Flow Control in the Presence of Interference Cancellation in Wireless CDMA Networks

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***Abstract*—We consider the control of uplink packet flow subject to in-cell and out-of-cell interference limitations, in the presence of imperfect Interference Cancellation (IC). The aim is to combine a location-based packet flow control algorithm with multi-user detection for IC. The algorithm assigns packets to be transmitted to separate queues, one for each spatial zone within which packets generate roughly the same in-cell interference and impose equal interference on a neighboring base station. The objective is to maximize data throughput while ensuring fairness among users and limiting queuing and transmission delays. Throughput and fairness are two conflicting objectives that need to be optimized. We show that IC combined with location based scheduling achieves a better tradeoff between throughput and fairness even under stringent resource limitations. Compared to throughput maximization, simulations suggest that maximum fairness can be achieved with a loss in throughput of only 13%, whereas the loss is 65% when IC is not combined with scheduling.**

I. Introduction

Code Division Multiple Access (CDMA) systems are interference limited. Managing the interference generated by packet transmissions is expected to improve transmission performance both in terms of throughput and fairness. The goal of this study is to provide an uplink flow control algorithm for packet data transmission where the control accounts for IC to achieve a better throughput-fairness tradeoff curve. The transmit layer algorithm exploits useful information that is made available by the physical layer and adapts easily to the resource availability.

The uplink flow control problem is tightly related to power control and can be formulated as the selection of packets to be transmitted from mobiles that have previously made a transmission request to the corresponding base station. The selection is made such that time variation in available resources is exploited while ensuring fairness among the active mobiles irrespective of their location within the cell. Fairness is a concern since mobiles that are near the edge of a cell need more transmission power per packet than those that are closer to the base station. These mobiles are, therefore, those that generate more interference to a neighboring base station, which may result in excessive outage if that cell is heavily loaded.

In a previous study, we proposed a flow control algorithm that adapts to the existing resource availability and results in significantly higher network utilization [1], [2]. We explored the advantages of dividing the cells into regions defined by equal resource requirements and showed that the algorithm responds to short-time resource variations to achieve high throughput with a low likelihood of overload. In this paper, we adapt our previously proposed formulation to the uplink, considering time-variant resources and including a fairness metric. We also propose a location-based control for packet flow at the base stations of power-controlled CDMA networks in the presence of imperfect IC. The new allocation algorithm is designed to take advantage of interference reduction capabilities to provide any desired tradeoff between throughput and fairness. The transmit strategy proposed is shown capable of achieving a better tradeoff between throughput and fairness compared to the case with no IC.

Despite the notable increase in capacity offered by various multi-user detection techniques, industrials have been reluctant as to its practical implementation. One sub-optimal but of reduced complexity technique is Interference Subspace Rejection (ISR) [3]. ISR is an IC technique that is able to operate at complexity levels as low as those offered by Successive or Parallel IC (SIC, PIC) detectors, while providing higher interference suppression efficiency. ISR can be performed either Successively (ISR-S), or in Parallel (ISR-P). Herein, we consider ISR-S. Incorporation of hybrid modes is left for future work. ISR-S successively nulls the interference originating from previously decoded users in the composite signal received at the base station. Subsequently decoded users will thereby experience reduced interference.

The remainder of this paper is organized as follows. In section II, we state the system model and describe the problem. Section III characterizes the resource consumptions and interference limitations used by the scheduling algo-

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rithm that is described in section IV. Finally, we give some application results in section V. Concluding remarks are drawn in the last section.

II. System Model and Problem Description

A. System Model

We consider a hexagonal cell geometry with a single layer of surrounding cells as illustrated in Figure 1. A cell is divided into three sectors with transmissions from a pair of regions each consisting of n_z zones. Each region of the pair generates interference to the base station opposing it. Consider BS_0 as the target base station; two neighboring base stations are identified, BS_1 and BS_2, each affected by transmissions from a one of the two regions of BS_0. A simple example of such a configuration is shown in Figure 2 with $n_z = 2$.

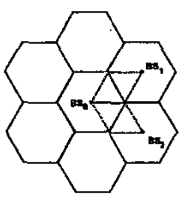

Fig. 1. The hexagonal cell geometry with first layer of surrounding cells.

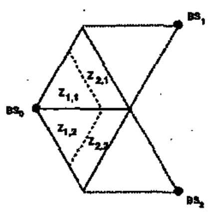

Fig. 2. Partitioning a sector into zones.

For packet transmission in a CDMA system, delay insensitive users try to use the available resources in the best effort fashion. Power control is assumed to be active and call admission prevents the introduction of more calls (stream and packet) than can be supported on the average.

We consider a discrete set of allowable rates that are multiples of a basic rate R_b. Transmissions are done in time slots; a packet being defined as the quantity of information that can be transmitted in a time slot at the basic rate R_b. In addition, data users are assumed to require the same quality of service and are allowed to transmit up to M packets per time slot. The different rates are accommodated by varying the spreading gain so that all the transmitted signals occupy the same total bandwidth.

B. Problem Statement

The objective of flow control is to determine the best transmission assignment per time slot to mobiles requesting packet transmissions, given the time-varying resource availability, mobility and time-varying transmission demands. For this purpose, mobiles are assigned to zones based on their current power requirements and are periodically reassigned to sectors and zones as a result of mobility. The flow control algorithm determines a transmit vector $\mathbf{n}^*(l)$ for each time slot l, such that the current in-cell and out-of-cell interference limitations are not exceeded.

If the only requirement is to maximize throughput, then all packets queued by mobiles in the inner zones should be transmitted first and the needs of mobiles in the outer zones should be considered only if additional resources are available. Such an assignment is unfair, leading to unacceptable delays for many users. We improve fairness by minimizing the variance in the delay of the resulting highest-delay packets in each queue. This is also expected to equalize the per-user average throughput in each zone since the corresponding users are considered to have the same average arrival rate, and transmit at the same rate determined by the algorithm.

However, when resource limitations are stringent, transmissions from mobiles in the outer zones cannot be allowed since they generate most of the interference to the neighboring base stations and hence delay for these users builds up. As a result, not only does unfairness increase, but also persists when the available resources vary slowly, and improves only when the interference is properly managed. We rely on successive IC to reduce the cost in interference associated to mobiles in outer zones. In the decoding process, these mobiles will be considered after those in the inner zones, thus reducing their transmission powers and thereby the interference they generate. This is expected to achieve more fairness while still striving to maximize throughput.

III. Resource Characterization

A. Resource Constraints

For a given sector, three resource constraints are identified: one in-cell, and two out-of-cell. The in-cell resource utilization corresponds to the total power received at the base station and is represented as a linear function of the number of packets transmitted from the inner and outer zones. The out-of-cell resource utilizations correspond to the out-of-cell interference generated in the facing neighboring base stations by the packets transmitted to the target base station. We assume that resource availabilities can be predicted adequately based on the resource utilization measurements for the current time slot and communicated between base stations at each time slot.

For target BS_0, let IC^l be the in-cell power limit during time slot l, and $OC^l_{j,\{j=1,2\}}$ the out-of-cell interference margins respectively allowed by $BS_{j,\{j=1,2\}}$ from transmissions originating from mobiles in zones $(i,j)_{\{i=1,\ldots,n_z\}}$. We normalize these in-cell and out-of-cell interference margins by the interference generated at the target BS_0 by an arriving packet with the minimum SIR required [5]. This power corresponds to the equal-power solution $S_k = S$ for $k = 1 \ldots N$, where N is the number of mobiles considered in the target BS_0. Thus, the limits for the considered sector respectively translate into corresponding tolerable numbers of packets per time slot, say NI^l and $NOC^l = [NOC^l_1, NOC^l_2]$. These limits actually stand for the maximum number of packets that can be transmitted from mobiles in the target sector after support of the ongoing stream services and without giving rise to excessive outage in the neighboring facing sectors.

B. Power Control with Interference Cancellation

In power controlled CDMA systems, users are decoded with the same Signal to Interference Ratio (SIR). We assume perfect power control so that signals originating from mobiles with a rate of m times the basic rate R_b are received at the base with m times the power level that is needed to transmit at R_b.

For one 120° sector with $2\,n_z$ zones, the SIRs of the N users can be written as follows:

$$\Gamma_k = \frac{S_k}{\sum_{i=k+1}^{N} S_i + \sum_{i=1}^{k-1} \theta S_i + N_0} \quad k = 1, \ldots, N \quad (1)$$

where, $\{S_k\}_{\{k=1,\ldots,N\}}$ are the receive powers per packet relative to the N users and arriving at the base station with just the minimum SIR required, N_0 is the background noise (includes the other-cell interference) and $0 \leq \theta \leq 1$ stands for the estimation error in cancelling the interference relative to the signal of a given user from the composite signal received at the target BS_0. θ is assumed known, equal for all i, and independent of k. This can be seen as the worst case scenario when choosing θ equal to the maximum of all the estimation errors. The interference rejection efficiency is then defined by $\eta = 1 - \theta$, where $\eta = 1$ refers to the case of perfect IC, and $\eta = 0$ when no IC is performed.

Setting $\Gamma_k = \Gamma$ for $k = 1 \ldots N$, the optimal set of powers $\{S_k\}_{k=1,..N}$ satisfies a recursive solution [4] given by:

$$S_k = S_{k-1} - \frac{\eta\, S_{k-1}^2}{V_{k-1} + N_0} \quad k = 2, \ldots, N \quad (2)$$

$$V_k = \sum_{i=1}^{N} S_i - \sum_{i=1}^{k-1} \eta S_i \quad k = 1, \ldots, N-1 \quad (3)$$

It is easy to see that this set of recursive equations reduces to the conventional equal-power solution $S_k = S$ for $k = 1, \ldots, N$ when $\eta = 0$.

The equations (2) are solved iteratively to an arbitrary accuracy, starting with initializing S_1 to S_T/N, where $S_T = \sum_{i=1}^{N} S_i$, and increasing it with some step size $\delta \ll S_1$. Convergence of this algorithm is assured as long as $\theta \leq 1$, the only constraint being to properly choose the step size δ which determines the number of iterations needed to converge to the optimal set of powers. In the remainder, we will use $\{S_k(\eta)\}_{\{k=1,\ldots,N\}}$ to denote the set of optimum powers corresponding to a given IC efficiency η.

C. Differential Resource Requirements

Transmissions at the basic rate R_b from mobiles in a zone (i,j) are considered to arrive at the target BS_0 with the same average power level and generate, on average, the same amount of out-of-cell interference to the facing BS_j. For the purpose of flow control, we differentiate the resource requirements among mobiles and zones on a per packet basis.

Let $\overline{\alpha}_{i,j}$ denote the normalized average power of an arriving packet at BS_0 from a given zone (i,j):

$$\overline{\alpha}_{i,j}(\eta) = \overline{S}_{i,j}(\eta)\;/\;S\,, \quad (4)$$

where, $\overline{S}_{i,j}(\eta) = \frac{\sum_{k \in \aleph_i} S_k(\eta)}{N_i}$, $\aleph_i$ is the set of indices of mobiles in zones $(i,j)_{\{j=1,2\}}$, and N_i is the number of these mobiles[1].

Now, let a packet be transmitted from zone (i,j) and calculate the average amount of interference generated by this transmission to the facing BS_j. Considering the path loss between the mobile and the target BS_0 proportional to $10^{(\xi/10)}d^{-4}$ (d is the distance from mobile in zone (i,j) to target BS_0 and ξ is a Gaussian random variable with zero mean and standard deviation σ = 8dB), the interference contributed by this packet transmission to BS_j is given by

$$\overline{S}_{i,j}(\eta)\,(d/d_j)^4\, 10^{(\xi/10)}\,, \quad (5)$$

where d_j is the distance from the mobile in zone (i,j) to BS_j as shown in Figure 3. For simplicity, we consider 4 zones in each sector as shown in Figure 2. The normalized interference generated by the transmission of a packet from zone (i,j) to the facing BS_j is given by:

$$\beta_{i,j}(\eta) = \overline{\alpha}_{i,j}(\eta)\,(d/d_j)^4\, 10^{(\xi/10)}\,. \quad (6)$$

If (x,y) are the mobile's coordinates (Figure 3), and given that $d = (x^2+y^2)^{1/2}$ and $d_j = ((R\sqrt{3}-x)^2+y^2)^{1/2}$, we calculate an average value of $\beta_{i,j}$ by

$$\overline{\beta}_{i,j}(\eta) = \overline{\alpha}_{i,j}(\eta)\,\overline{\gamma}_{i,j}\,. \quad (7)$$

Given that $\gamma(x,y) = (x^2+y^2)^2 \;/\; ((R\sqrt{3}-x)^2+y^2)^2$, and letting $A_{i,j}$ be the area of zone (i,j), the zone average coefficient $\overline{\gamma}_{i,j}$ is found by numerically calculating the integral:

$$\frac{1}{A_{i,j}} \iint_{\text{zone }(i,j)} \gamma(x,y)\,dx\,dy\,. \quad (8)$$

The symmetry of the subdivision (Figure 2) and the definition of $\overline{\alpha}_{i,j}$ imply that the average powers received at the target BS_0 originating from a packet transmission in the inner zones are equal ($\overline{\alpha}_{1,1}(\eta) = \overline{\alpha}_{1,2}(\eta)$) as are the average values corresponding to the outer zones ($\overline{\alpha}_{2,1}(\eta) = \overline{\alpha}_{2,2}(\eta)$). Similarly, for the associated average interference generated in the neighbor BS_1 and BS_2, $\overline{\beta}_{1,1}(\eta) = \overline{\beta}_{1,2}(\eta)$ for the inner zones, and $\overline{\beta}_{2,1}(\eta) = \overline{\beta}_{2,2}(\eta)$ for the outer zones. In the presence of significant shadowing, the power-based zone assignment may result in complex zone boundaries, thus for convenience we have omitted shadowing considerations from our calculations. The separation between the inner and outer zones is determined so as to minimize the mean-squared error between the actual zone coefficient values at any point in the zone and the averaged value relative to each zone. For a pair of inner and outer zones opposing BS_j, it is easy to show that the coefficient γ_s at the separation line between inner and outer zones is constant and lies on a circle with radius $r_s = \frac{R\sqrt{3}\sqrt{\gamma_s}}{1-\sqrt{\gamma_s}}$ and centered

[1] Note that the actual transmit powers are assigned by power control. The equal-resource assumption is made for the purposes of flow control only.

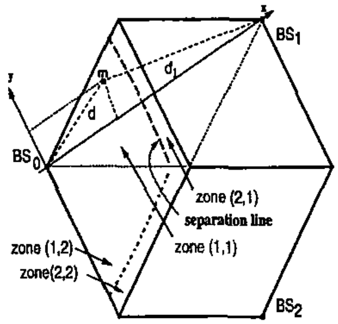

Fig. 3. Separation line between inner and outer zones.

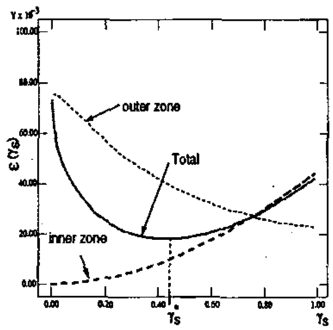

Fig. 4. Mean square error minimization.

at $(-r_s\ \gamma_s{}^{1/4}, 0)$, where R is the cell radius. The intersection between this circle and the 60^o region constitutes the separation between the zones (Figure 3). Given a separation line defined by the contour of constant γ_s, the mean squared error is expressed in (9), where $A_j = \sum_i A_{i,j}$.

$$\mathcal{E}(\gamma_s) = \frac{1}{A_j} \sum_i \iint (\gamma(x,y) - \overline{\gamma}_{i,j})\, dx\, dy\ . \qquad (9)$$

Let γ_s^* be the value of γ_s that corresponds to the line of separation that minimizes $\mathcal{E}$ (Figure 4). γ_s^* is found to be 0.44 (-3.57dB). This yields $\overline{\gamma}_{1,1} = \overline{\gamma}_{1,2} = 0.08$, and $\overline{\gamma}_{2,1} = \overline{\gamma}_{2,2} = 0.62$. These values will be used in the simulations.

IV. Packet Scheduler Design

A. Mathematical Formulation

Packet scheduling is formulated as a constrained integer optimization problem following the method in [2] for the downlink. The formulation uses an objective function composed of a weighted sum of throughput, fairness, and a function which quantifies the proximity to the available remaining resources. For one 120^o sector with 2 n_z zones, the resource constraints for a time slot l can be expressed as

$$\begin{aligned} &\sum_{i=1}^{n_z} \left(\overline{\alpha}_{i,1}(\eta)\, n_{i,1}^l + \overline{\alpha}_{i,2}(\eta)\, n_{i,2}^l\right) \le NI^l \\ &\sum_{i=1}^{n_z} \overline{\beta}_{i,1}(\eta)\, n_{i,1}^l \le NOC_1^l \\ &\sum_{i=1}^{n_z} \overline{\beta}_{i,2}(\eta)\, n_{i,2}^l \le NOC_2^l \\ &N_{i,j}^l \ \ge\ n_{i,j} \ \ge\ 0 \quad i = 1,\cdots,n_z; \quad j = 1,2 \end{aligned} \qquad (10)$$

where, in time slot l, $n_{i,j}^l$ is the number of packets transmitted from zone (i,j), and $N_{i,j}^l$ is the number of queued packets for zone (i,j).

We define a resource proximity function that measures the resource availability associated with an assignment vector $\mathbf{n}(l) = \{n_{1,1}^l, \cdots, n_{n_z,1}^l, n_{1,2}^l, \cdots, n_{n_z,2}^l\}$ in time slot l. This function is defined as the proximity to the nearest resource limit, measured in terms of the additional packets that may be transmitted from the most tightly constrained zone and is expressed as

$$\mathbf{P_n}(l) \ = \ \min_{i,j}\ \hat{n}_{i,j}(\mathbf{n}) \qquad (11)$$

where, $\hat{n}_{i,j}$ is the maximum number of packets that could be transmitted from zone (i,j) given the available remaining resources at time slot l, and expressed as

$$\hat{n}_{i,j}(\mathbf{n}) = \min\left\{\lfloor RNI^l(\mathbf{n})/\overline{\alpha}_{i,j}(\eta)\rfloor, \lfloor RNOC_j^l(\mathbf{n})/\overline{\beta}_{i,j}(\eta)\rfloor\right\} \qquad (12)$$

where $\lfloor\ .\ \rfloor$ denotes the integer part of a number, RNI^l and $RNOC_{\{j=1,2\}}^l$ being respectively the in-cell and out-of-cell available remaining resources at time slot l.

The flow control problem consists of finding, at each time slot l, the transmit vector $\mathbf{n}(l)$ which jointly maximizes throughput and fairness, while ensuring that the resource constraints (Eq. 10) are satisfied. To provide fair allocation of resources among users for equitable levels of service while maintaining an acceptable throughput, we define the optimization criterion as the maximization of the functional $\mathcal{OF}_\mathbf{n}(l)$ corresponding to an assignment $\mathbf{n}$ at time slot l

$$\mathcal{OF}_\mathbf{n}(l) = \mathbf{T_n}(l) + \mathbf{P_n}(l) + \lambda\, \mathbf{F_n}(l) \qquad (13)$$

where, $\mathbf{T_n}(l)$ is the throughput in total number of packets transmitted in time slot l, $\mathbf{P_n}(l)$ is the resource proximity resulting from assignment $\mathbf{n}(l)$ (Eq. 11), $\mathbf{F_n}(l)$ is the fairness of assignment $\mathbf{n}(l)$ defined in terms of the variance of delays on the remaining head-of-queue packets, and the coefficient λ is chosen to tune the trade-off between the throughput and fairness. The optimization problem can be formulated as finding, at each time slot l, the optimal assignment vector $\mathbf{n}^*(l)$ that maximizes the objective function (Eq. 13) under the identified constraints (Eq. 10).

B. Transmit Assignment Algorithm

For a given fairness coefficient λ, and an initial assignment vector, the algorithm iteratively updates the assignment vector $\mathbf{n}^{(m)}(l)$, increasing index m until the stopping criterion is met. Index m counts the iterations until the final assignment vector $\mathbf{n}^*(l)$ is reached. If the starting point is the zero vector, the index counts the packets in the assignment vector. Consequently, at each time slot l, the iterations start with the following initial conditions:

- $\mathbf{n}_s(l)$, the selected initialization vector,
- $m = 0$, index of iteration,
- $\Omega^{(m)}$, the initial state matrix, indicates which mobiles are allowed to transmit and if there still are packets to be transmitted from each zone,
- $RNI^l(\mathbf{n}_s)$, $RNOC_1^l(\mathbf{n}_s)$ and $RNOC_2^l(\mathbf{n}_s)$, the current resource availabilities.

As long as the resource constraints are satisfied and the objective function increases, the algorithm iterates on m according to the following steps and rules:

1) Define up to 2 n_z possible assignments that include one additional packet to be transmitted from non-empty queues.
2) Inhibit the assignments that violate the constraints.
3) If there are no feasible assignments, stop. Else, continue.
4) Determine the $\mathcal{OF}$ value associated with each assignment and select the assignment that results in the highest value.
5) Update the functional $\mathcal{OF}_{\mathbf{n}}^{(m)}(l)$, and the delay set corresponding to the heads of active queues.
6) Set $m = m + 1$ and repeat from 1.

V. Simulations and Discussions

We consider a four zone subdivision in each sector. Consider $N = 20$ users in the target sector with a distribution of [7 3 7 3], respectively in zones $[z_{1,1}\ z_{1,2}\ z_{2,1}\ z_{2,2}]$. Variable spreading allows each user M different values of spreading gain. For our example we let the available rates be $\{0, 1, \ldots, M\}$. Packets arrive to each user following a Poisson process. The average load per user is assumed to be M packets per time slot. For purposes of comparison, we use a time-to-completion measure defined as the number of time slots required to transmit all packets that arrive up to a given time slot. Herein, results are presented for a packet arrival interval of 50 time slots.

Given the traffic load offered, different operating conditions can be examined to evaluate the performance of the transmission strategy. Such conditions can be simulated by setting the average available resources to result in a system limited in terms of in-cell, out-of-cell or both resources. The algorithm has been studied for a wide range of operating conditions but results provided herein correspond to a worst-case scenario. The latter chosen so that the traffic load exceeds the available resources both in in-cell and out-of-cell. The example depicted is represented by the following parameters: $\overline{NI}$ = 40 packets / time slot, $\overline{NOC}$ = [2,2], M = 3 packets per user / time slot.

Two values of the parameter η for error estimation are considered, namely $\eta = 0$ for no IC, and $\eta = 0.8$ for an imperfect IC that corresponds to an amount of residual interference $\theta = 0.2$. This value $\eta = 0.8$ can be enabled in practice [6] using the IC technique implemented in this work. We present the results in terms of throughput and queuing delays for different values of the fairness coefficient λ. Four values of λ are considered: $\lambda = 0$ for throughput maximization only, λ approaching ∞ for extreme importance assigned to fairness, and two intermediate values.

Results are organized in two parts. First, we show the effect of fairness on throughput with and without IC, given a set $\{\overline{NI}, \overline{NOC}\}$ of average available resources. In the second part, we show the increase in performance achieved when exploiting the variations in the available resources resulting from the implementation of IC.

First, consider the case where no IC is performed. We can see in Figure 5 that during the packet arrival interval, the mean throughput decreases as λ increases. This decrease is traded off for an increase in fairness. This improvement is achieved by striving to equalize the delays of the head-of-queue packets. Delay equalization is indeed improved as λ increases, as can be seen in Figure 6 showing the maximum delay at the head of each queue for $\lambda = \infty$, compared to the results corresponding to $\lambda = 0$ and shown in Figure 7. Using different operating conditions, the performance has been evaluated for different values of λ to allow operation with two intermediate values that we define by $\lambda = 20$ for modest fairness and $\lambda = 50$ for high fairness. Fairness results for these values are not provided in terms of delay, and would be discussed in terms of time-to-completion.

Our scheduling algorithm is capable of ensuring reasonable fairness for both intermediate values of λ without a significant decrease in throughput from the maximum achievable corresponding to $\lambda = 0$. However, when the available resources are very stringent as in the example depicted here, the maximum fairness that can be achieved not only cannot perfectly equalize the delays but results in a loss in throughput of 55% compared to throughput maximization only. This decrease is of 10% for $\lambda = 20$ and 15% for $\lambda = 50$. Consider that a loss of 15% is tolerated and compare the time-to-completion corresponding to the inner and outer zones. The results provided in Table I show how acceptable equalization cannot be achieved under the stringent out-of-cell limits. Considering the same values of λ, throughput results with IC used with an efficiency $\eta = 0.8$ are represented in Figure 8. Take $\lambda = 0$, the use of IC in favor of the users in the outer zones decreases the total throughput compared to no IC. However, as we can see in Figure 9 fairness is considerably increased. Table I shows

TABLE I

Comparison of the algorithm time-to-completion for the average available resources: $\overline{NI} = 40$, $\overline{NOC} = [2, 2]$.

	$\lambda = 0$	$\lambda = 20$	$\lambda = 50$	$\lambda = \infty$
$\eta = 0$	(60, 214)[2]	(66, 205)	(70, 202)	(138, 187)
$\eta = 0.8$	(64, 165)	(70, 151)	(72, 149)	(124, 140)

[2] Pairs correspond to the algorithm time-to-completion for the inner and outer zones.

that the time-to-completion corresponding to the outer users is reduced from 214 to 165 when the one corresponding to the inner users increases by 4 time slots only. A result that comes at the cost of reduction in throughput by only 10%. This percentage also corresponds to using $\lambda = 20$ with no IC, but yielding a patently unfair service.

TABLE II

COMPARISON OF THE ALGORITHM TIME-TO-COMPLETION FOR $\overline{NI} = 40$: (A) $\eta = 0$ & $\overline{NOC} = [1,1]$ (B) $\eta = 0.8$ & $\overline{NOC} = [3,3]$.

$\overline{NOC} = [1,1]$ & $\eta = 0$	$\lambda = 0$	$\lambda = 20$	$\lambda = 50$	$\lambda = \infty$
	(73, 483)[2]	(78, 481)	(84, 453)	(180, 437)
$\overline{NOC} = [3,3]$ & $\eta = 0.8$	$\lambda = 0$	$\lambda = 20$	$\lambda = 50$	$\lambda = \infty$
	(69, 104)	(69, 101)	(70, 100)	(89, 92)

For $\lambda = \infty$, comparing the results of Figure 10 to those shown in Figure 6 for no IC, we can see how the algorithm is capable of approaching complete fairness. Complete equalization of the delays cannot be achieved due to the fact that the out-of-cell resource limits are very tight. In this case, the gap between the time-to-completion of the inner and outer zones goes from 49 without IC to 16 when IC is implemented, when at the same time, the average throughput in the arrival interval increases by 20%. Taking the extreme cases of $\lambda = 0$ and $\lambda = \infty$, the loss in throughput is 55% without IC, while it is only 37% when IC is implemented.

We study now the advantages of our scheduling algorithm in the presence of IC as a function of the availability of resources. Consider that our target sector is subject to more stringent out-of-cell limits due to greater load in the facing sectors, say $\overline{NOC} = [1,1]$. With no IC implemented, remote users experience unacceptable delays and complete fairness cannot be achieved even with $\lambda = \infty$ (Table II). As can be seen in Table II, the time-to-completion for the outer zones, with $\lambda = \infty$, is only 46 time slots lower than that of $\lambda = 0$. The resources being stringent, transmissions from mobiles in the outer zones cannot be allowed. IC on the other hand, when applied to all the sectors in the network allows lowering the transmit power of the outer zone users, thus translating into more available resources to handle the out-of-cell interference. This increase in capacity results in less stringent out-of-cell limits. The new limits can be approximated as: $\overline{NOC}(\eta) = \frac{(1+f)}{(1+f-\eta)}\,\overline{NOC}(\eta = 0)$, where f is the other-cell to in-cell interference ratio for which a typical value $f = 0.55$ is chosen, assuming a path loss exponent of 4, shadowing standard deviation of $\sigma = 8$dB, and equally loaded cells [7]. This yields an average out-of-cell limit of $\overline{NOC} = [3,3]$ allowed for the target sector when the IC efficiency is $\eta = 0.8$.

We show in Figure 11 the throughput values for both sets of out-of-cell resources. Denote for simplicity the resource limits $\overline{NOC} = [1,1]$ by Case$_A$ and $\overline{NOC} = [3,3]$ by Case$_B$. As can be seen in the figure, throughput is considerably increased for Case$_B$ compared to Case$_A$. For a given value of λ, we observe how the algorithm exploits the availability of resources to increase throughput and considerably decrease the completion time as shown in Table II. If fairness is of importance, a value of $\lambda = \infty$ is used. In this case, while a loss in throughput of 65% for Case$_A$ would reduce the completion time for the outer zones from 483 to 437, the use of IC allows maximum achievable fairness with a loss of only 13% compared to throughput maximization only. As can be seen in Figure 12, while the use of $\lambda = \infty$ yields high delay values both for the inner and outer zones, the implementation of IC allows more resources to be available allowing higher performance. It is important to mention that the results provided here under heavy load are chosen to emphasize the flexibility of our algorithm in achieving any desirable trade-off between throughput and fairness, and its capability of providing high fairness that is difficult to achieve when the resources vary slowly and under stringent out-of-cell resource limits.

VI. CONCLUSION AND FUTURE WORK

The control of uplink packet flow subject to in-cell and out-of-cell interference limitations was considered. The objective was to devise a low-complexity flow control scheme that takes benefit of IC and efficiently uses the resources. Our scheme assigns packets to be transmitted to separate queues, one for each spatial zone defined by equal average resource requirements. We showed that using flow control with IC can indeed provide for fairness among users without a loss in throughput even under stringent resource limitations. The algorithm is designed to provide adequate compromise between throughput and fairness even under limited IC capability. While we focused on a uniform distribution of mobiles and assumed equal rate requested by all of them, our formulation is general enough to account for these situations. Further work includes the benefits of nonhomogeneous organization of zones, effects of mobility and operation under hybrid modes of ISR.

REFERENCES

[1] S. Aïssa and P. Mermelstein, "Downlink Flow Control in WCDMA Networks," *In Proc. of ICT, Acapulco, Mexico*, pp 41–45, May 2000.

[2] S. Aïssa and P. Mermelstein, "Downlink Flow Control for Wireless CDMA Packet Data Networks," *IEEE Trans. on Vehicular Technology*, in press.

[3] S. Affes, H. Hansen, and P. Mermelstein, "Interference Subspace Rejection: A Framework for Multiuser Detection in Wideband CDMA", *IEEE Jour. on Selec. Areas in Comm.*, vol. 20, no. 2, pp. 287–302, February 2002.

[4] J. Andrews and T. Meng, "Amplitude and Phase Estimation Considerations for Asynchronous CDMA with Successive Interference Cancellation", *In Proc. of VTC*, vol. 3, pp. 1211–15, September 2000.

[5] J. Kuri, P. Mermelstein, "Call Admission on the Uplink of a CDMA System based on Total Received Power," *IEEE International Conf. on Communications*, vol. 3, pp. 1431–1436, 1999.

[6] S. Affes, K. Cheikhrouhou, and P. Mermelstein, "High-Speed Data Access with Enhanced Interference Suppression over Wideband CDMA Networks", Invited Paper, *Proc. of IEEE Intl. Conf. on Systems, Man and Cybernetics SMC'2002, Hammamet, Tunisia*, to appear, October 6-9, 2002.

[7] A. J. Viterbi, A. Viterbi, and E. Zehavi, "Other-Cell Interference in Cellular Power Controlled CDMA," *IEEE Trans. on Vehicular Technology*, vol. 40, no. 2, 1991.

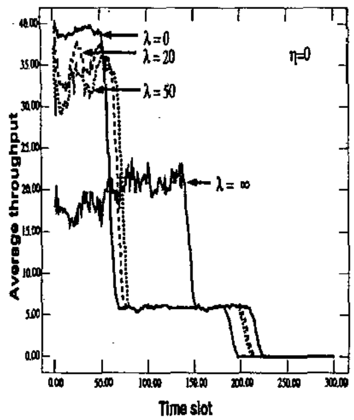

Fig. 5. Average throughput for $\eta = 0$, $\overline{NI}$=40, and $\overline{NOC}$=[2,2].

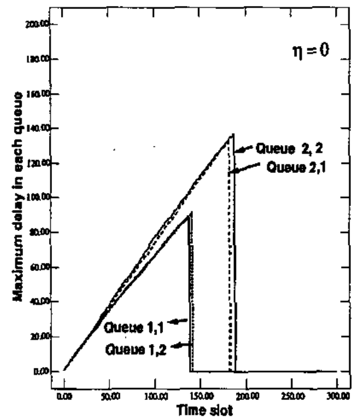

Fig. 6. Maximum delay at the head of each queue resulting from fairness maximization ($\lambda = \infty$) for $\overline{NI}$=40 and $\overline{NOC}$=[2,2].

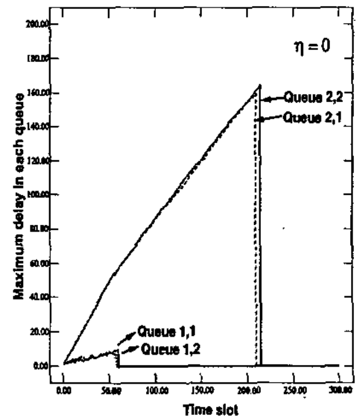

Fig. 7. Maximum delay at the head each queue resulting from throughput maximization ($\lambda = 0$) for $\overline{NI}$=40 and $\overline{NOC}$=[2,2].

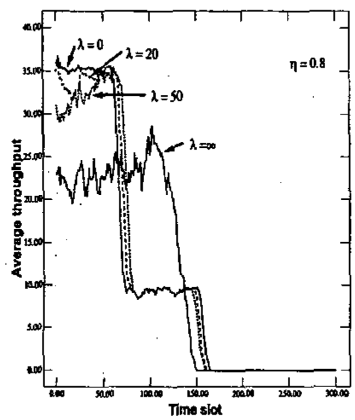

Fig. 8. Average throughput for $\eta = 0.8$, $\overline{NI}$=40, and $\overline{NOC}$=[2,2].

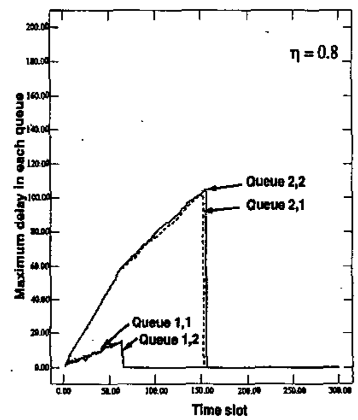

Fig. 9. Maximum delay at the head each queue resulting from throughput maximization ($\lambda = 0$) for $\eta = 0.8$, $\overline{NI}$=40 and $\overline{NOC}$=[2,2].

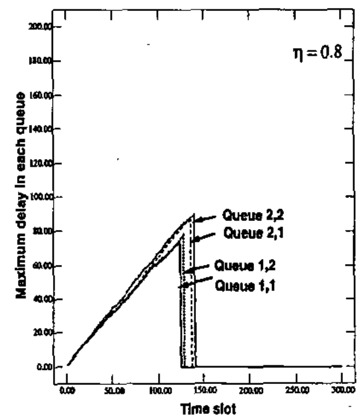

Fig. 10. Maximum delay at the head each queue resulting from fairness maximization ($\lambda = \infty$) for $\eta = 0.8$, $\overline{NI}$=40 and $\overline{NOC}$=[2,2].

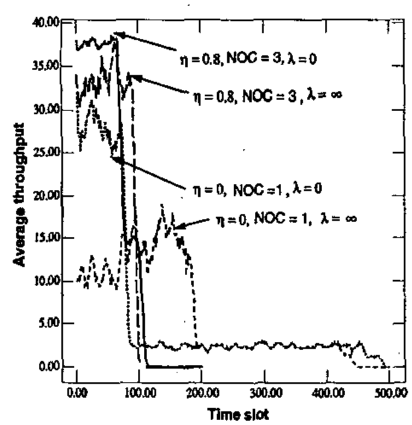

Fig. 11. Comparison of the average throughput for $\overline{NI} = 40$, $\eta = 0$ and $\overline{NOC} = [1, 1]$ versus $\eta = 0.8$ and $\overline{NOC} = [3, 3]$.

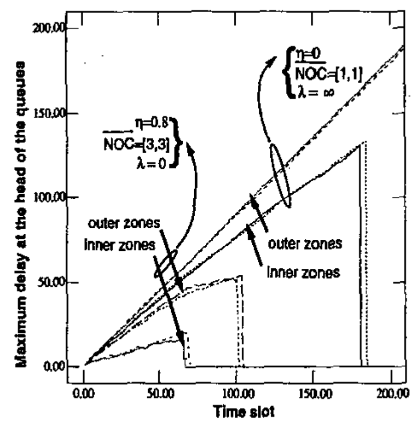

Fig. 12. Comparison of the maximum delay at the head each queue for $\overline{NI} = 40$, $\eta = 0$ and $\overline{NOC} = [1, 1]$ versus $\eta = 0.8$ and $\overline{NOC} = [3, 3]$.