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Call Admission Policies Based on Calculated Power Control Setpoints in SIR-Based Power-Controlled DS-CDMA Cellular Networks

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Abstract. In this paper, we develop call admission control algorithms for SIR-based power-controlled DS-CDMA cellular networks. We consider networks that handle both voice and data services. When a new call (or a handoff call) arrives at a base station requesting for admission, our algorithms will calculate the desired power control setpoints for the new call and all existing calls. We will provide necessary and sufficient conditions under which the power control algorithm will have a feasible solution. These conditions are obtained through deriving the inverse of the matrix used in the calculation of power control setpoints. If there is no feasible solution to power control or if the desired power levels to be received at the base station for some calls are larger than the maximum allowable power limits, the admission request will be rejected. Otherwise, the admission request will be granted. When higher priority is desired for handoff calls, we will allow different thresholds (i.e., different maximum allowable power limits) for new calls and handoff calls. We will develop an adaptive algorithm that adjusts these thresholds in real-time as environment changes. The performance of our algorithms will be shown through computer simulation and compared with existing algorithms.

Keywords: call admission control, power control, cellular networks, wireless networks, CDMA

1. Introduction

Call admission control schemes are critical to the success of future generations of wireless networks. On one hand, call admission control schemes provide the users with access to wireless networks for services. On the other hand, they are the decision making part of the network carriers with the objectives of providing services to users with guaranteed quality and at the same time, achieving as high as possible resource utilization. It is therefore conceivable that call admission control policy is one of the critical design parameters in wireless networks [1,5,14,18,19,22,30].

It is known that the reverse link (up link) capacity is limited by the interference received at the base station [7], which is closely related to traffic characteristics, power control, radio propagation, sectorization, and other factors. Power control is essential to minimize each user's interference on the reverse link in varying radio environments and traffic conditions. Earlier studies [7] have considered power control systems that keep each user's signal arriving at the home base station with the same signal power strength. The base station measures the received power level and compares it with a desired value and then transmits power control bit(s) to the mobile units adjusting their power levels. Networks of this type are referred to as strength-based power-controlled CDMA cellular networks. Several researchers have studied call admission control algorithms for strength-based power-controlled CDMA networks [12,14]. On the other hand, researchers have argued that the signal-to-interference ratio (SIR) is more important than signal strength in determining channel characteristics (e.g., bit error probability) [13,26]. SIR-based power control schemes determine the value of the power control bit(s) by comparing the received SIR with the desired SIR threshold. The simulation results of [2] suggest the potential of higher network performance in an SIR-based power-controlled DS-CDMA network for constant bit rate traffic environments. The analysis results of [13] show that the reverse link capacity of SIR-based power-controlled DS-CDMA networks that support ON–OFF traffic is higher than that of the strength-based power-controlled CDMA networks. In [6,23,29], call admission schemes for SIR-based power-controlled DS-CDMA networks have been proposed.

In the present paper, we will develop call admission control algorithms for SIR-based power-controlled DS-CDMA cellular networks that provide both voice and data services [17,22]. The present paper is organized as follows. In section 2, we derive a formula that is used to determine the desired power level (setpoint) for the new call or the handoff call based on the information obtained when it arrives at a base station. We will give necessary and sufficient conditions under which the power control will have a feasible solution. Our results are obtained through deriving the inverse of the matrix used in the calculation of power control setpoints, and thus, our results complement existing results in the literature. In section 3, we present our call admission control algorithms for SIR-based power-controlled DS-CDMA networks. Our call admission control algorithms will be derived from the viewpoint of controlling the SIR levels for all calls at a base station. Our algorithms will be presented in its basic form where the thresholds are fixed and in adaptive form where the

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thresholds are adjusted in real-time as environment changes. Our adaptive call admission control algorithm will adjust automatically the thresholds of received power strength in order to achieve the overall optimal performance. In section 4, we study the performance of the present algorithms through computer simulation and compare with existing call admission control algorithms. The simulation studies will show that the present adaptive call admission control algorithm outperforms existing call admission control algorithms. Finally, in section 5, we conclude the present paper with a few pertinent remarks.

The call admission control schemes in the present paper use the idea of calculating power control setpoints before an admission decision is made. Major benefits of such schemes include admission decision making in a more timely manner when a call is destined to be rejected and the potential of prolonging mobile unit's battery life. In many existing call admission schemes, the decision about admission is made after power adjustment process involving the new caller and all existing mobile units. If the power control algorithm converges to a feasible solution, the new call is automatically accepted. Otherwise, the call will be rejected. When a call is destined to be rejected, in these schemes, there will still be a mobile power adjustment process to determine that the power control algorithm will not reach a feasible solution. Such a process involves not only the new caller but also all existing callers in the system. Therefore, in these existing systems, before a rejection decision is made, precious mobile battery power may have been wasted; while in the present schemes, a rejection decision is made using a software calculation that determines what the power control setpoints will be at the end of the mobile power control adjustment process. The present method for determination of power control setpoints involves only simple calculations and it can easily be implemented.

2. Calculation of power control setpoints

In the DS-CDMA cellular network model used in this paper, we assume that separate frequency bands are used for the reverse link and the forward link, so that the mobile units only experience interference from the base stations and the base stations only experience interference from the mobiles. We consider cellular networks that support both voice and data services. Assume that there are K classes of services provided by the wireless network under consideration, where $K \geqslant 1$ is an integer. We define a mapping $\sigma : Z^+ \to \{1, \ldots, K\}$ to indicate the fact that the nth connection is from the service class $\sigma(n)$, where Z^+ denotes the set of nonnegative integers. We assume that each connection in our network may belong to a different service class that requires a different qualify of service target (e.g., in terms of different bit error rate for each service class). This includes the case when we allow each call to specify its own quality of service requirements. We assume that traffic from the same service class has the same data rate, the same activity factor, the same desired SIR value, and the same maximum power limit that can be received at the base station.

Consider a base station currently with N active connections. The power received at the base station from the user (mobile station) of the nth connection is denoted by S_n, $n = 1, \ldots, N$. In an SIR-based power-controlled DS-CDMA network [2,6,13,23], the desired value of S_n is a function of the number of active home connections and total other cell interference. If we assume that the maximum received power at a base station is limited to H_k for connections from service class $k = \sigma(n)$, then S_n is a random variable in the range of $(0, H_k]$.

In CDMA networks, the bit SIR (or the bit energy-to-interference ratio) for the nth connection at the base station (in a cell) can be expressed in terms of the received powers of the various connections as [7]:

$$\left(\frac{E_b}{N_0}\right)_n = \frac{S_n W}{I_n R_{\sigma(n)}}, \tag{1}$$

where S_n is the power level of the nth connection received at the base station, W is the total spread bandwidth (or the chip rate), and $R_{\sigma(n)}$ is the data rate of service class $\sigma(n)$. I_n in (1) indicates the total interference to the nth connection received at the base station and it is given by

$$I_n = \sum_{i=1, i\neq n}^{N} \nu_{\sigma(i)} S_i + I_n^{\text{other}} + \eta_n, \tag{2}$$

where $\nu_{\sigma(i)}$ is the traffic (e.g., voice) activity factor of the ith connection which is from the service class $\sigma(i)$, I_n^{other} is the total interference from neighboring cells, η_n is the background (or thermal) noise, and N is the number of active connections in the network. In [26–28], it has been shown that the total interference from neighboring cells, I_n^{other}, can be expressed as

$$I_n^{\text{other}} = f \sum_{i=1, i\neq n}^{N} \nu_{\sigma(i)} S_i,$$

where f is called the intercell interference factor with a typical value of 0.55 [26–28]. We can then rewrite (2) as

$$I_n = (1 + f) \sum_{i=1, i\neq n}^{N} \nu_{\sigma(i)} S_i + \eta_n.$$

In the above, the value of f may not always be constant in a system. Its value can be calculated using existing measurements and can be updated periodically to reflect changes in traffic conditions and traffic distributions.

To fully utilize the network capacity, calls must be admitted according to the actual network capacity instead of the fixed capacity. Actual network capacity is limited by the amount of interference allowed in the network. In DS-CDMA cellular networks, interference increases as the traffic load increases. However, interference must be limited to meeting the required E_b/N_0 in the link to satisfy the quality of service constraints. For example, the quality of service requirement for voice users with a maximum bit error rate of 10^{-3} can be satisfied by the power control mechanism keeping E_b/N_0 at a required value of 7 dB or higher [7,14,23]. If more calls than the actual network capacity can accommodate are admitted into the network, the required E_b/N_0 will not be satisfied. Equation (1) implies how network capacity must be limited so that the required E_b/N_0 can be ensured. For SIR-based power-controlled cellular networks, the desired power levels received at a base station will reflect the total interference level in the network coupled with the information about the connection's service class. If the total interference is high, the required power levels will be high, and vice versa. If the required bit error rate is low, the required power levels must be high to ensure the corresponding SIR.

Assume that there are N active calls (connections) in a cell at the time when a new call or handoff call requesting for admission. If this new call request (henceforth, the 0th call) is accepted by the cell, then it will increase the interference to other active calls in the cell. Other active mobiles need to boost their powers to reach the E_b/N_0 requirements. This process continues until a steady state is reached when the requirement $(E_b/N_0)_n \geqslant \gamma_{\sigma(n)}$ is satisfied for all calls, including the new call (i.e., satisfied for $n = 0, 1, \ldots, N$). This implies that at the steady state, we have

$$\frac{S_n W}{R_{\sigma(n)}\gamma_{\sigma(n)}} \geqslant (1+f) \sum_{i=0, i\neq n}^{N} \nu_{\sigma(i)} S_i + \eta_n, \qquad n = 0, 1, \ldots, N. \tag{3}$$

We can rewrite (3) in a matrix format as

$$AS \geqslant b, \tag{4}$$

where $S = [S_0, S_1, \ldots, S_N]^{\mathrm{T}}$,

$$A = \begin{bmatrix} \Delta_0 & -\delta_1 & \ldots & -\delta_N \\ -\delta_0 & \Delta_1 & \ldots & -\delta_N \\ \vdots & \vdots & \ddots & \vdots \\ -\delta_0 & -\delta_1 & \ldots & \Delta_N \end{bmatrix} \tag{5}$$

with $\Delta_i = W/(R_{\sigma(i)}\gamma_{\sigma(i)})$ and $\delta_i = (1+f)\nu_{\sigma(i)}$ for $i = 0, 1, \ldots, N$, and $b = [\eta_0, \eta_1, \ldots, \eta_N]^{\mathrm{T}}$.

The solution of (4) that requires the minimum power while satisfying the SIR constraints $\gamma_{\sigma(n)}$ for every connection is given by

$$S^* = \left[S_0^*, S_1^*, \ldots, S_N^*\right]^{\mathrm{T}} = A^{-1}b, \tag{6}$$

where A^{-1} is the inverse of matrix A. The solution in (6) requires that the matrix A be nonsingular and each element of S^* be positive and be less than the maximum allowed power limit. In this case, we say that the power control algorithm has a feasible solution. We have the following proposition to specify necessary and sufficient conditions under which the matrix A is nonsingular.

Proposition 2.1. The matrix A defined in (5) is nonsingular if and only if

$$\sum_{i=0}^{N} \frac{\delta_i}{\Delta_i + \delta_i} \neq 1. \tag{7}$$

Proof. First we prove that the determinant of matrix A has the following form:

$$\det(A) = \prod_{i=0}^{N}(\Delta_i + \delta_i) - \sum_{i=0}^{N} \delta_i \prod_{j=0, j\neq i}^{N} (\Delta_j + \delta_j). \tag{8}$$

We will prove (8) using mathematical induction. When $N = 1$, we have

$$\begin{aligned} &\det(A_{(1)}) \\ &\quad = \Delta_0\Delta_1 - \delta_0\delta_1 \\ &\quad = (\Delta_0 + \delta_0)(\Delta_1 + \delta_1) - \delta_0(\Delta_1 + \delta_1) - \delta_1(\Delta_0 + \delta_0) \end{aligned}$$

which implies that (8) is true for $N = 1$. Now, we assume that (8) is true for $N = k$, i.e.,

$$\det(A_{(k)}) = \prod_{i=0}^{k}(\Delta_i + \delta_i) - \sum_{i=0}^{k} \delta_i \prod_{j=0, j\neq i}^{k} (\Delta_j + \delta_j).$$

Let $N = k + 1$. The matrix $A_{(k+1)}$ is given by

$$A_{(k+1)} = \begin{bmatrix} \Delta_0 & -\delta_1 & \ldots & -\delta_k & -\delta_{k+1} \\ -\delta_0 & \Delta_1 & \ldots & -\delta_k & -\delta_{k+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ -\delta_0 & -\delta_1 & \ldots & \Delta_k & -\delta_{k+1} \\ -\delta_0 & -\delta_1 & \ldots & -\delta_k & \Delta_{k+1} \end{bmatrix} = \begin{bmatrix} & & & \vdots & -\delta_{k+1} \\ & A_{(k)} & & \vdots & \vdots \\ & & & \vdots & -\delta_{k+1} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ -\delta_0 & \ldots & -\delta_k & \vdots & \Delta_{k+1} \end{bmatrix}.$$

Therefore,

$$\begin{aligned} &\det(A_{(k+1)}) \\ &\quad = \Delta_{k+1}\det(A_{(k)}) + \sum_{i=0}^{k} (-1)^{(k+1+i)}(-\delta_i)|M_{k+1,i}|, \end{aligned}$$

where $|M_{k+1,i}|$ is the minor corresponding to the ith element $-\delta_i$ on the last row of $A_{(k+1)}$. Each minor $|M_{k+1,i}|$ has the following form:

$$\begin{vmatrix} \Delta_0 & -\delta_1 & \ldots & -\delta_{i-1} & -\delta_{i+1} & \ldots & -\delta_k & -\delta_{k+1} \\ -\delta_0 & \Delta_1 & \ldots & -\delta_{i-1} & -\delta_{i+1} & \ldots & -\delta_k & -\delta_{k+1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ldots & \vdots & \vdots \\ -\delta_0 & -\delta_1 & \ldots & \Delta_{i-1} & -\delta_{i+1} & \ldots & -\delta_k & -\delta_{k+1} \\ -\delta_0 & -\delta_1 & \ldots & -\delta_{i-1} & -\delta_{i+1} & \ldots & -\delta_k & -\delta_{k+1} \\ -\delta_0 & -\delta_1 & \ldots & -\delta_{i-1} & \Delta_{i+1} & \ldots & -\delta_k & -\delta_{k+1} \\ \vdots & \vdots & \ldots & \vdots & \vdots & \ddots & \vdots & \vdots \\ -\delta_0 & -\delta_1 & \ldots & -\delta_{i-1} & -\delta_{i+1} & \ldots & \Delta_k & -\delta_{k+1} \end{vmatrix}.$$

Subtracting the ith row from all other rows, we can easily get

$$|M_{k+1,i}| = (-1)^{(i+k)}(-\delta_{k+1}) \prod_{j=0, j\neq i}^{k} (\Delta_j + \delta_j).$$

Thus,

$$\begin{aligned}\det(A_{(k+1)}) &= \Delta_{k+1}\det(A_{(k)}) \\ &\quad + \sum_{i=0}^{k}(-1)^{(2k+2i+1)}(-\delta_i)(-\delta_{k+1}) \\ &\qquad \times \prod_{j=0,j\neq i}^{k}(\Delta_j+\delta_j) \\ &= \Delta_{k+1}\det(A_{(k)}) \\ &\quad - \delta_{k+1}\sum_{i=0}^{k}\delta_i\prod_{j=0,j\neq i}^{k}(\Delta_j+\delta_j) \\ &= \Delta_{k+1}\det(A_{(k)}) - \sum_{i=0}^{k}\delta_i\prod_{j=0,j\neq i}^{k+1}(\Delta_j+\delta_j) \\ &\quad + \Delta_{k+1}\sum_{i=0}^{k}\delta_i\prod_{j=0,j\neq i}^{k}(\Delta_j+\delta_j) \\ &= \Delta_{k+1}\prod_{i=0}^{k}(\Delta_i+\delta_i) - \sum_{i=0}^{k}\delta_i\prod_{j=0,j\neq i}^{k+1}(\Delta_j+\delta_j) \\ &= \prod_{i=0}^{k+1}(\Delta_i+\delta_i) - \sum_{i=0}^{k+1}\delta_i\prod_{j=0,j\neq i}^{k+1}(\Delta_j+\delta_j),\end{aligned}$$

which implies that (8) is true for $N = k+1$, As a result, (8) is true for all $N \geqslant 1$.

Matrix A is singular if and only if $\det(A) = 0$, or

$$\begin{aligned}\det(A) &= \det(A_{(N)}) \\ &= \prod_{i=0}^{N}(\Delta_i+\delta_i) - \sum_{i=0}^{N}\delta_i\prod_{j=0,j\neq i}^{N}(\Delta_j+\delta_j) \\ &= 0\end{aligned}$$

which implies

$$\sum_{i=0}^{N}\delta_i\prod_{j=0,j\neq i}^{N}(\Delta_j+\delta_j) = \prod_{i=0}^{N}(\Delta_i+\delta_i).$$

This is equivalent to

$$\sum_{i=0}^{N}\frac{\delta_i}{\Delta_i+\delta_i} = 1,$$

which completes the proof. □

Remark 2.1. Conditions similar to those in the present proposition 2.1 have been derived in the literature [21,31] under different network environment settings. Our proposition 2.1 complements those results in [21,31] under the network environment settings of the present paper.

The next proposition provides necessary and sufficient conditions for S_i^*, $i = 0, 1, \ldots, N$, to be positive.

Proposition 2.2. Each elements of S^* in (6) is positive if and only if

$$\frac{1}{1-\sum_{i=0}^{N}\delta_i/(\Delta_i+\delta_i)} > -\frac{\min_{0\leqslant i\leqslant N}(\eta_i)}{\sum_{i=0}^{N}\eta_i\delta_i/(\Delta_i+\delta_i)} \tag{9}$$

when condition (7) is satisfied.

Proof. If $\sum_{i=0}^{N}\delta_i/(\Delta_i+\delta_i) \neq 1$, we know that matrix A is nonsingular. Let $A^{-1} = [c_{ij}]$ and $\xi_i = \sum_{j=0}^{N} c_{ij}$, $i = 0, 1, \ldots, N$. Then, from $A^{-1}A = I_{N+1}$, where I_{N+1} is the $(N+1)\times(N+1)$ identity matrix, it follows that,

$$\begin{aligned}0 &= \Delta_0 c_{i0} - \delta_0(\xi_i - c_{i0}), \\ &\vdots \\ 0 &= \Delta_{i-1}c_{i,i-1} - \delta_{i-1}(\xi_i - c_{i,i-1}), \\ 1 &= \Delta_i c_{ii} - \delta_i(\xi_i - c_{ii}), \\ 0 &= \Delta_{i+1}c_{i,i+1} - \delta_{i+1}(\xi_i - c_{i,i+1}), \\ &\vdots \\ 0 &= \Delta_N c_{iN} - \delta_N(\xi_i - c_{iN}).\end{aligned}$$

From these equalities, we get

$$\begin{aligned} c_{ij} &= \frac{\delta_j\xi_i}{\Delta_j+\delta_j}, \quad i\neq j, \quad \text{and} \\ c_{ii} &= \frac{1+\delta_i\xi_i}{\Delta_i+\delta_i}.\end{aligned} \tag{10}$$

Adding these equalities together, we have

$$\xi_i = \frac{1}{\Delta_i+\delta_i} + \xi_i\sum_{j=0}^{N}\frac{\delta_j}{\Delta_j+\delta_j},$$

i.e.,

$$\begin{aligned}\xi_i &= \frac{1}{(\Delta_i+\delta_i)(1-\sum_{j=0}^{N}\delta_j/(\Delta_j+\delta_j))}, \\ & i = 0, 1, 2, \ldots, N.\end{aligned} \tag{11}$$

From (6), we have

$$\begin{aligned} S_i^* &= A^{-1}b \\ &= \sum_{j=0}^{N} c_{ij}\eta_j \\ &= c_{ii}\eta_i + \sum_{j=0,j\neq i}^{N} c_{ij}\eta_j \\ &= \frac{\eta_i(1+\delta_i\xi_i)}{\Delta_i+\delta_i} + \sum_{j=0,j\neq i}^{N}\frac{\eta_j\delta_j\xi_i}{\Delta_j+\delta_j} \\ &= \frac{\eta_i}{\Delta_i+\delta_i} + \xi_i\sum_{j=0}^{N}\frac{\eta_j\delta_j}{\Delta_j+\delta_j}.\end{aligned} \tag{12}$$

Clearly, $S_i^* > 0$ is equivalent to

$$\xi_i > -\frac{\eta_i/(\Delta_i + \delta_i)}{\sum_{j=0}^{N} \eta_j \delta_j/(\Delta_j + \delta_j)}.$$

Combining with (11), we get

$$\frac{1}{1 - \sum_{j=0}^{N} \delta_j/(\delta_j + \Delta_j)} > -\frac{\eta_i}{\sum_{j=0}^{N} \eta_j \delta_j/(\Delta_j + \delta_j)}.$$

For $S_i^* > 0, i = 0, 1, \ldots, N$, it is clear that the solution given in (12) is positive if and only if

$$\frac{1}{1 - \sum_{i=0}^{N} \delta_i/(\Delta_i + \delta_i)} > -\frac{\min_{0 \leqslant i \leqslant N}(\eta_i)}{\sum_{i=0}^{N} \eta_i \delta_i/(\Delta_i + \delta_i)}.$$

This completes the proof. □

Equation (12) gives the componentwise solution to $S^* = A^{-1}b$ in (6). The direct calculation of the inverse of an $n \times n$ matrix would usually be impractical since it involves too much computation when the size of the matrix is large. In the present paper, due to the special structure of matrix A defined in (5), we were able to derive the inverse of the matrix A in an analytical form. We note that the calculation of the power control setpoints given in (12) involves only simple computations and thus it can easily be implemented. We also note that when calculating S^* in (12), we need to know the values of the background noise $\eta_i, i = 0, 1, \ldots, N$. The values of the background noise will be measured periodically and reported to the base station controller using a measurer similar to the power strength measurer used in [23]. Since the background noise changes from time to time, its most recent measurement must be used in (12).

Remark 2.2. If every element of b in (4) has the same value, i.e., if $\eta_i = \eta$ for $i = 0, 1, \ldots, N$, the condition (9) reduces to $\sum_{i=0}^{N} \delta_i/(\Delta_i + \delta_i) < 1$, which has been mentioned by other researchers in [20,21,25,31]. We note that the present propositions 2.1 and 2.2 provide complete proof to the feasibility condition of power control in the CDMA cellular networks studied herein. Equation (10) provides the inverse of matrix A in an analytical form and equation (12) provides power setpoint calculation for each connection.

Remark 2.3. When $K = 1$, i.e., when there is only a single class of service in the system, condition (7) becomes $N + 1 = W/(\nu R \gamma(1 + f))$, which is similar to the condition given in [7].

We will assume the use of a power control algorithm that achieves the power control setpoints calculated in (12). We note that many of the power control algorithms provided in the literature (cf. [1,3,10]) can be used for this purpose. In the next section, we develop call admission control algorithms based on proposition 2.2 and equation (12).

3. Fixed and adaptive call admission control algorithms

In most existing call admission control algorithms involving power control [1,3,6,10,12,14,23], the speed of call admission control decision process depends on the speed of power vector convergence, for only after the power vector is converged, we can make a decision about whether or not to grant the new connection request. In the present algorithms, we do not need to wait for the power vector to converge to make a decision due to the simple calculation in (6) (or (12)). The special form of matrix A in (5) renders a simple analytical solution to its inverse as described in the previous section (cf. (10)). We note that such a calculation can easily be performed in the processor at a base station.

Our main objective in the present paper is to develop an adaptive call admission control algorithm for SIR-based power-controlled DS-CDMA cellular networks. We first introduce a static call admission control algorithm based on power strength measurements. Equations (6) or (12) indicates the minimum power that must be received by the home base station from each mobile station in order to guarantee the minimum SIR given by $\gamma_k, k = 1, \ldots, K$, where K is the total number of service classes. Assuming that the maximum power limit that may be received by a base station is H_k for service class k, $k = 1, \ldots, K$, then we have the following static admission control scheme:

```
If condition (9) is satisfied
  If ($S_n^* \leqslant H_{\sigma(n)}$ for all $n = 0, 1, \ldots, N$), accept the call;
  Otherwise, reject the call;
Otherwise, reject the call.
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This algorithm indicates that when condition (9) is not satisfied, there will be no feasible solution to the power control algorithm and thus the call should be rejected. On the other hand, when $S_n^* > H_{\sigma(n)}$ for some n, we will also reject the call since otherwise either we would require some mobile stations to transmit more power than they can possibly do or the acceptance of the new call will severely damage the quality of service of existing connections, especially those near the cell boundary. The maximum power limits $H_k, k = 1, \ldots, K$, are determined by the power limit of mobile transmitters, the cell size, the path loss information, and the user's service class. They have been used in several previous works on call admission control [7,14,23]. We assume that each connection may belong to a different service class among a total of K service classes. For example, we can choose $H_k = P_k E_k[L]$, $k = 1, \ldots, K$, where P_k is the maximum power that can be transmitted by a mobile in class k and $E_k[L]$ is the expected value of path loss for service class k from the cell boundary to the base station.

The grade of service (*GoS*) in cellular networks is mainly determined by the new call blocking probability and the handoff blocking probability [34]. The first determines the fraction of new calls that are blocked, while the second is closely related to the fraction of admitted calls that terminate prematurely due to dropout. The static algorithm presented above does not give any priority to handoff calls. Dropping a call in progress is generally considered to be more problematic than blocking a new call and needs to be kept under control. Handoff calls are more important than new calls and we need to give priority to handoff calls [9,19,23,24]. The trunk reservation scheme (also called the guard channel scheme) has been extensively studied in the traditional voice-centric cellular networks [9,19,23]. The basic idea is to reserve a fixed number of channels at each base station exclusively for handoff calls. In the present approach, we can choose a fixed threshold $T_k < H_k$, $k = 1, \ldots, K$, for new calls to allow higher priority for handoff calls, where we assume that the new call belongs to a particular service class, i.e., $1 \leqslant \sigma(0) \leqslant K$. Choosing $T_k < H_k$ would usually admit less new calls than the case when $T_k = H_k$. The static threshold admission policy which gives the handoff call higher priority is given as follows:

```
If condition (9) is satisfied
  If (new call) then
    If ($S_0^* \leqslant T_{\sigma(0)}$ and $S_n^* \leqslant H_{\sigma(n)}$ for all $n = 1, 2, \ldots, N$), accept the call;
    Otherwise, reject the call;
  If (handoff call) then
    If ($S_n^* \leqslant H_{\sigma(n)}$ for all $n = 0, 1, \ldots, N$), accept the call;
    Otherwise, reject the call;
Otherwise, reject the call.
```

$T_{\sigma(0)}$ used in the above algorithm is determined according to the service class of the new call. The GoS metrics are strongly influenced by the call admission control algorithm, which determines whether a new call should be admitted or blocked. Blocking more new calls generally improves the forced-termination probability of the calls that are admitted, and thus there is always a tradeoff. Efficient bandwidth allocation schemes have to ensure that the call dropping probability is maintained below a predefined level while at the same time minimizing the new call blocking probability (or maximizing the bandwidth utilization). For a given set of parameters including traffic statistics and mobility characteristics, fixed call admission control schemes can sometimes yield optimal solutions [4,19]. All such schemes (cf. [9,19,23]), however, by reserving a fixed part of capacity, cannot adapt to changes in the network conditions due to its static nature. This is clearly not suitable when the network traffic changes its characteristics over time. Therefore, an adaptive and dynamic call admission control scheme is essential to the operation of call admission control algorithms in modern and future wireless networks [17,33].

It is noted that new call thresholds T_k, $k = 1, \ldots, K$, in the present algorithm are key design parameters which have a tremendous effect on the performance of wireless networks. In our adaptive call admission control algorithm to be introduced next, the thresholds T_k are adjusted adaptively according to the handoff call blocking rate (for calls in the same class), which is a primary measure of traffic load. Such calculations are restricted to each individual base station, thus eliminating the signaling overhead for information exchange among cells. The main idea is as follows [15,32]. When a base station experiences high handoff call blocking rate, we will decrease the corresponding threshold T_k so that handoff calls will be given increasing priority. When a base station maintains the handoff call blocking rate much lower than the threshold over a significant period of time, we can gradually increase the threshold. In doing so, we want to make sure that the handoff call blocking rate is under the maximum allowable level while fully utilizing the network capacity.

We present the following adaptive algorithm for determining automatically the new call threshold T_k to achieve optimal admission control performance:

```
$P_k^h$, $P_k^l$ = thresholds for handoff call blocking probability for class k with $P_k^l < P_k^h$
$P_k^d$ = handoff call blocking rate for class k
$T_k = T_k^{\text{init}} = T_k^M$ for class k (initial value)
$m_k = 0, k = 1, \ldots, K$
While (time increases)
  If (a mobile is handed off to the current cell) then
    Calculate $P_{\sigma(0)}^d$;
    $m_{\sigma(0)} = m_{\sigma(0)} + 1$;
    If (it is blocked) then
      If ($P_{\sigma(0)}^d \geqslant P_{\sigma(0)}^h$) then
        $T_{\sigma(0)} = \max(\alpha_d T_{\sigma(0)}, T_{\sigma(0)}^m)$
        $m_{\sigma(0)} = 0$;
    If ($P_{\sigma(0)}^d \leqslant P_{\sigma(0)}^l$) then
      If ($m_{\sigma(0)} \geqslant M$) then
        $T_{\sigma(0)} = \min(\alpha_u T_{\sigma(0)}, T_{\sigma(0)}^M)$;
        $m_{\sigma(0)} = 0$,
where $\alpha_u > 1$, $\alpha_d < 1$, and $M > 0$ are design parameters and $T_k^m$ and $T_k^M$ denotes the minimum and the maximum thresholds for service class k, $k = 1, \ldots, K$, respectively.
```

In the above algorithm, α_u, α_d, and M may also be chosen differently for different service classes. The admission algorithm will keep a record of the values P_k^l, P_k^h, P_k^d, m_k, and T_k for each service class k, $k = 1, \ldots, K$. This algorithm adjusts the new call threshold $T_{\sigma(0)}$ (for the service class $\sigma(0)$) automatically according to the measured blocking rate of handoff calls in the same service class. It will only decrease the threshold $T_{\sigma(0)}$ when a handoff call is blocked under the condition that $P_{\sigma(0)}^d \geqslant P_{\sigma(0)}^h$, and it will only increase the threshold $T_{\sigma(0)}$ after a number of consecutive handoff calls indicated by the number M under the condition that $P_{\sigma(0)}^d \leqslant P_{\sigma(0)}^l$. It tries to make sure that the handoff call blocking rate is below the given threshold $P_{\sigma(0)}^h$. It also tries to reduce the new call blocking rate by incrementing $T_{\sigma(0)}$ when it is observed that $T_{\sigma(0)}$ is lower than needed.

Remark 3.1. The development of the present adaptive call admission control algorithm involves the following three steps.

1. The first step is the simple static call admission algorithm where the idea of performing call admission con-

trol based on calculated power control setpoints is first used. Such an approach will in general be more favorable than others. This is especially true in the case when a call needs to be rejected. In the present approach, such a rejection decision is made after calculating the power control setpoints. However, in existing call admission control algorithms involving power control, such a decision can only be made until the actual power control process is converged which may lead to improper power level assignments [1,3,10]. Such a process involves the power adjustment of all connections in the cell (and possibly users in the surrounding cells as well) and it takes times and wastes energy (therefore, shortens the battery life of the mobile units). On the other hand, the present approach saves time and does not waste energy for those calls that are destined to be rejected.

2. The second step in the present development is the call admission control algorithm with priorities given to handoff calls. Such an approach has been in general accepted by practitioners and has been employed in actual implementations [9,18,19]. The present algorithm assigns a smaller threshold for new call admission than for handoff call admission to guarantee higher priorities for handoff calls.

3. The third step is the adaptive algorithm that automatically adjusts the threshold values for new calls used in the present call admission control algorithm. The main idea is build upon our previous adaptive guard channel algorithms for call admission control in wireless networks (usually non-CDMA networks) [15,32]. We note that the present algorithm for adjusting threshold values is simple to implement and efficient in applications (see the next section for simulation results).

4. Simulation results

According to the digital European codless telecommunication (DECT) specifications [34], the grade of service (GoS) is defined as

$$GoS = P(\text{new call blocking}) + w \cdot P(\text{handoff failure}),$$

where $P(a)$ is the probability of event a. In the present simulation studies we choose $w = 10$ as in the case of [23]. The arrival rate consists of the new call attempt rate λ_c and the handoff call attempt rate λ_h. λ_c depends on the expected number of subscribers per cell. λ_h depends on such network parameters as traffic load, user velocity, and cell coverage areas [8,9]. In our simulation, we assume that $\lambda_c : \lambda_h = 5 : 1$ [9]. A channel is released by call completion or handoff to a neighboring cell. The channel occupancy time is assumed to be exponentially distributed [8,9,16], with the mean value $1/\mu = 3$ minutes.

We first conduct simulation studies for a network with single class of service (e.g., voice). The network parameters used in the present simulation are taken similarly as the parameters used in [13,23] (cf. table 1). The parameters used in the present adaptive algorithm are listed in table 2. The values of P^l and P^h are chosen such that they give the range of traffic conditions that trigger the parameter adaptation algorithm. T^m and T^M generates an operation region for the adaptation algorithm. A larger value of α_u (increment factor) and a smaller value of α_d (decrement factor) make the algorithm more aggressive, i.e., more responsive to changes in traffic conditions. A smaller value of the parameter M makes the algorithm more sensitive to changes in traffic load conditions.

Table 1
Network parameters.

Parameters	Values	Parameters	Values
W	1.2288 Mcps	R	9.6 kbps
η	$1 \cdot 10^{-14}$ W	H	$1 \cdot 10^{-14}$ W
E_b/N_0	7 dB	v	3/8

Table 2
Simulation parameters.

Parameters	Values	Parameters	Values
α_u	1.1	α_d	0.95
T^m	0	T^M	H
M	3	P^l	$0.9P^h$

In the following, we conduct comparison studies between the present adaptive call admission control algorithm and that of [23]. We then conduct comparison studies between our fixed and adaptive call admission control algorithms. Using the algorithm in [23], the base station controller reads the current interference from the power strength measurer. It then estimates the current interference margin (*CIM*) and handoff interference margin (*HIM*), where $CIM < HIM$. A total interference margin (*TIM*) is set according to the quality of service target. If $CIM > TIM$, reject the call admission request. If $HIM < TIM$, accept the call request. If $CIM < TIM < HIM$, then only handoff calls will be accepted.

Figure 1 compares the present adaptive call admission control algorithm with the algorithm in [23] that reserves 1, 2, 3 channels for handoff calls, respectively. The arrival rate in all neighboring cells is fixed at 6 calls/minute. We assume the use of hexagonal cell structure. The parameter P^h is chosen as 0.001 because of light traffic load. From figure 1, we see that the present algorithm has the best *GoS* when call arrival rate is low in the center cell and very close to the best *GoS* when the arrival rate is high in the center cell. We also see that using the algorithm in [23], when the traffic load changes in the center cell, the values of *GoS* varies differently for different values of *GC* (the number of guard channels). In fact, the algorithm in [23] is a kind of guard channel algorithm used in CDMA systems. Therefore, when the load is low, $GC = 1$ performs the best, and when the load is high, $GC = 3$ performs the best. However, our algorithm can adapt to varying traffic load conditions. It has the best overall performance under various traffic loads. Figure 2 displays the plot of the threshold T for this experiment. The display is for call arrival rate of 18 calls/minute at the center cell. It is clear from

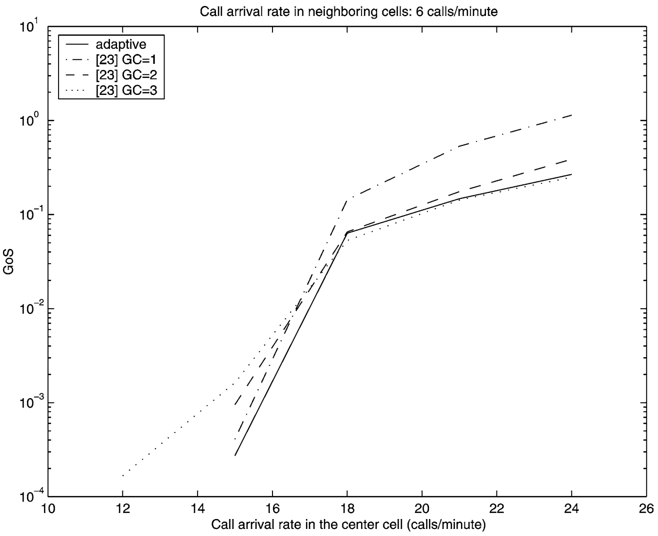

Figure 1. Neighboring cells with low load.

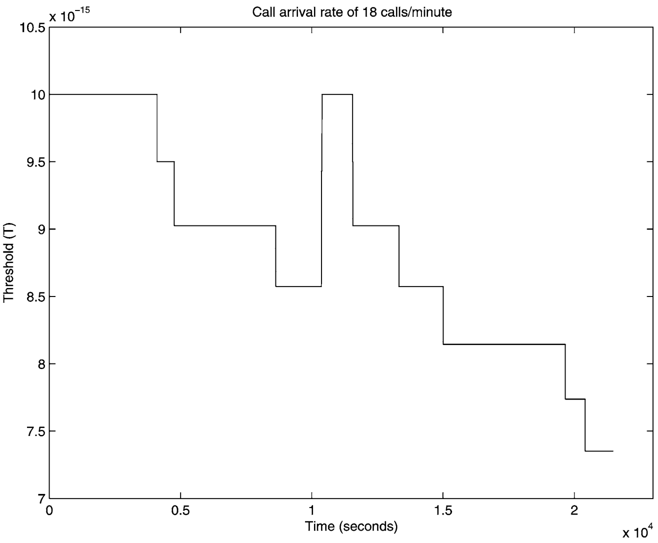

Figure 2. A plot of the threshold T.

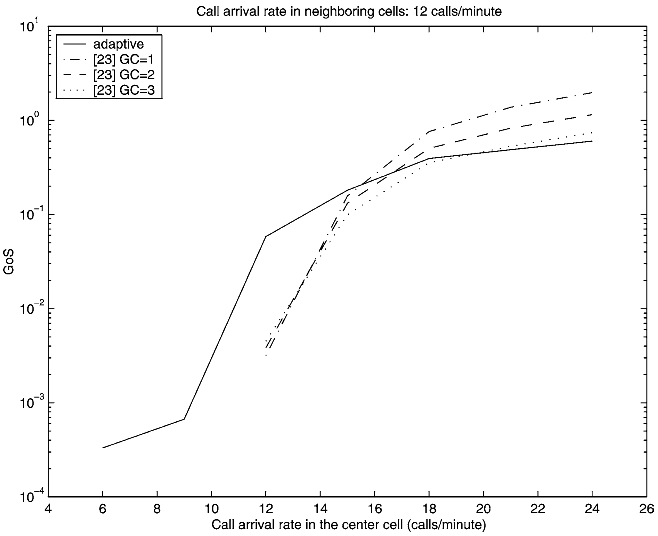

Figure 3. Neighboring cells with normal load.

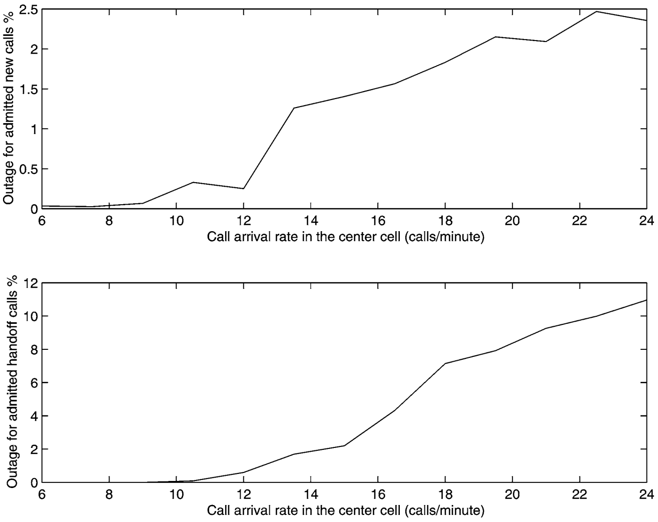

Figure 4. Outage rate of admitted calls.

the display that the value of threshold T changes often during the whole period of simulation. We note that the threshold T changes in the range of $0.75 \cdot 14^{-14}$ W to $1.0 \cdot 10^{-14}$ W which is about 25% of the maximum power H.

Figure 3 compares the present adaptive algorithm with the algorithm in [23] that reserves 1, 2, 3 channels for handoff calls, respectively. In this case we double the arrival rate in neighboring cells to 12 calls/minute. The parameter P^{h} is chosen as 0.01 because of high traffic load. From figure 3 we see that the *GoS* of the present algorithm is higher than that of [23] when the arrival rate is low in the center cell. The reason is that when the interference from neighboring cells is high due to high arrival rate, our calculation for power control setpoints indicates that the signal strength required in the center cell is sometimes higher than the limit H in order to satisfy the voice quality requirement. In this case, more calls are rejected by our algorithm. However, using the algorithm in [23], although the required signal strength is over the limit H, *CIM* and *HIM* are still under *TIM* because of the light traffic condition in the center cell. Thus, using the algorithm in [23], calls are still admitted, and as a result, the quality of service for all calls in the cell will be compromised. For example, there is a new call rejected by our algorithm when the call arrival rate is 10 calls/minute in the center cell. At that moment, the required signal power strength received at the base station is $1.024 \cdot 10^{-14}$ (W) $>$ H, where H is given in table 1 as the highest power strength that may be received at the base station. If we accept that call, we would get the E_b/N_0 equal to 6.94 dB at that moment. Since 6.94 dB is less than 7 dB required by the quality of service constraints, the quality of communication cannot be guaranteed using the algorithm in [23]. Figure 4 shows the actual outage percentage of the admitted new calls and handoff calls using the algorithm in [23] for the same simulation. Here outage means that when a call is admitted, its SIR does not meet the minimum requirement and thus the quality of service will be compromised for all calls in the cell. Note that figure 4 shows the percentage of call outage, not the actual numbers of call outage.

Figure 5 compares between our adaptive call admission control algorithm and our fixed algorithm with static thresholds given by H, $0.8H$, and $0.6H$, respectively. The arrival rate in all neighboring cells is fixed at 12 calls/minute. The parameter P^h is chosen as 0.01 because of high traffic load. From figure 5, we see that the present adaptive algorithm has the best *GoS* for almost all call arrival rates tested. We can conclude that the present adaptive algorithm performs better than the fixed algorithms due to the fact that the adaptive algorithm can adapt to varying traffic load conditions.

Finally, we conduct simulation studies for cellular networks with two classes of services. One class is voice service and the other is data service. We note that similar results can easily be obtained for cases with more than two service classes. Network parameters in our simulations are chosen in reference to the parameters used in [11,20] (cf. table 3). In our simulation, the data traffic is similar to that in [11], i.e., low resolution video or interactive data. In this case, the data traffic can be specified by a constant transmission rate. The background noise in this case is chosen to be the same as in table 1. Figures 6 and 7 compare between our adaptive call admission control algorithm and our fixed algorithm with static thresholds given by H and $0.8H$, respectively. The arrival rates of voice users and data users in all neighboring cells are fixed at 18 calls/minute and 2.4 calls/minute, respectively. For both type of services, the parameters α_u, α_d, M, T^m, and T^M are chosen as in table 2. We choose P^h as 0.1 and 0.03 for voice users and for data users, respectively. Figure 6 shows the results of the *GoS* for voice users in our simulations and figure 7 shows the results of the *GoS* for data users. The simulation results show that the present adaptive call admission control algorithm performs better than the fixed algorithms for networks with two classes of services.

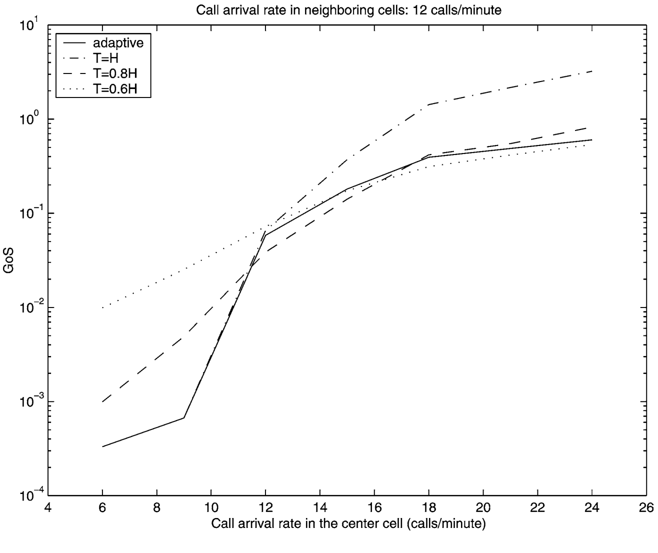

Figure 5. Comparison between our adaptive and fixed call admission control algorithms.

Table 3
Network parameters.

Voice users		Data users	
Parameters	Values	Parameters	Values
W_v	4.9152 Mcps	W_d	4.9152 Mcps
R_v	9.6 kbps	R_d	38.4 kbps
H_v	$1 \cdot 10^{-14}$ W	H_d	$1 \cdot 10^{-13}$ W
$(E_b/N_0)_v$	7 dB	$(E_b/N_0)_d$	9 dB
v_v	3/8	v_d	1

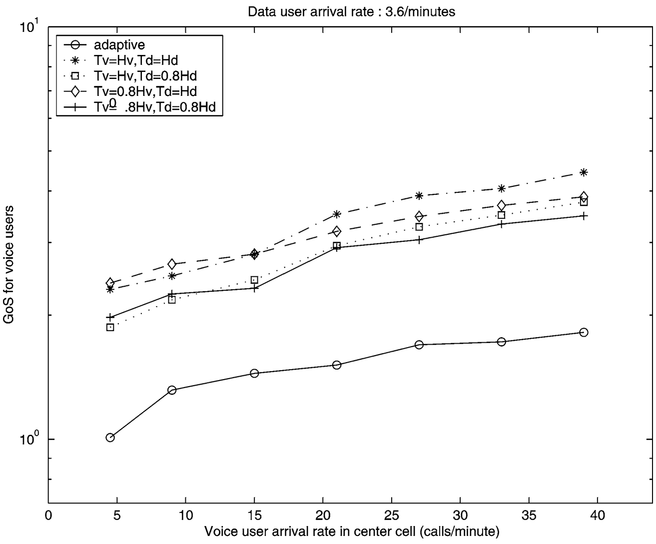

Figure 6. GoS for voice calls.

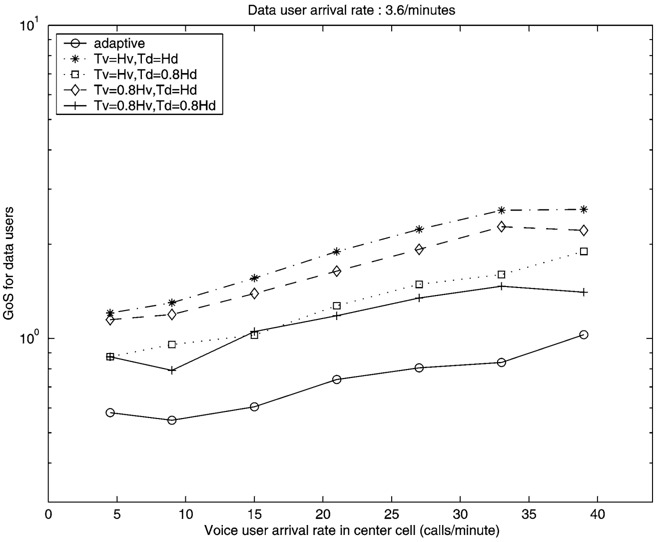

Figure 7. GoS for data users.

5. Conclusions

In this paper, we developed fixed and adaptive call admission control algorithms for multiclass traffic in SIR-based power-controlled DS-CDMA cellular networks. The present algorithms were based on the calculation of required power setpoints for mobile stations to be received at a base station in a cell. We established necessary and sufficient conditions under which the power control algorithm will have a feasible solution. These conditions were obtained through deriving the inverse of the matrix used in the calculation of power control setpoints. If there is no feasible solution to power control algorithm, or if the calculated power setpoints exceed the maximum power that can be generated by a mobile station or exceed the maximum power allowed in the cell, we simply reject the call. To give handoff calls higher priority than new calls, we use smaller thresholds for new calls than that for handoff calls. Our adaptive algorithm can search automatically the optimal thresholds for the power levels of new calls. We note that changes in traffic conditions are inevitable in reality. Thus, fixed call admission control policies are less preferable in applications. Our simulation results show that when traffic load condition changes, fixed admission policy will suffer either from higher new call blocking rate, higher handoff call blocking rate or higher interference than the tolerance.

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