Distributed Admission Control for Power-Controlled Cellular Wireless Systems

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***Abstract*—It is well known that power control can help to improve spectrum utilization in cellular wireless systems. However, many existing distributed power control algorithms do not work well without an effective connection admission control (CAC) mechanism, because they could diverge and result in dropping existing calls when an infeasible call is admitted. In this work, based on a system parameter defined as the discriminant, we propose two distributed CAC algorithms for a power-controlled system. Under these CAC schemes, an infeasible call is rejected early, and incurs only a small disturbance to existing calls, while a feasible call is admitted and the system converges to the Pareto optimal power assignment. Simulation results demonstrate the performance of our algorithms.**

***Index Terms*—Cellular system, connection admission control, distributed admission control, power control, signal-to-interference ratio, wireless.**

I. Introduction

THE TREMENDOUS success of cellular phones has generated great interest in wireless networks. Wireless subscribers have now begun to expect many advanced networking capabilities, such as multimedia applications, multicasting, and guaranteed quality of service (QoS). However, the wireless network is characterized by scarce radio spectrum, an unreliable propagation channel (with shadowing, multipath fading, etc.), and node mobility, all of which lead to a number of interesting open problems for network management in these systems [1]. In this paper, we address one such important problem: connection admission control (CAC).

The goal of an efficient CAC scheme is to guarantee the quality of service of the ongoing connections, while at the same time efficiently using the available radio spectrum. Connection admission control in the form of bang-bang control (admission or rejection) by itself is not effective to control and guarantee QoS. This is especially true when a cellular system adopts fixed channel allocation (FCA) with neither power control nor mobility prediction. However, armed with dynamic channel allocation (DCA), power control, and mobility prediction, CAC has many more degrees of freedom, and can be very useful in guaranteeing QoS. Our goal is to design an efficient CAC scheme that is efficient, simple, and robust enough to implement.

Power control in a cellular system has been shown to have numerous benefits. It reduces cochannel interference and guarantees the signal to interference ratio (SIR) of ongoing connections, resulting in a higher utilization and/or better QoS. If power levels are tuned continuously, power control can be a strong enhancement to the bang-bang type of call admission control. There have been numerous papers on power control, especially for CDMA systems. From the viewpoint of practical applications, distributed power control schemes are of special interest and importance. In [2], Yates unifies most of the known distributed power control schemes under a framework called *standard power control*. Every algorithm under this framework converges for both synchronous and asynchronous cases, when the system is feasible. However, if there is no feasible power assignment, a distributed power control algorithm can diverge or result in dropping an existing call. Thus, a criterion is needed to decide if a set of mobiles in the system can be served at the same time. A well-known criterion can be found in [3], [4], but it requires global information and is not suitable for distributed implementation.

Hence, the challenge to implement admission control for such a power-controlled system lies in the limited (locally) available information, as well as in the variable system capacity, which depends on other cochannel users in the system. In power-controlled systems, by adjusting the transmitted power, a communication link interacts with the rest of the network and can get feedback information by monitoring the interference induced on its receiver by the other reacting links. This feedback information turns out to be sufficient for making admission decisions in a distributed fashion. In this paper, we develop two distributed CAC schemes that can be applied to power-controlled systems. The basic procedure in our CAC schemes is as follows (for convenience, assume the downlink case). When a user W first arrives and wishes to be admitted, it measures the interference at its receiver and then sets up a "control transmission" at a fixed power level. The power control algorithms for the other users will then react to this control transmission by correspondingly increasing their power levels to overcome the associated interference. After the power levels for the other users have converged, user W again measures the resulting interference at its receiver. If this new interference is greater than twice the original interference, then the user is rejected; otherwise, it is admitted. While this scheme is a simple distributed procedure, we show that the scheme is optimal in the sense that it never admits any infeasible user and at the same time no other scheme can admit more calls into the network. By an "infeasible user," we

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mean a user whose admission into the system would result in the undesirable situation where it is impossible for all users to meet their SIR requirements.

Our scheme is based on a system parameter called the discriminant. The discriminant characterizes the feasibility of a new call arriving to a system with a set of feasible calls in service. Our CAC algorithms are independent of the underlying power control schemes and multiple access techniques used. They are measurement based, and assume nothing about the traffic statistics. We also show how the discriminant can be used as a system robustness measure, and present several extensions to our algorithms.

The rest of the paper is organized as follows. In Section II, we first present the system model, and then some existing results (mainly from [3], [5]). In Section III, we define the discriminant, describe the admissibility conditions, and propose distributed CAC mechanisms for power-controlled systems. In Section IV, we discuss and extend the proposed algorithms. Numerical results are given in Section V. Finally, Section VI concludes the paper and discusses directions toward future work.

II. System Model and Overview of Related Work

We consider a power-controlled cellular system where the transmitted powers are continuously tunable. In the system, every mobile is associated with a base station (called its home base station) to communicate. To maintain a connection between the mobile and its home base station, the SIR at the receiver must be no less than some threshold, which corresponds to a QoS requirement such as the bit-error rate. If a system has no maximum constraint on the transmitted power level, we call it *unconstrained*, otherwise, *constrained*. We first deal with unconstrained systems; we defer the constrained case to Section IV-A. Though a call must be admissible in both uplink and downlink to get admitted, we consider only downlink transmissions in this paper, because the uplink can be treated similarly.

Let $M_n = \{m_1, m_2, \ldots, m_n\}$ be the set of n mobiles in the system, and let p_i be the downlink power level of mobile m_i. Let G_{ij} denote the gain from the home base station of m_j to mobile m_i. Then the power received at mobile m_i from the downlink of m_j is $G_{ij}p_j$. Let η_i be the thermal noise received at mobile m_i, and let γ_i be its required SIR threshold. Then we require that

$$\mathrm{SIR}_i \equiv \frac{G_{ii}p_i}{\sum_{j\neq i} G_{ij}p_j + \eta_i} \geq \gamma_i \tag{1}$$

to maintain the downlink connection for mobile m_i. Note that this model is general enough to represent DS-CDMA systems with matched-filter receivers [6], [7] or TDMA/FDMA systems [3], by giving specific interpretations to the parameters.

We can rewrite (1) as $p_i - \sum_{j\neq i}(\gamma_i G_{ij}/G_{ii})p_j \geq (\gamma_i\eta_i/G_{ii})$. Let I_n be the $n \times n$ identity matrix, $P_n = [p_1, p_2, \ldots, p_n]^{\mathrm{T}}$, $U_n = [\gamma_1\eta_1/G_{11}, \gamma_2\eta_2/G_{22}, \ldots, \gamma_n\eta_n/G_{nn}]^{\mathrm{T}}$, and F_n be the $n \times n$ nonnegative matrix with (i, j) entry $F_{ij} = \gamma_i G_{ij}/G_{ii}$, if $i \neq j$, otherwise 0. Then the power assignment P_n is *feasible* if

$$\begin{cases} (I_n - F_n)P_n \geq U_n \\ P_n > \vec{0}_n \end{cases} \tag{2}$$

where $\vec{0}_n$ is the all-zero vector with dimension n, and the inequalities are componentwise. A power assignment P'_n is said to be *Pareto optimal* (or simply *optimal*) if it is feasible and any other feasible power assignment P_n satisfies $P_n \geq P'_n$ componentwise. For the system we just described, we now state a theorem and two corollaries that directly follow from results in [5], [4].

Theorem 1: The following statements are equivalent:

1) There exists a feasible power assignment P_n.
2) The maximum modulus eigenvalue (Perron–Frobenius eigenvalue) of F_n is smaller than 1.
3) $(I_n - F_n)^{-1} = \sum_{k=0}^{\infty}(F_n)^k$ exists and is componentwise positive.

Corollary 1: If $P'_n = (I_n - F_n)^{-1}U_n$ is not componentwise positive, then there is no feasible P_n; Otherwise, P'_n is Pareto optimal.

Corollary 2: If a Pareto optimal assignment P'_n exists, then the iterative power updating algorithm $P_n(k+1) = F_nP_n(k) + U_n$, or equivalently

$$p_i(k+1) = \frac{\gamma_i}{\mathrm{SIR}_i(k)}\, p_i(k), \quad \text{for } i = 1, \ldots, n \tag{3}$$

converges (from arbitrary $P_n(0) > 0$) to P'_n with geometric convergence.

The algorithm (3) is distributed and autonomous because it relies only on local information. It is also asynchronously convergent [4]. However, this algorithm does not work well without an effective CAC, because it diverges and results in some existing calls being dropped if there is no feasible power assignment. A modified algorithm of (3), DPC-ALP [5], may also experience convergence problems. The technique of probing [8], [9] and a similar method in [10] aim to overcome this problem, but they depend on approximations involving measurements of small quantities and may not be easy to implement.

Two CAC schemes have been proposed in [6] for CDMA systems: the transmitter-power-based call admission control (TPCAC) and the receiver-power-based call admission control (RPCAC). TPCAC is intended for a constrained system, and a new call is admitted by it if and only if no constraint is violated at *all* base stations after convergence. TPCAC is optimal and can prevent the divergence resulting from infeasibility, but it is not distributed. RPCAC admits a new call if and only if the received power is lower than some threshold. This scheme is distributed, but it is a heuristic and may admit inadmissible calls resulting in divergence, as will be shown by Corollary 3 in the next section.

In [3], it has been shown that the problem of finding the Pareto optimal power assignment P_n can also be reformulated as finding a basic feasible solution $[P_n^{\mathrm{T}}\ X_n^{\mathrm{T}}]^{\mathrm{T}}$, through Gaussian reduction, for the following set of linear equations:

$$\begin{cases} (I_n - F_n)P_n + I_nX_n = U_n \\ P_n^{\mathrm{T}}X_n = 0;\ P_n, X_n \geq \vec{0}_n. \end{cases} \tag{4}$$

The procedure can decide the feasible subset of mobiles in M_n, as well as the optimal power assignment. Though this algorithm is centralized, it gives us the insight that a mobile is admissible if and only if its pivoting variable in the Gaussian reduction tableau is positive. Based on this insight, we next provide an admissibility criterion and two distributed CAC algorithms.

III. Admissible Conditions and Distributed CAC Algorithms

The role of admission control is to decide if a new call can be accepted; if yes, the problem then becomes one of using which channel (or signature code) and at what power level. To achieve higher spectrum utilization, the power control algorithm used should converge to the Pareto optimal assignment, when it is feasible. We call a power control algorithm satisfying this condition *optimal*. Many existing power control algorithms [e.g., algorithm (3)] are optimal, but DPC-ALP [5] is not. We only consider the CAC problem for systems under optimal power control throughout the paper. We also assume that the existing system is initially in steady state. In this section, we consider the case where n feasible calls (namely, $m_1, \ldots, m_n$) are in service, and a new call m_{n+1} arrives and tries to get admission. Let B_{n+1} denote the base station assigned to the new call.

A. Admissible Condition for Unconstrained Systems

Before admitting mobile m_{n+1}, there are n feasible calls in the system, with power assignment $P_{n,\text{old}}$. Hence, the following inequality holds:

$$\begin{cases} (I_n - F_n)P_{n,\text{old}} \geq U_n \\ P_{n,\text{old}} > \vec{0}_n \end{cases} \tag{5}$$

and the optimal power assignment is $P^*_{n,\text{old}} = (I_n - F_n)^{-1}U_n$. The newly arrived mobile m_{n+1} (with SIR threshold γ_{n+1}, and thermal noise η_{n+1}) is *admissible* if and only if there exists a power assignment P_{n+1} for the $(n+1)$ downlinks satisfying

$$\begin{cases} (I_{n+1} - F_{n+1})P_{n+1} \geq U_{n+1} \\ P_{n+1} > \vec{0}_{n+1}. \end{cases} \tag{6}$$

To be specific, there exist positive power assignments P_n and p_{n+1} for the n existing mobiles and m_{n+1}, respectively, such that

$$\begin{bmatrix} I_n - F_n & -\vec{F}_{\cdot,\, n+1} \\ -\vec{F}^{\,\mathrm{T}}_{n+1,\,\cdot} & 1 \end{bmatrix} \begin{bmatrix} P_n \\ p_{n+1} \end{bmatrix} \geq \begin{bmatrix} U_n \\ u_{n+1} \end{bmatrix} \tag{7}$$

where

$$\vec{F}_{\cdot,\, n+1} = [F_{1,\, n+1},\, F_{2,\, n+1},\, \ldots,\, F_{n,\, n+1}]^{\mathrm{T}}$$

with

$$F_{i,\, n+1} = \frac{\gamma_i G_{i,\, n+1}}{G_{ii}}$$
$$\vec{F}_{n+1,\,\cdot} = [F_{n+1,\, 1},\, F_{n+1,\, 2},\, \ldots,\, F_{n+1,\, n}]^{\mathrm{T}}$$

with

$$F_{n+1,\, i} = \frac{\gamma_{n+1} G_{n+1,\, i}}{G_{n+1,\, n+1}}$$
$$u_{n+1} = \frac{\gamma_{n+1}\eta_{n+1}}{G_{n+1,\, n+1}}.$$

The quantity $F_{i,\, n+1}$ corresponds to the interference from the downlink of m_{n+1} to mobile m_i, and $F_{n+1,\, i}$ from the downlink of m_i to mobile m_{n+1}.

Let $\Delta_{n+1} = 1 - \vec{F}^{\,\mathrm{T}}_{n+1,\,\cdot}(I_n - F_n)^{-1}\vec{F}_{\cdot,\, n+1}$. We call Δ_{n+1} the *discriminant of* m_{n+1}, because it provides a criterion for the admissibility of m_{n+1}. This criterion is given by the following theorem.

Theorem 2: Mobile m_{n+1} is admissible if and only if $\Delta_{n+1} > 0$. Further, if m_{n+1} is admissible, then the optimal power assignment P^*_{n+1} is given by

$$P^*_{n+1} = \begin{bmatrix} P^*_n \\ p^*_{n+1} \end{bmatrix} = \begin{bmatrix} P^*_{n,\text{old}} + (I_n - F_n)^{-1}\vec{F}_{\cdot,\, n+1}p^*_{n+1} \\ \dfrac{\gamma_{n+1}}{G_{n+1,\, n+1}\Delta_{n+1}} R^{\text{initial}}_{n+1} \end{bmatrix} \tag{8}$$

where $R^{\text{initial}}_{n+1} = [G_{n+1,\, 1},\, G_{n+1,\, 2},\, \ldots,\, G_{n+1,\, n}]P^*_{n,\text{old}} + \eta_{n+1}$.

Note that even though R^{initial}_{n+1} (the total interference power received by mobile m_{n+1} when it arrives) is lower than some threshold, the discriminant Δ_{n+1} can be negative if the SIR requirement for the new mobile m_{n+1} is high enough such that

$$\gamma_{n+1} > \frac{G_{n+1,\, n+1}}{[G_{n+1,1},\, G_{n+1,2},\, \ldots,\, G_{n+1,n}](I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}}. \tag{9}$$

Hence, we have the following Corollary:

Corollary 3: RPCAC in [6] can admit an inadmissible call and result in divergence.

By Theorem 2, the inequality $P^*_n > P^*_{n,\text{old}}$ always holds. In other words, every time a new call enters the system, all the existing downlinks have to increase their powers to overcome the interference resulting from the new call. The quantity $\vec{F}_{\cdot,\, n+1}p^*_{n+1}$ in (8) is the extra power required to overcome the interference from the downlink of m_{n+1} alone. The matrix $(I_n - F_n)^{-1}$ represents the coupling between the n existing downlinks.

The quantity

$$\frac{\gamma_{n+1}R^{\text{initial}}_{n+1}}{G_{n+1,\, n+1}} \stackrel{\text{def}}{=} p^{\text{initial}}_{n+1}$$

is the transmitted power needed by base station B_{n+1} to overcome interference R^{initial}_{n+1}. However, there is a self-coupling effect for the new mobile m_{n+1}: the initial power transmitted at the downlink of m_{n+1} results in a power increase of the n existing downlinks, and this increase in turn makes the downlink transmitted power of m_{n+1} itself increase. This effect is totally captured by the discriminant Δ_{n+1}, because

$$p^*_{n+1} = p^{\text{initial}}_{n+1}/\Delta_{n+1}. \tag{10}$$

Note that the discriminant Δ_{n+1} only depends on information contained in matrix F_{n+1}, so it is a parameter inherent to the system. Unfortunately, the matrix F_{n+1} involves global information. In fact, the quantity $1/\Delta_{n+1}$ is just the $(n+1)$th pivoting variable in the Gaussian reduction tableau [see (4)], which results in a centralized CAC criterion [3]. Therefore, the discriminant by itself appears to be unsuitable as a distributed

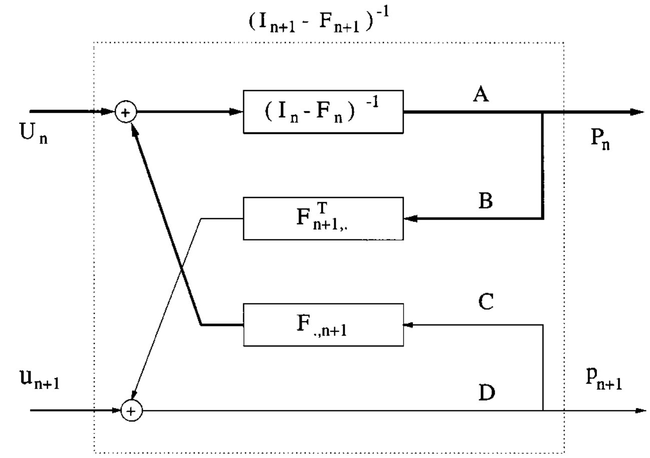

Fig. 1. Power assignment for $n+1$ users.

CAC criterion. We next provide a technique to overcome this limitation, resulting in a distributed CAC scheme.

B. Distributed CAC Schemes for Unconstrained Systems

A diagram illustrating the centralized power assignment scheme (8) is shown in Fig. 1. In this diagram, the thick lines represent vector information flows, the thin lines represent scalar flows, and all flows are power. Here, each block represents a matrix multiplication [of the kind in (8)]. For m_{n+1}, there is a feedback loop (with gain $1-\Delta_{n+1}$), which gives rise to the self-coupling effect and the problem of feasibility.

Before admitting mobile m_{n+1}, the n existing downlinks are feasible. If we cut the forward path D in Fig. 1, i.e., let base station B_{n+1} communicate with m_{n+1} at a fixed power level (we take p_{n+1}^{initial} defined above, to keep the initial SIR of the downlink at γ_{n+1}), then the feasibility of the n existing downlinks will not change. This is true because, for the existing downlinks, the additional interference resulting from m_{n+1} is equivalent to an increase in U_n. The existing downlinks only have to increase the transmitted power from $P^*_{n,\text{old}}$ to $P^*_{n,\text{old}} + (I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}p_{n+1}^{\text{initial}}$, to maintain their desired SIRs. After this increase, the downlink of m_{n+1} has lower SIR than γ_{n+1}, because the received interference changes to

$$\begin{aligned} R_{n+1}^{\text{new}} \triangleq R_{n+1}^{\text{initial}} &+ [G_{n+1,1}, G_{n+1,2}, \ldots, G_{n+1,n}] \\ &(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}p_{n+1}^{\text{initial}} > R_{n+1}^{\text{initial}}. \end{aligned} \tag{11}$$

To increase the SIR back to γ_{n+1}, base station B_{n+1} has to increase the transmitted power for m_{n+1} by $\vec{F}^{\text{T}}_{n+1,\cdot}(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}p_{n+1}^{\text{initial}}$. We define

$$\begin{aligned} p_{n+1}^{\text{new}} &= \frac{\gamma_{n+1}R_{n+1}^{\text{new}}}{G_{n+1,n+1}} \\ &= p_{n+1}^{\text{initial}} + \vec{F}^{\text{T}}_{n+1,\cdot}(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}p_{n+1}^{\text{initial}} \\ &= p_{n+1}^{\text{initial}} + (1-\Delta_{n+1})p_{n+1}^{\text{initial}}. \end{aligned} \tag{12}$$

Then, the above equation yields

$$\Delta_{n+1} = 2 - \frac{p_{n+1}^{\text{new}}}{p_{n+1}^{\text{initial}}} = 2 - \frac{R_{n+1}^{\text{new}}}{R_{n+1}^{\text{initial}}}. \tag{13}$$

By Theorem 2, we have

Corollary 4: Mobile m_{n+1} is admissible if and only if $p_{n+1}^{\text{new}} < 2p_{n+1}^{\text{initial}}$, which is equivalent to $R_{n+1}^{\text{new}} < 2R_{n+1}^{\text{initial}}$.

Note that quantities p_{n+1}^{initial}, p_{n+1}^{new}, R_{n+1}^{initial}, and R_{n+1}^{new} are independent of the iterative power control algorithm used. The CAC criterion only requires the algorithm to be optimal. Thus, the admissibility criterion given above is very general. Most importantly, we can check the criterion in a distributed and asynchronous manner, as described next.

Δ-CAC Algorithm: In the above derivation, we assume that the downlink power of m_{n+1} is fixed at p_{n+1}^{initial}. However, as mentioned before, arbitrary positive $p_{n+1}(0)$ in place of p_{n+1}^{initial} works. Then we have

$$\Delta_{n+1} = 1 - \frac{\gamma_{n+1}(R'_{n+1} - R_{n+1}^{\text{initial}})}{G_{n+1,n+1}p_{n+1}(0)} \tag{14}$$

where $R'_{n+1} = R_{n+1}^{\text{initial}} + [G_{n+1,1}, G_{n+1,2}, \ldots, G_{n+1,n}](I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}p_{n+1}(0)$ is analogous to R_{n+1}^{new}. With the distributed computation of Δ_{n+1}, we have the following distributed CAC algorithm (see Fig. 2 for the flowchart):

Δ-CAC:

1) Mobile m_{n+1} measures and reports to base station B_{n+1} its received interference power R_{n+1}^{initial}. The base station transmits to m_{n+1} at a fixed power level $p_{n+1}(0)$.
2) The downlinks of the n existing mobiles increase their corresponding powers iteratively according to some distributed, optimal power control algorithm [e.g., (3)].
3) After convergence, mobile m_{n+1} reports its received interference power R'_{n+1} to base station B_{n+1}. The base station calculates Δ_{n+1} according to (14). If $\Delta_{n+1} \le 0$, then the new call is rejected. Otherwise, the base station admits the call, and the $(n+1)$ downlinks adjust the transmitted power iteratively to the Pareto optimal assignment.

According to Theorem 2, if the system becomes infeasible, mobile m_{n+1} is rejected by the algorithm; otherwise it is admitted, and the system will converge to the optimal power assignment. Note that Δ-CAC makes the admission decision after the system converges, so the delay until a call is rejected may be large. We next present another algorithm, R-CAC, to overcome this limitation. Our simulations show that with R-CAC, the delay until rejecting an infeasible call is reduced to one iteration for most of the cases.

R-CAC Algorithm: If an optimal power control algorithm monotonically increases the transmitted powers (from the steady state values) during the admission process, we call it *monotonic and optimal*. An example of such an algorithm is algorithm (3). It should be pointed out, however, that the SIRs may not increase monotonically during the admission process. The monotonic and optimal power control is of special interest and importance in CAC, because it is less aggressive and will result in a more stable system. Note that the interference R_{n+1} received by mobile m_{n+1} will increase monotonically during

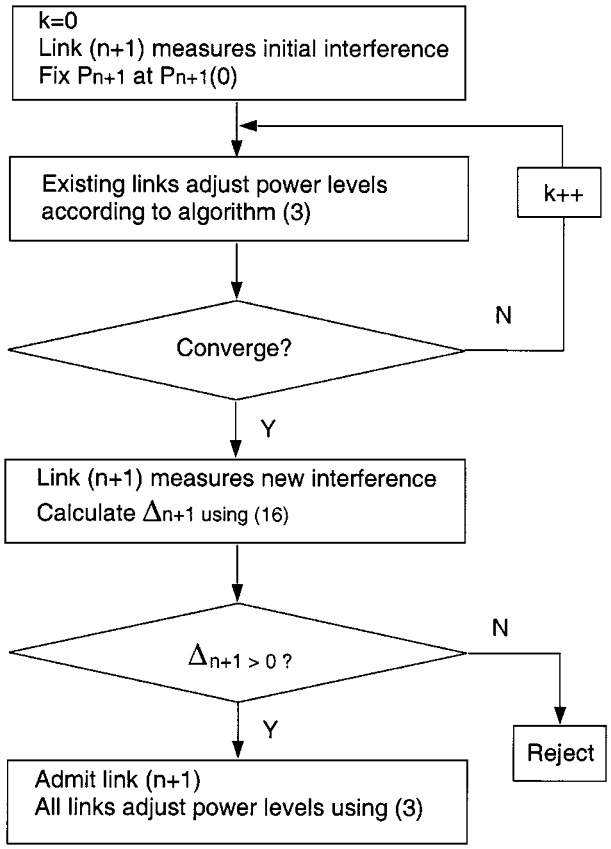

Fig. 2. Algorithm Δ-CAC.

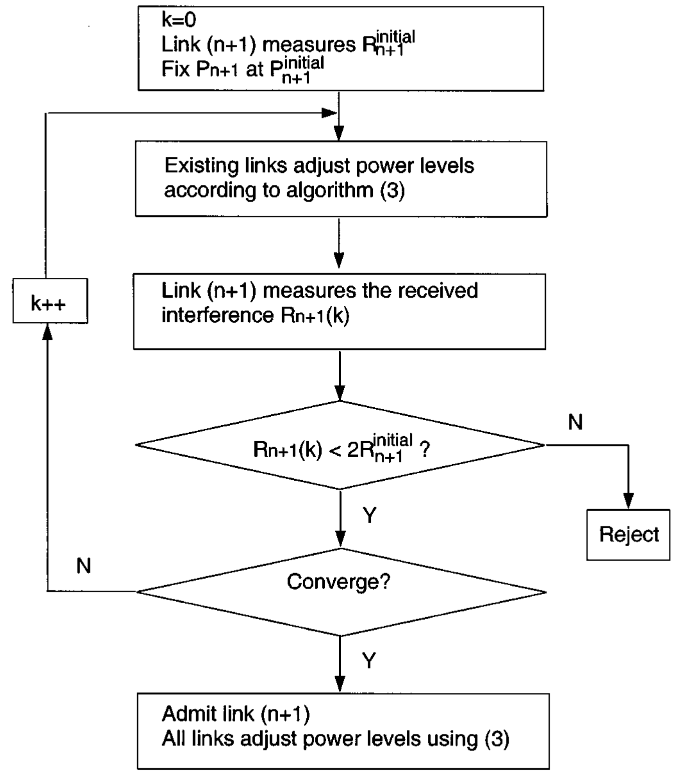

Fig. 3. Algorithm R-CAC.

the iterations of a monotonic and optimal power control. In this case, we can use the result of Corollary 4 as a CAC criterion, which is better than $\Delta_{n+1} > 0$, because in the former we do not need to wait until convergence to reject an infeasible call, thus resulting in a smaller disturbance. Based on this new criterion, we have the following simplified and improved distributed admission algorithm (see Fig. 3 for the flowchart):

R-CAC:

1) Mobile m_{n+1} measures its total interference R_{n+1}^{initial} and reports this value to its home base station B_{n+1}. The base station transmits to mobile m_{n+1} at fixed power level $p_{n+1}^{\text{initial}} = (\gamma_{n+1}/G_{n+1,\,n+1})R_{n+1}^{\text{initial}}$.
2) The downlinks of the n existing mobiles increase their corresponding powers iteratively according to some distributed, monotonic and optimal power control algorithm.
3) During the process of iteration mobile m_{n+1} measures its received interference power R_{n+1}. If it reaches (or exceeds) $2R_{n+1}^{\text{initial}}$, then the new call is rejected. Otherwise, after convergence, it is admitted. Mobile m_{n+1} measures and reports its received interference power R_{n+1}^{new} to base station B_{n+1}. The base station calculates Δ_{n+1}, and adjusts the transmitted power to $p_{n+1}^{\text{initial}}/\Delta_{n+1}$; the n existing downlinks correspondingly increase their associated power levels.

As in Δ-CAC, we can use $P_{n+1}(0)$ instead of P_{n+1}^{initial} for the initial transmission, but the criterion should be adjusted accordingly. We may also let all $(n+1)$ downlinks iteratively increase power after admitting m_{n+1}, rather than adjust the power for m_{n+1} to $P_{n+1}^{\text{initial}}/\Delta_{n+1}$ in one step, to reduce the disturbance to existing calls.

We next discuss some implementation issues. Note that the power control schemes considered here are not exactly those in the third-generation WCDMA systems, which use fixed step size updates (one-bit feedback) [11]. The schemes we assume are not of fixed step size, so more than one-bit feedback information of SIR is required for power adjustment. The power measurement and the SIR estimation must be done over a proper timescale, such that the fluctuations due to fast fading are averaged out and the shadowing effect is tracked. This timescale is typically longer than those specified in the third-generation WCDMA systems. One possible implementation using current technology is to feedback the SIR information over multiple periods, one bit at a time. We should point out that it may be difficult to implement such power control and admission control schemes in a fast moving environment. To have a system working well under such situations, we may have to sacrifice a little optimality by leaving some admission margin, which is further discussed in Section IV-B-1.

IV. Discussions and Extensions

In this section, we discuss and extend the above results. So far, we have only considered SIR requirements, but no constraint on the assigned power level. In practice, we may wish to take into account constraints on the transmitted power, which is the topic of the first subsection below. We then demonstrate that the discriminant can be used as a system robustness measure, and present ways to improve system robustness. We also consider several extensions to the above described CAC algorithms.

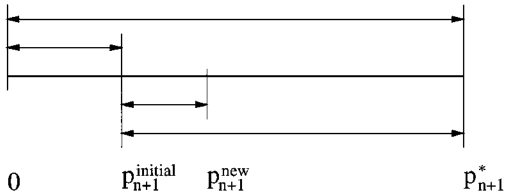

Fig. 4. $p_{n+1}^{\text{initial}}/p_{n+1}^{*} = (p_{n+1}^{\text{new}} - p_{n+1}^{\text{initial}})/(p_{n+1}^{*} - p_{n+1}^{\text{initial}}) = \Delta_{n+1}$.

These extensions will greatly increase applicability and improve the system performance.

A. Constrained Systems

In practical systems, a power constraint exists in both the downlink and the uplink. The power constraint is more serious for the uplink transmission, where the transmitter (mobile) is powered by a battery with limited power and lifetime. As before, consider the case where n feasible calls are in service at optimal downlink power, and a new call m_{n+1} arrives and attempts to be admitted. However, the difference here is that the system is constrained, i.e., it has a maximum power constraint.

For the unconstrained systems, mobile m_{n+1} is admissible if and only if discriminant Δ_{n+1} is positive. Further, if the transmitted power of the downlink for m_{n+1} is fixed, the feasibility of the existing downlinks will not change. However, this is not necessarily true for constrained systems, because even when $\Delta_{n+1} > 0$, the optimal unconstrained power assignment P_{n+1}^{*} may still have some component exceeding its corresponding constraint. Our R-CAC and Δ-CAC fail here.

Another difference is that the optimal distributed power control algorithm applied to a constrained system will always converge; when the system is feasible, the resulting power assignment is Pareto optimal; but when it is infeasible, there exists a mobile of which the transmission power hits the constraint and the achieved SIR is lower than its threshold [6]. From this fact, a simple CAC criterion is recognized and used for TPCAC: a new call is admissible if and only if no constraint is violated at *all* cells after convergence [6]. Unfortunately, this criterion is not suitable for distributed implementation, because the admission of a new call may result in violation of maximum power at a cell far away. In [9], admission control for the constrained case is done by broadcasting a *distress signal* when an existing link hits the constraint boundary. This problem is also addressed in [12], which presents both noninteractive and interactive schemes. The noninteractive admission control scheme is based on a maximum-interference threshold, and may be subject to both types of admission errors. The interactive scheme is referred to as "soft and safe" admission control, which is free from admission errors but requires exchanging global information on admission margins. As far as we know, there is no effective way to overcome this problem.

B. Further Discussions on the Discriminant

Having discussed the CAC algorithms, we now further elaborate on the discriminant Δ_{n+1}, which plays a fundamental role in this paper.

1) Relationship Between Discriminant and Transmitted Power: From Theorem 2, if mobile m_{n+1} is admissible, then

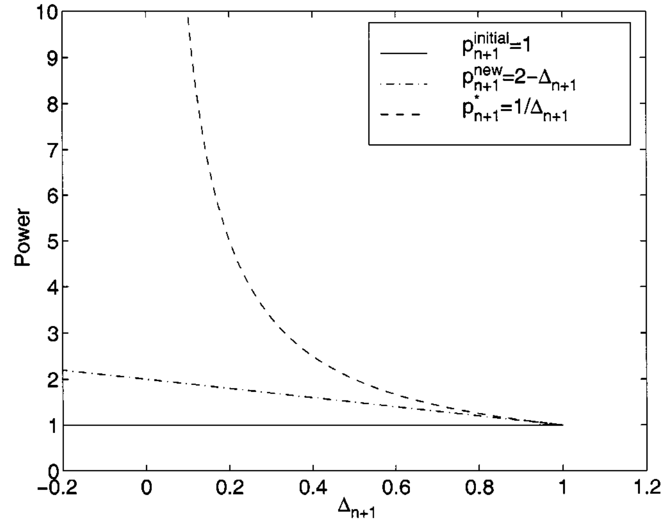

Fig. 5. Powers versus Δ_{n+1}.

we have $\Delta_{n+1} = p_{n+1}^{\text{initial}}/p_{n+1}^{*}$ by (10). Combining this with (13) yields

$$\Delta_{n+1} = \frac{p_{n+1}^{\text{initial}}}{p_{n+1}^{*}} = \frac{p_{n+1}^{\text{new}} - p_{n+1}^{\text{initial}}}{p_{n+1}^{*} - p_{n+1}^{\text{initial}}}. \quad (15)$$

We illustrate the above relationship in Fig. 4. Clearly, the condition $p_{n+1}^{\text{new}} = 2p_{n+1}^{\text{initial}}$ will drive p_{n+1}^{*} to ∞ (i.e., system diverges), because $p_{n+1}^{\text{initial}} > 0$. This provides further insight into our CAC criterion.

By fixing p_{n+1}^{initial} at 1, we obtain $p_{n+1}^{\text{new}} = 2 - \Delta_{n+1}$, and if m_{n+1} is admissible, then $p_{n+1}^{*} = 1/\Delta_{n+1}$. Fig. 5 shows the three powers p_{n+1}^{initial}, p_{n+1}^{new}, and p_{n+1}^{*}, versus Δ_{n+1}. The plot ends at $\Delta_{n+1} = 1$ because the n existing calls are feasible, and so by definition $\Delta_{n+1} \leq 1$. The three powers are equal at $\Delta_{n+1} = 1$, which corresponds to $n = 0$. When m_{n+1} is not admissible (i.e., $\Delta_{n+1} \leq 0$), p_{n+1}^{*} goes to ∞, but p_{n+1}^{new} remains bounded and small. This observation illustrates the benefit of using our CAC criterion together with a power control algorithm compared to using the power control algorithm by itself. To elaborate, we start from p_{n+1}^{initial} to get p_{n+1}^{new}, then decide on admissibility, and only when m_{n+1} is admissible will the power be tuned to p_{n+1}^{*}. In contrast, in the case of using power control by itself, the scheme tries to achieve p_{n+1}^{*} directly, and may fail, resulting in divergence. Note that though fixed to 1 here, the power p_{n+1}^{initial} depends on Δ_{n+1}. Qualitatively, a smaller Δ_{n+1} corresponds to a larger interference R_{n+1}^{initial}, and hence also a larger p_{n+1}^{initial}, which worsens the situation when m_{n+1} is not admissible.

The monotonicity of p_{n+1}^{*} with Δ_{n+1} also suggests that a larger Δ_{n+1} indicates a more robust system. To prevent the transmitted powers and admission delays becoming impractically large, we need to leave some robustness margin for the system during the admission process. This can be achieved by modifying our CAC criteria into $\Delta_{n+1} > \varepsilon$, where ε is a predefined small positive number. Another robustness consideration is the integrated base station assignment [6] and channel selection, by which we always choose the channel and base station that maximize the discriminant (or minimize the transmitted power). We next discuss the robustness issue as it pertains to the discriminant.

2) Discriminant as Robustness Measure: While the power assignment P^*_{n+1} given in Theorem 2 is optimal (when feasible), it is on the border of infeasibility, and needs to be updated whenever there is a path gain variation (e.g., due to user mobility). However, a desirable system should be *robust*, i.e., it should still be feasible despite these variations. According to Theorem 1, the maximum modulus eigenvalue of F_{n+1} dominates the convergence rate of distributed power controls, such as (3), so this value provides a good measure for *system robustness*, which indicates how far a feasible system is from the infeasibility boundary [10]. Hence, one way to improve system robustness is to leave some robustness margin during the admission process. However, due to mobility, an initially robust system can become unrobust or even infeasible.

In an unrobust system, we call the mobile corresponding to the maximum modulus eigenvalue the "bottleneck," because its departure can improve the system robustness most. We are interested to determine, in a distributed way, which mobile among all in the system is the bottleneck. Once determined, the bottleneck mobile is encouraged to take an appropriate action (such as inter/intracellular handoff, transmission rate regulation, or even dropping from the system), so that the transmitted power levels for the remaining links in the system will decrease significantly. In this way, we can improve the robustness of the system. The process to ascertain and hand off the bottleneck is just the reverse process of admission; while the former improves the robustness of the system, the latter tends to worsen the robustness.

Theorem 2 hints at a relationship between the discriminant and the established system robustness measure. Next, we will derive the relationship to show that the discriminant is also an appropriate robustness measure. Following the discussion in [5], [4], the matrix F_{n+1} has nonnegative entries and it is irreducible, since the links interact with each other; therefore, by the Perron–Frobenius Theorem [4], [13], the maximum modulus eigenvalue of F_{n+1} is real, positive, and simple, while the corresponding eigenvector is componentwise positive (or negative). Without loss of generality, assume that in the feasible system, mobile m_{n+1} is the bottleneck. Denote the corresponding eigenvalue by λ_{n+1}, and let $[\vec{V}^{\mathrm{T}} \ \ 1]$ be an associated left eigenvector (remember that it is positive componentwise). Then it is easy to show that the smallest modulus eigenvalue of $(I_{n+1} - F_{n+1})$ is $(1 - \lambda_{n+1})$, and corresponds to the same eigenvector. Therefore, we have

$$\begin{bmatrix}\vec{V}^{\mathrm{T}} & 1\end{bmatrix}\begin{bmatrix} I_n - F_n & -\vec{F}_{\cdot,\,n+1} \\ -\vec{F}^{\mathrm{T}}_{n+1,\,\cdot} & 1\end{bmatrix} = (1-\lambda_{n+1})\begin{bmatrix}\vec{V}^{\mathrm{T}} & 1\end{bmatrix} \tag{16}$$

that is,

$$\begin{cases} \lambda_{n+1} = \vec{V}^{\mathrm{T}}\vec{F}_{\cdot,\,n+1} \\ \vec{V}^{\mathrm{T}} = \vec{F}^{\mathrm{T}}_{n+1,\,\cdot}(\lambda_{n+1}I_n - F_n)^{-1} \\ \Delta_{n+1} = (1-\lambda_{n+1})\left(1 + \vec{V}^{\mathrm{T}}(I_n - F_n)^{-1}\vec{F}_{\cdot,\,n+1}\right). \end{cases} \tag{17}$$

Note that the third equation in (17) just means that the product of the eigenvector $[\vec{V}^{\mathrm{T}} \ \ 1]$ and the last column of $(I_{n+1} - F_{n+1})^{-1}$ equals $1/(1-\lambda_{n+1})$, which is the maximum modulus eigenvalue of $(I_{n+1} - F_{n+1})^{-1}$. Thus the discriminant Δ_{n+1} is related to the robustness measure λ_{n+1} by

$$\begin{aligned} \frac{1}{\Delta_{n+1}} &= \frac{1}{(1-\lambda_{n+1})(1+\vec{V}^{\mathrm{T}}(I_n - F_n)^{-1}\vec{F}_{\cdot,\,n+1})} \\ &< \frac{1}{1-\lambda_{n+1}}. \end{aligned} \tag{18}$$

If the value of $1/\Delta_{n+1}$ is large, then $1/(1-\lambda_{n+1})$ is larger, so the eigenvalue λ_{n+1} is close to 1, and the system is unrobust. On the other hand, if eigenvalue λ_{n+1} is close to 1, then $1/\Delta_{n+1}$ takes large values, because

$$\begin{aligned} \Delta_{n+1} &= 1 - \vec{F}^{\mathrm{T}}_{n+1,\,\cdot}(I_n - F_n)^{-1}\vec{F}_{\cdot,\,n+1} \\ &\approx 1 - \vec{F}^{\mathrm{T}}_{n+1,\,\cdot}(\lambda_{n+1}I_n - F_n)^{-1}\vec{F}_{\cdot,\,n+1} \\ &= 1 - \vec{V}^{\mathrm{T}}\vec{F}_{\cdot,\,n+1} \\ &= 1 - \lambda_{n+1}. \end{aligned} \tag{19}$$

Thus, the discriminant can be used as a good indicator of robustness. We may treat the calls with small values of discriminant as candidates for the bottleneck.

3) Adaptive Transmission: Considering the hostile environment encountered in wireless systems, sometimes it can be difficult or expensive to guarantee QoS for users. On the other hand, some users may tolerate degraded service (lower transmission rate or quality) when the transmission environment deteriorates. Adaptive transmission schemes, including link adaptation [14] and rate control [15], [16], have been proposed for this purpose. The extension of admission control in such a scenario is partial admission, which provides a degraded service, instead of dropping a connection, when an admissible condition is not satisfied.

The extension of our distributed algorithm to such systems turns out to be straightforward. By definition of the discriminant Δ_{n+1}, we have

$$\begin{aligned} \frac{1-\Delta_{n+1}}{\gamma_{n+1}} = \frac{1}{G_{n+1,\,n+1}}&[G_{n+1,\,1}, \ldots, G_{n+1,\,n}] \\ &\cdot (I_n - F_n)^{-1}\vec{F}_{\cdot,\,n+1}. \end{aligned} \tag{20}$$

If the admissible condition is $\Delta_{n+1} \geq \hat{\Delta}_{n+1}$, then the maximum admissible SIR for mobile m_{n+1} is

$$\hat{\gamma}_{n+1} = \frac{1-\hat{\Delta}_{n+1}}{1-\Delta_{n+1}}\,\gamma_{n+1} \tag{21}$$

which can be locally calculated. When the admissible condition is not satisfied, we only have to lower the SIR threshold of mobile m_{n+1} from γ_{n+1} to $\hat{\gamma}_{n+1}$, which can be translated into lower transmission rate or degraded quality of service.

C. Handoff Prioritization

So far, we have made efforts to use the spectrum efficiently, and have not distinguished handoffs from new calls. However, it is well known that dropping an ongoing call is more undesirable than rejecting a new call. To give priority to handoff calls, guard channels should be reserved for these calls in some form. While our algorithms are flexible enough to combine with different reservation schemes such as those in [17], [18], we may also realize handoff prioritization using another method, discussed next.

In the power-controlled system, a call always generates inter fence to its neighboring cells, and the closer the caller to a cell the stronger the interference, which tends to exclude the same channel from other calls in that cell. Thus, even before a call hands off to a neighboring cell, it has effectively occupied some bandwidth in the cell. We can exploit this fact through the "channel carrying" scheme [19], where a mobile can continue to use its previous channel after handoff. One advantage of "channel carrying" is that it does not require channel allocation during handoffs to maintain communication. The original scheme is based on FCA, and has to partition the channel set carefully in advance, so that high cochannel interference will not result from the "channel carrying." In our case, any channel is usable in each cell so long as the SIR and power constraints are satisfied, so predefined channel partitioning is not necessary. If the channel to be carried is not usable, then we can still choose the best available channel using channel selection. Note that in the downlink a feasible call is unlikely to become infeasible after "channel carrying," because though the base station changes in the handoff, the interference to and from the call and the path gain will not change much. We should point out that channel carrying is not the same as soft handoff. The latter is used in CDMA systems to keep connections with several neighboring base stations, while the former involves only one base station during the communication.

V. Simulation Results

For simplicity, we consider a one-channel linear cellular system consisting of 51 cells. Base stations use omnidirectional antennas and are located at the center. The location of a mobile in a cell is uniformly distributed. In the context of SIR-based power control, the effect from fast fading is often assumed to be averaged out in power measurements or by diversity [6], [20]. Thus, the path gain G_{ij} is modeled as

$$G_{ij} = \frac{A_{ij}}{d_{ij}^4} \tag{22}$$

where d_{ij} is the distance between mobile m_i and home base station of mobile m_j, and the attenuation factor A_{ij} models the power variation due to shadowing. We assume all A_{ij} to be independent and identically log-normally distributed random variables with 0-dB expectation and 8-dB log-variance as in [3], [6].

A. Channel Utilization

It is well known that power control can drastically improve spectrum utilization and lower the blocking probability [6], [20]. The degree of improvement depends on the CAC scheme used.

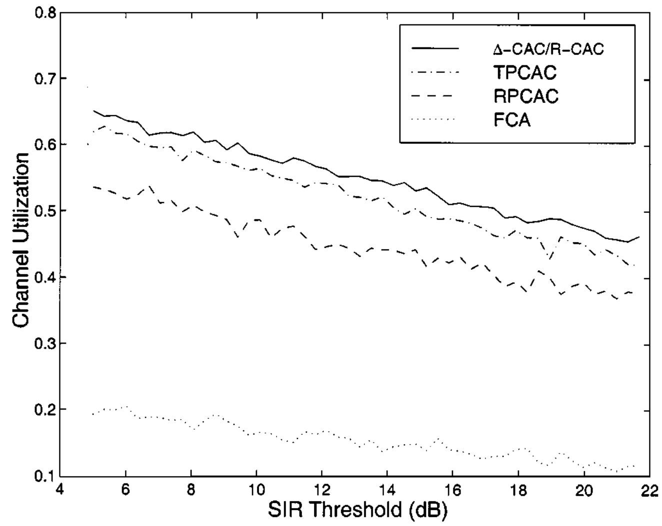

Fig. 6. Channel utilization of linear cellular system.

To compare the performance of different CAC schemes, we simulate the *channel utilization*, which is defined as the fraction of cells in the system that can share a channel.

The simulation starts with no calls, and adds calls until the blocking probability exceeds 2% for the central cell. We simulate the channel utilization for the linear cellular systems under optimal CAC, TPCAC, RPCAC, and FCA schemes. The optimal CAC rejects a call if and only if the call is inadmissible, so it provides the upper bound for CAC schemes. Our Δ-CAC and R-CAC are examples of optimal CAC schemes. TPCAC is optimal for constrained systems, but it is not distributed. RPCAC admits a call only when the received interference is lower than some threshold, which is taken to be 0.5 here. Unlike the above schemes, FCA is for systems without power control, where all calls transmit at the maximum power. We assume the power constraints for all calls to be 1 in the simulations of FCA and TPCAC.

The channel utilization plots for the linear cellular systems are shown in Fig. 6, where one hundred simulations are performed for each SIR threshold. Clearly, the power-controlled system under optimal CAC has significant gains over FCA. TPCAC and RPCAC have lower channel utilization than the optimal CAC, depending on the power constraint and interference threshold respectively. The utilization of RPCAC can be improved by choosing a larger threshold, but larger threshold is more likely to result in divergence due to admission of inadmissible call. We can also get the channel utilization of DPC-ALP [5] by simply shifting the curve for optimal CAC by $10 \log \delta$ dB leftward, where δ is the increased factor of SIR requirement in DPC-ALP, which takes value greater than 1 [5].

B. Power Control and CAC Schemes

In this section, we simulate the evolution of power and SIR for different algorithms to illustrate that our distributed CAC algorithms can reject infeasible calls without resulting in divergence, and admit feasible calls using optimal power assignment. Since the power control (3) is monotonic and optimal, it is used throughout the simulations. The SIR threshold for each call is

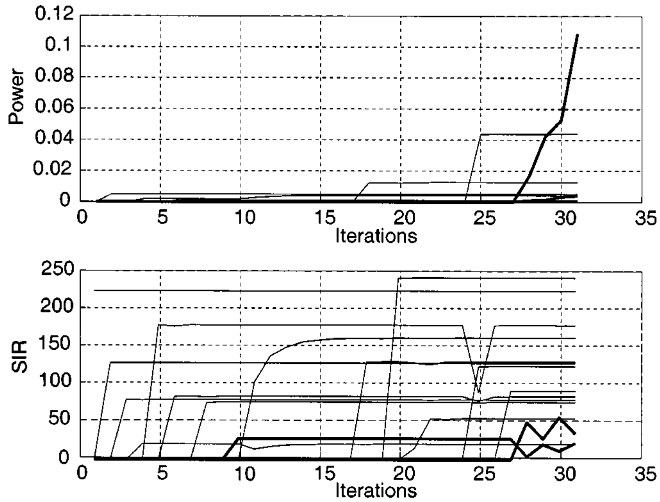

Fig. 7. Power control without CAC (the two thick lines corresponds to the infeasible call and the heavily disturbed call).

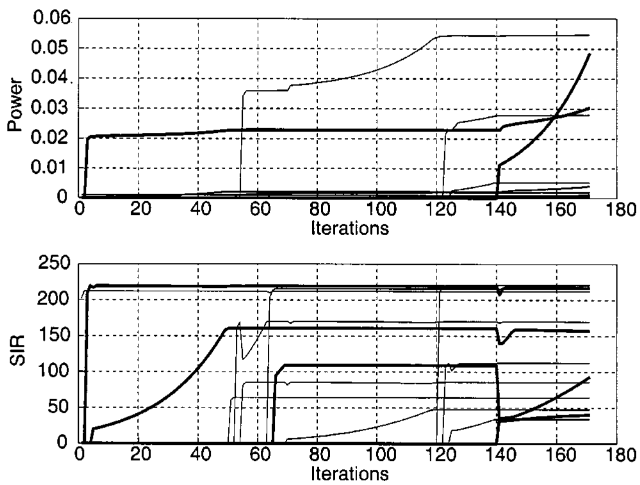

Fig. 8. Evolution of power and SIR under DPC-ALP (the thick lines correspond to the infeasible call and the heavily disturbed calls).

randomly chosen to illustrate that we can deal with heterogeneous QoS requirements. To compare the admission delay of different algorithms, we assume that a new call admission begins right after the existing calls settle down (within 0.05 dB of the required SIRs).

The simulation results of the power control algorithm (3) without CAC are shown in Fig. 7. We can see from the figure that powers of all existing calls will increase during the admission process. Also shown in the figure is the admission delay, which depends on the position and circumstance of the arriving call. In the simulation, 15 calls are admitted within 30 iterations, and the longest admission delay is less than ten iterations. However, when an infeasible call is admitted, the power control algorithm will become unstable. This is shown by the power blow-up and SIR oscillation highlighted in the figure. If we do not reject this call, the SIRs of all existing calls will eventually drop and oscillate while the power levels increase without bound.

Fig. 8 plots the evolution of power and SIR for DPC-ALP with $\delta = 1.05$ [5]. The scheme works well when the system is not congested. However, when the system becomes more unrobust (or infeasible), big disturbance and long admission delays (or divergence) arise, as shown by the highlighted lines in Fig. 8.

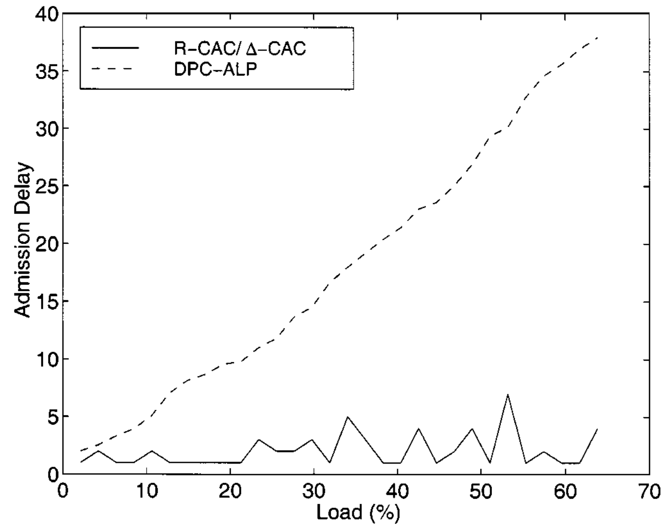

Fig. 9. Average admission delay versus traffic load.

An important performance index of CAC is its correctness, i.e., whether an admissible call is admitted and an inadmissible call is rejected. FCA rejects all inadmissible calls and some admissible calls, so its channel utilization is low. DPC-ALP and RPCAC reject less admissible calls, but at the same time some infeasible calls may slip in and result in divergence. TPCAC does not make a wrong admission decision, but it is not distributed. Our simulations verify the analytic result that Δ-CAC and R-CAC satisfy both conditions of being distributed and rejecting only when necessary.

Another performance index of CAC is the delay until decision. Note that FCA and RPCAC can make immediate admission decisions, so they have no delay in admitting or rejecting an arriving call. We next simulate how long a distributed CAC algorithm takes to admit or reject a call on average. It would be interesting to simulate the delay versus the probability of infeasibility. However, the probability is not easy to obtain, because the feasibility depends on locations, shadowing, and SIR thresholds, etc. We simulate the delay versus the load instead. For each load, 50 distribution patterns are simulated to calculate the average delays. From Fig. 9, the admission delay of DPC-ALP increases rapidly with the traffic load (in term of channel utilization), while that of our Δ-CAC and R-CAC is low and insensitive to the load. Since DPC-ALP may admit infeasible calls and result in divergence, we only compare the delay until rejection for Δ-CAC and R-CAC. Fig. 10 illustrates that R-CAC can reject an infeasible call in approximately one iteration, no matter what the traffic load. However, the delay until rejection (different from the admission delay shown in Fig. 9) for Δ-CAC increases with the traffic load, which agrees with the intuition that a higher traffic load corresponds to a more unrobust system.

VI. Conclusions and Further Work

We have studied the admission control problem for cellular systems under optimal distributed power control. These systems can achieve high spectrum utilization; however, if an infeasible

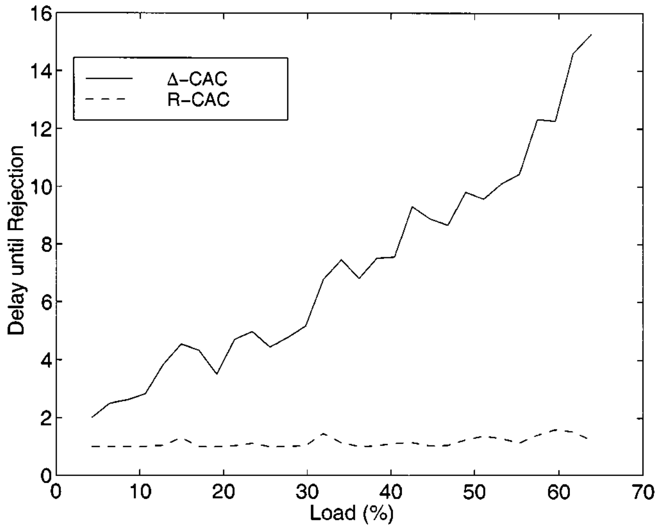

Fig. 10. Average delay until rejection versus traffic load.

call is admitted, the power levels may diverge and result in dropping an existing call.

We defined a system parameter for the newly arrived mobile, called the discriminant, which provides an admissibility criterion. Based on this criterion, we proposed a distributed CAC scheme called Δ-CAC. One disadvantage of Δ-CAC is that it has to wait until the system settles down to make an admission decision. We overcame this limitation, for systems under monotonic and optimal power control, by using a simpler distributed scheme called R-CAC. Both algorithms are distributed, in the sense that they only require locally available information. Our CAC schemes for power-controlled systems are general, because we need not assume any particular multiple access technique, specific power control algorithm, or knowledge about the traffic. In combination with DCA and power control, our CAC schemes can greatly improve the spectrum efficiency over traditional CAC schemes.

We illustrated that the discriminant can be used as a robustness measure for power-controlled systems, and provided distributed ways to improve system robustness. We also extended the CAC algorithm to systems with handoff prioritization and adjustable transmission rates.

In this work, we have not explicitly taken into account user mobility; admissibility here depends only on the path gains at the time of admission. Future work could incorporate mobility models into the CAC criteria. However, our current CAC criteria are still applicable in some mobility situations. First, in certain wireless data services, "burst connections" are set up whenever a burst of data is to be transmitted [21], and the duration of such connections may be short relative to the mobility of users. In this case, the CAC mechanism is used at the initiation of every burst connection, and the effect of mobility can be ignored. Second, in cellular systems with dynamic base station assignment or macrodiversity, the feasibility of a set of users is not strongly dependent on their locations (see [22], [23]). Moreover, we believe that incorporating some robustness margin in our scheme would be an effective way to deal with mobility.

While this work focuses on circuit-switched cellular systems, we are exploring related issues that may arise in packet-switched systems (e.g., maximizing throughput). Finally, another issue needing further investigation is an optimal distributed CAC algorithm for systems with power constraints.

$$
\begin{aligned}
(I_{n+1} - F_{n+1})^{-1} &= \begin{bmatrix} I_n - F_n & -\vec{F}_{\cdot,\, n+1} \\ -\vec{F}^{\mathrm{T}}_{n+1,\cdot} & 1 \end{bmatrix}^{-1} \\
&= \begin{bmatrix} (I_n - F_n)^{-1} + \dfrac{(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}\vec{F}^{\mathrm{T}}_{n+1,\cdot}(I_n - F_n)^{-1}}{\Delta_{n+1}} & \dfrac{(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}}{\Delta_{n+1}} \\ \dfrac{\vec{F}^{\mathrm{T}}_{n+1,\cdot}(I_n - F_n)^{-1}}{\Delta_{n+1}} & \dfrac{1}{\Delta_{n+1}} \end{bmatrix}
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
\begin{bmatrix} P_n^* \\ p_{n+1}^* \end{bmatrix} &= (I_{n+1} - F_{n+1})^{-1} \begin{bmatrix} U_n \\ u_{n+1} \end{bmatrix} \\
&= \begin{bmatrix} (I_n - F_n)^{-1}U_n + \dfrac{(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}\vec{F}^{\mathrm{T}}_{n+1,\cdot}(I_n - F_n)^{-1}}{\Delta_{n+1}} U_n + \dfrac{(I_n - F_n)^{-1}\vec{F}_{\cdot,n+1}}{\Delta_{n+1}} u_{n+1} \\ \dfrac{\vec{F}^{\mathrm{T}}_{n+1,\cdot}(I_n - F_n)^{-1}U_n + u_{n+1}}{\Delta_{n+1}} \end{bmatrix} \\
&= \begin{bmatrix} P^*_{n,\,\mathrm{old}} + (I_n - F_n)^{-1}\vec{F}_{\cdot,\, n+1}p^*_{n+1} \\ \dfrac{\gamma_{n+1}}{G_{n+1,n+1}\Delta_{n+1}} R^{\mathrm{initial}}_{n+1} \end{bmatrix}
\end{aligned} \tag{24}
$$

APPENDIX
PROOF OF THEOREM 2

Proof: We have (23), shown at the bottom of the page. From Corollary 1, we have (24), also at the bottom of the page. Further, by (6), mobile m_{n+1} is admissible if and only if $p^*_{n+1} > 0$ and $P^*_n > \vec{0}_n$, which is equivalent to $\Delta_{n+1} > 0$, since the n existing downlinks are feasible and the matrix $(I_n - F_n)^{-1}$ is componentwise positive. ■

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