quantities, for example, data rate or received power. The performance will be similar.

V. Simulation Results

In order to quantify the performance gain by applying optimal/sub-optimal scheduling algorithms, a discrete-event simulator has been used to evaluate them in a single cell CDMA system with 40 users. All

users have the same load and traffic pattern on the uplink. The uplink is implemented as a slot based (Time Division) data transmission mechanism, for example, in 3G1xEV-DO (HDR).

Since every mobile user experiences the same uplink load, we will use the time-averaged queue length as the criterion to compare different uplink scheduling algorithms. Individual as well as total average queue lengths are considered for comparison.

In the simulation we further make the following assumptions:

1) The scheduling decision is made by the base station for every time slot We use 1.6667 msec time slot as defined in 3G1xEV-DO (HDR).
2) The location of the mobiles are assumed to be uniformly distributed in the cell area.
3) It is assumed that the link gains have the following form

$$G_i(k) = d_i^{-4}(k) A_i(k) B_i(k) \tag{13}$$

where $d_i(k)$ is the distance from the ith mobile to the base station at time instant k, A_i is a log-normal distributed stochastic process (shadowing). B_i is a fast fading factor (Rayleigh distributed).

4) It is assumed that the cell diameter is 2 km. $d_i(k)$ is a 2-D uniformly distributed random variable.
5) It is assumed that the standard deviation of A_i is 8 dB, [10].
6) It is assumed that the Doppler frequency is 8 Hz, corresponding to pedestrian mobile users, [10].
7) It is assumed that all users share 1.25 MHz bandwidth.
8) It is assumed that the uplink traffic of each mobile user is Poisson with the same inter-arrival time 0.05 sec.
9) It is assumed that packet length is exponentially distributed with mean 1024 bits.
10) Simulation time = 10 minutes.
11) Discrete rate sets, as in 3G1xEV-DV: $9.6Kbps, 19.2Kbps, ...2.4Mbps$ roughly in powers of 2.

The results are summarized in the following table.

Scheduling Algorithms	Total Averaged Queue Length
Max QR	70688
Average-SIR	42895
QRP	34219
optimal	27663

TABLE I

COMPARISON OF UPLINK SCHEDULING ALGORITHMS IN TERMS OF THE TOTAL AVERAGED QUEUE LENGTH.

From Table 1, we observe that using QRP scheduling will increase efficiency by more than 50% comparing with using Max QR scheduling. Furthermore, QRP scheduling only gives up 15% efficiency comparing with the optimal scheduling algorithm, which has much more computational complexity, thus requires much more processing power and makes the implementation of optimal scheduling algorithm difficult. On the other hand, the QRP scheduling algorithm requires much less processing at the base station.

Another observation is that the Average-SIR scheduling algorithm also performs well (more than 40% efficient comparing with using Max QR scheduling). A feature of the Average-SIR scheduling algorithm is that it requires even less processing than the QRP scheduling algorithm, which is very attractive for implementation. We will discuss implementation details in the next section.

The total average queue length of all 40 users is shown in Figure 2. Note that QRP scheduling has more than 50% gain over Max QR algorithm. Furthermore, the queue length of a typical "weak" mobile user (see Figure 3(b)), and the queue length of a typical "strong" mobile user (see Figure 3(a)), clearly indicate that QRP algorithm improves fairness among mobile users as well as increases throughput. It shows that QRP algorithm, which allowing either multiple "weak" mobile users transmitting simultaneously or a single

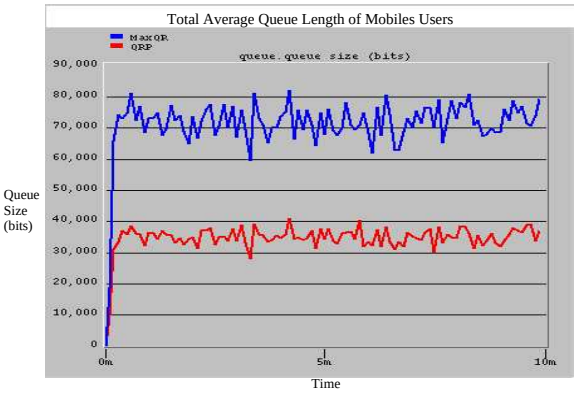


Fig. 2. Total average queue length: Max QR vs. QRP scheduling

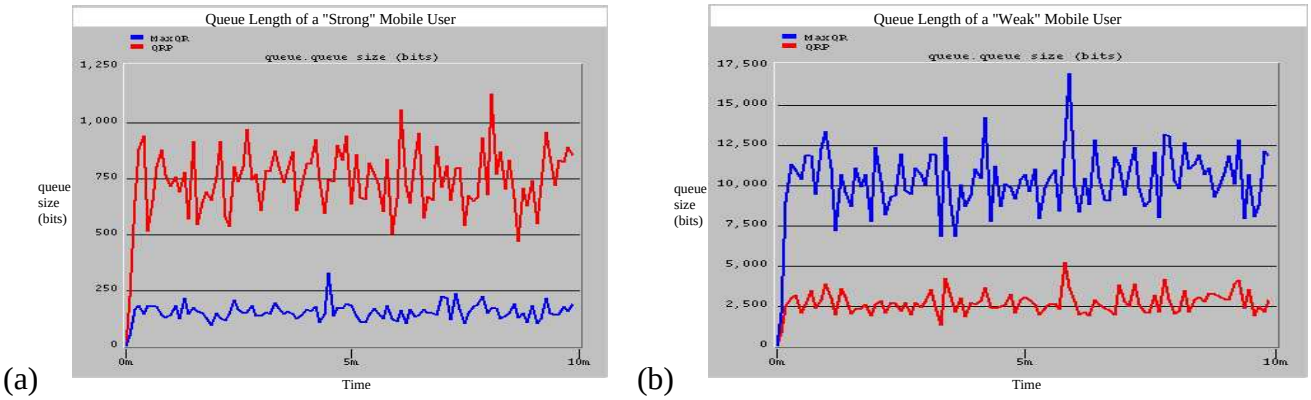


Fig. 3. Queue length of (a) a typical "strong" mobile user and (b) a typical "weak" mobile user: Max QR vs. QRP scheduling

"strong" mobile user transmitting, achieve most performance gain by reducing the queue lengths of the "weak" mobile users.

An interesting plot (Figure 4(a)) shows how the performance gain of QRP over MaxQR changes with the percentage of "weak" mobile users. When the cell is lightly loaded, all the scheduling algorithms have similar performance. However, when the cell becomes more and more heavily loaded, the QRP algorithm will provide more and more performance gain, which is most needed in these cases.

Figure 4(b) depicts the distribution of number of simultaneously transmitting users for a single run with 20 users employing the QRP algorithm. It shows that there are a signifi cant number of slots with single user transmission, coresponding to the selection of a "strong" user by the algorithm. However, the majority of the slots have multiple (probably "weak") users transmitting, which is the main source of throughput gain from the algorithm over maxQR. The plot also implicitly reflects the fact that distributing users uniformly in the cell area results in a large fraction of distant, i.e. "weak", users. Rarely do more than 8 of the 20 users transmit simultaneously in this scenario, even though about twice that number classifi ed as "weak" users.

In order to evaluate the performance of different scheduling algorithms, we ran simulations for 20 mobile users in a single cell, under different offered load from 20 kbps to 50 kbps uniformly for each mobile user, for each of the 4 different scheduling algorithms, namely, MaxQR, Proportional Fair (PF), QRP and the optimal algorithm (OPT). The results are shown in Figure 5 in terms of (a) total average queue length, (b) queue length of a typical "strong" user and (c) queue length of a typical "weak" user. Note that, while OPT is uniformly better by all metrics, QRP is quite competitive, and even offers better performance than OPT for the "weak" users under heavy load at the cost of some increase in "strong" user and average queue lengths. PF is good for average queue length at lighter loads, but offers poor service to the "weak" users compared to OPT and QRP. Also, as expected, PF performs signifi cantly worse than the other algorithms at heavy loads, since PF does not take queue length into account and can therefore be unstable.

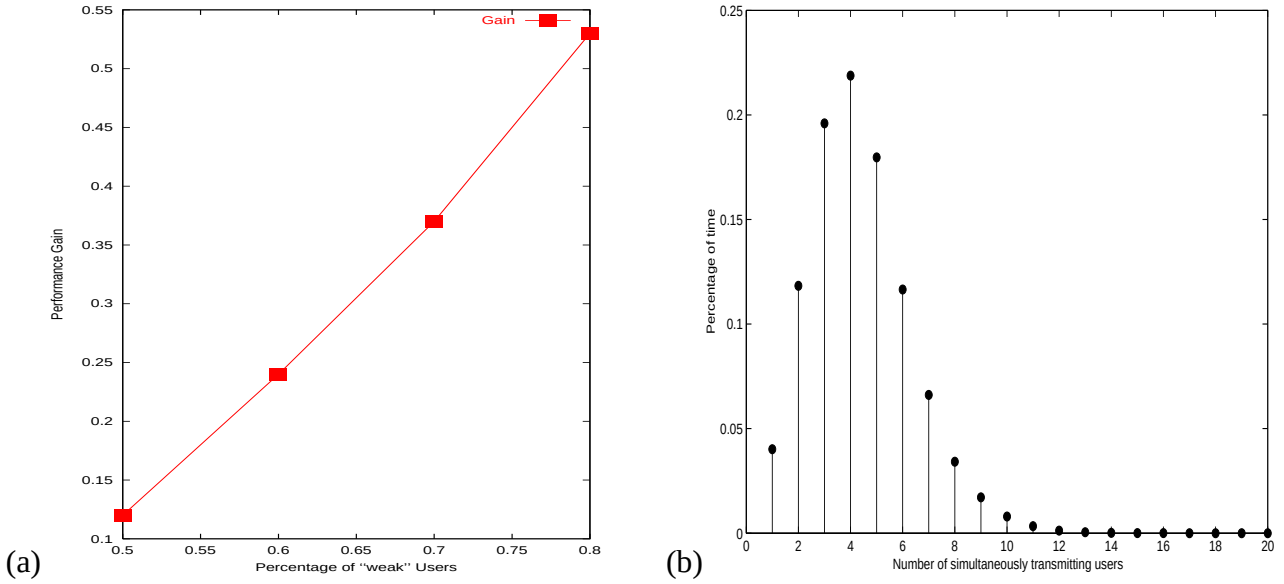


Fig. 4. (a) Performance gain of QRP over MaxQR vs. percentage of "weak" mobile users (b) Distribution of simultaneously transmitting users.

VI. Further Discussions

In this section, we will discuss the implementation details of the proposed algorithms. For example, In the 3G1xEV-DV systems, in order to implement the sub-optimal algorithms, including the QRP algorithm, the Max QR algorithm and the Average-SIR algorithm, the following enhancements to the system are needed:

(1). Each active mobile station reports its queue length at every time slot through uplink signaling.

(2). Base station decides which mobile station(s) will transmit in the next time slot based on the reported queue length and measured SIR, using either QRP, Average-SIR or Max QR algorithms.

(3). Base station notifies the chosen mobile station(s) through downlink signaling. Since every mobile station transmits with maximum power, we may replace the power control bit(s) by scheduling bit(s), to indicate whether the mobile station should transmit or not. This requires only a minor change within the standard.

Note that required change (1) may be undesirable in certain systems. If this is the case, we may use the following simplified options:

- Option I: In QRP algorithm, set $Q_i = 1$ for users with non-empty queues, and $Q_i = 0$ for others.
- Option II: If even empty status of queue cant be obtained, set $Q_i = 1$ for all users. This amounts to maximizing rate sum, and will incur frame-fill inefficiencies.
- Option III: Instead of using $maxQ_iR_i$ product as criterion, we simply categorize mobile users as two groups: one group with low SIR and the other group with high SIR. Then use Round Robin among them.

Another concern is that the measured (received) SIR at the base station receiver represents the uplink quality in the past time slot(s). In the scheduling algorithm, a predicted uplink quality is needed. There are two ways to accommodate this: If the mobile user is experiencing mainly slow (shadow) fading, it is reasonable to assume that uplink quality will not change abruptly most of the time, because the time-scale of slow fading is much larger than the time-scale of scheduling (time slot). Then we could use a filter with forgetting factor to update SIR measurements. If the fast fading effect is significant, then a channel predictor may be used to predict uplink quality. One choice of such predictors could be discrete-time Kalman filter or H_∞ filter [5]. The first case would be typical in reality since usually data service users have low mobility.

VII. Conclusion

We have proposed optimal uplink scheduling algorithms for a single CDMA cell, and related efficient approximate algorithms for practical implementation. Simulations demonstrate substantial performance im-

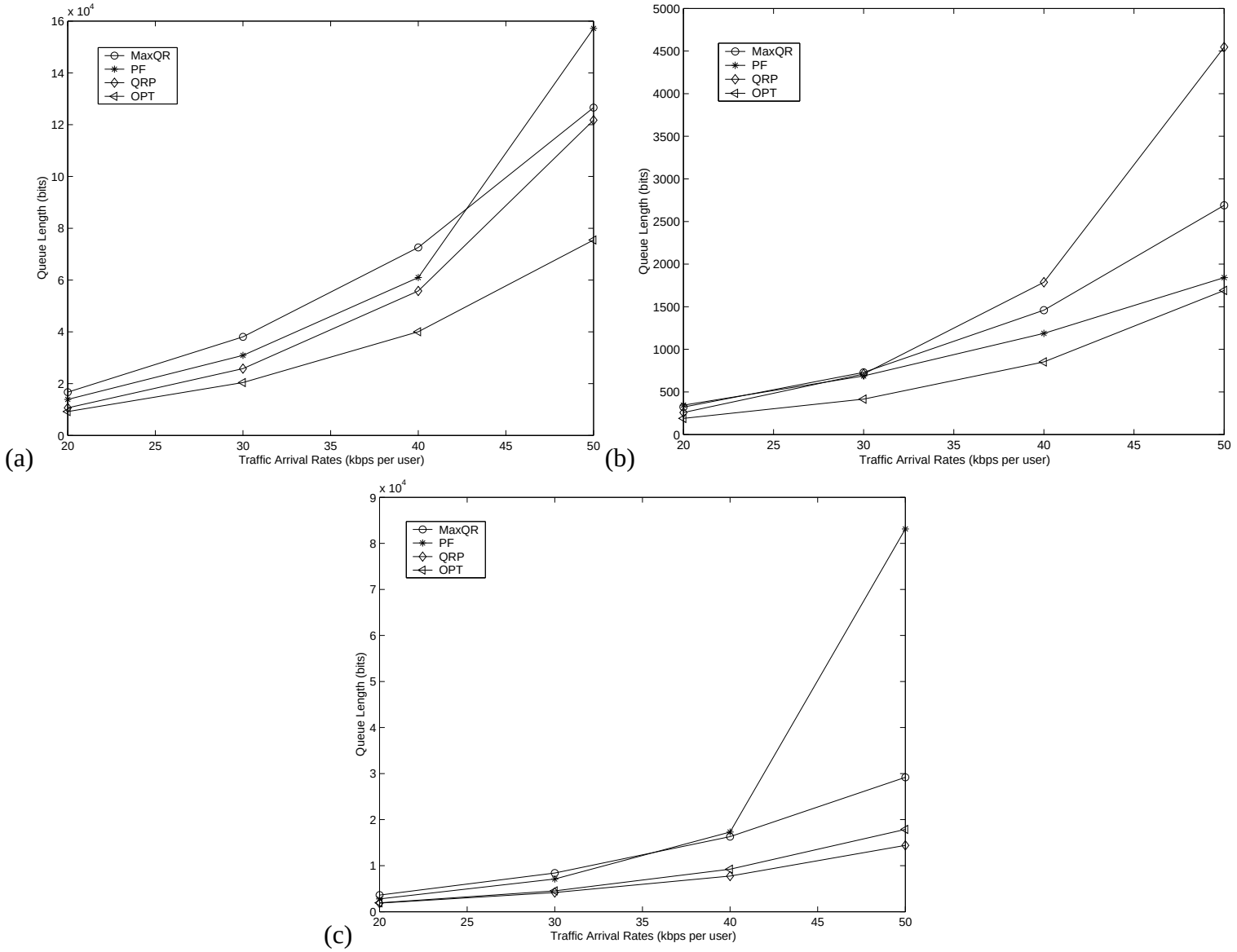


Fig. 5. (a) Total average queue length (b) Queue length of a typical "strong" user (c) Queue length of a typical "weak" user, applying MaxQR, PF, QRP and OPT vs. offered traffic.

provement with these algorithms, and we also discuss the implementation requirements they entail. Further research is required to address multi-cell systems, and also to incorporate the effects of soft-handoff, which may have a significant influence in uplink scheduling.

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