Grade of Service and Quality of Service Provisioning in CDMA Cellular Networks

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Abstract: - In code division multiple access (CDMA) systems, call admission control (CAC) must be designed to guarantee both grade of service (GoS) at the call level and quality of service (QoS) at the packet level. Basically, there are two types of CAC schemes for CDMA systems: number-based CAC (NCAC) and interference-based CAC (ICAC). Unlike some previous studies assuming that handoff arrival rate is independent of the new call arrival rate, the handoff call arrival rate is allowed to depend on the new call arrival rate and other system parameters. Furthermore, the distributions of both cell dwell times and call durations are assumed to be hyper-exponential distributions, which is more bursty than the often-used exponential distribution. To prioritize handoff calls over new calls, guard channels are reserved for handoff calls. The appropriate multi-dimensional Markov chain models and analytical methods are derived to compute the performance measures for the considered CAC schemes. The performance measures of interest are new call blocking probability, handoff failure probability, and weighted cost for GoS, and loss probability of the communication quality for QoS. The effects of the variances of cell dwell time and call duration and guard channels on GoS and QoS are studied.
Key-Words: - CDMA, quality of service, grade of service, guard channels, call admission control

1 Introduction

Code division multiple access (CDMA) has been the core technology for the third-generation mobile communication systems. As is well known, CDMA system is interference-limited. Therefore, in CDMA systems, new users can be accepted as long as the interference level is below some threshold or the signal-to-interference (SIR) is above some threshold, i.e., an acceptable QoS (Quality of Service) for the existing calls can be maintained. Thus, the capacity in a CDMA system is soft capacity, i.e., it depends on the interference level. To ensure a satisfactory link quality, the interference must be limited to be within a preset level, i.e., the number of simultaneous users must be limited. Call admission control (CAC) thus plays a very important role in CDMA systems because it directly controls the number of accepted users and the aggregate interference [1][2]. CAC must be designed to guarantee both grade of service (GoS) at the call level, e.g., the new call blocking probability and handoff failure probability, and quality of service (QoS) at the packet level, e.g., the loss probability for communication quality [3][4]. For CAC in CDMA systems, there are two design issues: 1) setting an appropriate CAC threshold to guarantee both QoS and GoS and 2) maximizing the Erlang capacity of each cell [5].

When a mobile station has moved from the coverage area of a base station into that of a different one, a handoff occurs. Generally speaking, blocking the handoff calls which results in the forced termination of ongoing call is significantly undesirable than blocking the new call attempts. Thus, call admission policies that prioritize handoff calls have been intensively studied [6]. For reducing the probability of forced termination, priority can be given to handoff calls over new calls by reserving a number of channels exclusively for handoffs. The reserved channels are referred to as the guard channels. In this paper, guard channels are used to prioritize handoff calls over new calls.

Traditionally, both cell dwell times and call holding times are assumed to be exponentially distributed. However, a number of recent studies of the traffic in both wired and wireless networks have shown that call durations and cell dwell times are not exponential distributed; rather, they typically behave according to distributions with larger variance and heavier tail than exponential distributions. Hyper-exponential distributions are utilized to approximate call holding time and cell dwell time in [7]. In this paper, both cell dwell time and call holding time are assumed to be hyper-exponentially distributed.

Many mathematical models for CAC in DS/CDMA cellular networks have been proposed. Some of them are based on a pre-determined maximum number if users in the system [8]. This approach, called number-based CAC (NCAC), is simple but may not be adequate, because the CDMA system is interference-limited and each user may result in different interference. Some researchers determine whether to accept a call or not based on the interference; i.e., a call is accepted if the total interference in the system is less than a certain threshold [6]. Those algorithms are called interference-based CAC (ICAC). In [5], NCAC and ICAC are compared and design methods are proposed using expressions for the CAC threshold and the Erlang capacity of the reverse link.

In this paper, the issue of how to design a CAC scheme satisfying both QoS and GoS requirements is studied. This paper is based on [5] with three major differences. First, the effect of multiple cells is studied by allowing the handoff call arrival rate to depend on the new call arrival rate and other system parameters. Second, the effect of guard channels on lowering handoff failure probability and improving GoS is studied. Third, the distributions of both dwell times and call durations are assumed to be hyper-exponential distributions, instead of exponential distribution. Thus, the effect of the variances of cell dwell time and call duration on GoS and QoS is studied. For performance analysis, a 4-dimensional Markov chain model is developed, based on the capacity threshold and the proposed CAC scheme.

This paper is organized as follows. In section 2, the system model is described. Analytical results obtained from mathematical modeling are presented in section 3. Finally, section 4 concludes this paper.

2 System Model

In this section the analytical models for the ICAC and NCAC for CDMA cellular networks are described.

2.1 System Capacity

Each user (voice call) is assumed to require the same data rate R_v bps for communication and the same signal-to-interference-power ratio (SIR). It is also assumed that a voice activity detection mechanism is employed. Each user transmits at probability ρ independently of others, and the user that transmits its data is referred as an active user. The transmit power of each mobile station (MS) is perfectly controlled based on the receiving level at the communicating base station.

Letting $I_{0,req}$ and I_{other} be the maximum tolerable interference and interference from other cells, respectively, the communication quality is satisfied if

$$E_b(k-1)/pg + N_0 + I_{other} \le I_{0,req} \tag{1}$$

where k, E_b, N_0, and pg are the number of active users in the same cell, bit energy, thermal noise power density and processing gain, respectively. In order to investigate communication quality based on queueing theory, I_{other} is transformed into an equivalent number of users m using $m = I_{other}\ pg/E_b$.

Solving the above inequality, the following can be obtained:

$$m + k \le \frac{pg\cdot(1-\eta^{-1})}{E_b / I_{0,req}} + 1 = C_{\max} \tag{2}$$

In this expression, η is defined as $\eta = I_{0,req}/N_0$, which controls the maximum transmit power of the MS's. In this paper, other-cell interference is taken into account via its probability density function (pdf) $p_{\text{int}}(m)$. As an example, for the single-cell case, the maximum acceptable number of active users $C_{\max 0}$ is obtained by letting $m = 0$ in (2). $C_{\max 0}$ represents the maximum acceptable number for the cell when $\rho = 1$. On the other hand, the Erlang capacity of the cell a_0 can be calculated using Erlang's B formula.

2.2 Traffic Model

The call holding time t_c is assumed to be a two-phase hyper-exponential distribution such that

$$f_{t_c}(t) = \alpha_c \mu_{c1} e^{-\mu_{c1}t} + (1-\alpha_c)\mu_{c2} e^{-\mu_{c2}t} \tag{3}$$

The cell dwell time t_d is also assumed to be a two-phase hyper-exponential distribution such that

$$f_{t_d}(t) = \alpha_d \mu_{d1} e^{-\mu_{d1}t} + (1-\alpha_d)\mu_{d2} e^{-\mu_{d2}t} \tag{4}$$

The channel assigned to a call will be held until either the service is completed or the mobile station moves out of the cell before service completion. Specifically, the channel holding time is the minimum of the call holding time and the cell dwell time, i.e., $t_h = \min(t_c, t_d)$. Based on the chosen call holding time and cell dwell time distributions, the users can be classified into four classes where class-ij users have call service arte μ_{ci} and cell dwell rate $\mu_{dj}, i, j = 1,2$. Let n_{ij} denote the number of ongoing class-ij calls. Obviously, the channel holding time for class-ij calls is also exponentially distributed with channel holding rate $\mu_{ij} = \mu_{ci} + \mu_{dj}$.

The call arrival process at the cell is given by the superposition of the arrivals of new calls and handoff calls from neighboring cells. It is assumed that the new (handoff) call arrivals at a cell follow a Poisson process with average call arrival rate $\lambda_c(\lambda_h)$. It is noted that the handoff arrival rate is derived iteratively by equating the handoff rate into a cell to handoff rate out of it.

2.3 NCAC

With NCAC, a cell can be characterized with a 4-dimensional Markov chain. The system state includes four parameters: $n_{11}, n_{12}, n_{21}, n_{22}$, i.e., the numbers of each class of ongoing users. Specifically, let the state vector be $S = (n_{11}, n_{12}, n_{21}, n_{22})$ and $n_{NT} = n_{11} + n_{12} + n_{21} + n_{22}$ Furthermore, the state space, i.e., the set of all feasible states is given by

$$F_{NCAC} = \{(n_{11}, n_{12}, n_{21}, n_{22}) \mid 0 \le n_{11} + n_{12} + n_{21} + n_{22} \le C\} \quad (5)$$

Let P_S be the steady state probability that system is in the state $S = (n_{11}, n_{12}, n_{21}, n_{22})$. Once all the state transition rates are identified, the associated equilibrium state equations can be derived. The equilibrium state probability distribution can be derived iteratively by solving the associated state equations plus the normalization equation.

Next the performance measures of interest are derived. First, the performance measures for GoS at the call level are considered. Based on the NCAC scheme, any new call is blocked if the total number of ongoing calls is greater than or equal to $C - R$. Hence

$$P_{block} = \sum_{n_{NT} \ge C-R} P_S \quad (6)$$

The handoff failure probability P_h is the probability that the total number of ongoing calls is equal to C . Thus,

$$P_h = \sum_{n_{NT} = C} P_S \quad (7)$$

Furthermore, the weighted cost incorporating both new call blocking probability and handoff failure probability is given by

$$C_W = P_{block} + \alpha P_h \quad (8)$$

where α is the parameter showing the relative importance of handoff calls with respect to new calls. Throughout this paper α = 10.

Next, the performance measures for QoS at the packet level are considered. The probability P_k that exactly k calls are active can be expressed as follows.

$$P_k = \sum_{n_{NT} \ge k} b(k; n_{NT}, \rho) P_S \quad (9)$$

where $b(k; n_{NT}, \rho) = \binom{n_{NT}}{k} \rho^k (1-\rho)^{n_{NT}-k}$ is the probability that exactly k out of n_{NT} ongoing calls are active. Therefore, the loss probability of communication quality P_{loss} is given by

$$P_{loss} = \frac{\sum_k k P_k \int_{C_{\max}-k}^{\infty} p_{\text{int}}(m)dm}{\sum_k k P_k} \quad (10)$$

where $p_{\text{int}}(m)$ denotes the probability density function of other-cell interference.

2.4 ICAC

With ICAC, a cell can be characterized with a 4-dimensional Markov chain. The system state includes four parameters: $n_{11}, n_{12}, n_{21}, n_{22}$. Let the state vector be $S = (n_{11}, n_{12}, n_{21}, n_{22})$ and $n_{IT} = n_{11} + n_{12} + n_{21} + n_{22}$. The state space is given by

$$F_{ICAC} = \{(n_{11}, n_{12}, n_{21}, n_{22}) \mid 0 \le n_{11} + n_{12} + n_{21} + n_{22}\} \quad (11)$$

In contrast to the NCAC scheme, this scheme does not limit the number of calls that can be admitted simultaneously, as long as the total interference is below a predetermined threshold so as to keep the QoS of each accepted call at an acceptable level. On the other hand, since forced termination of ongoing calls is less desirable than blocking of new calls, handoff calls are given priority over new calls. Specifically, if the sum of the numbers of new and handoff calls is less than C , then both new calls and handoff calls are admitted to the system if the observed interference is less than T_{block} . Once the sum of the numbers of new and handoff calls is no less than C , only handoff calls are admitted to the system if the observed interference is less than T_{block} . Let $P_I(j)$ be the probability that a call arrival is accepted, i.e., the total interference power is below the interference threshold T_{block} , when j calls already exist. Obviously,

$$p_I(j) = 1 - \sum_{k=0}^{j} b(k; j, \rho) \int_{T_{block}}^{\infty} p_{\text{int}}(m)dm \quad (12)$$

Once all the state transition rates are identified, the associated equilibrium state equations can be derived. Similar to that for NCAC, the equilibrium state probability distribution can be derived iteratively by solving the associated state equations plus the normalization equation.

Based on the ICAC scheme, any new call is blocked if the number of calls exceeds C or the total interference exceeds the predetermined threshold. Thus, the new call blocking probability is given by

$$P_{block} = \sum_{n_{IT} < C} \{1 - P_I(n_{IT})\} \cdot P_S + \sum_{n_{IT} > C} P_S \quad (13)$$

On the other hand, a handoff call is admitted as long as the total interference is below the predetermined threshold. Therefore, the handoff failure probability P_h is given as

$$P_h = \sum_{n_{IT} \in F_{ICAC}} \{1 - P_I(n_{IT})\} \cdot P_S \tag{14}$$

The probability P_k that exactly k users are active is given by

$$P_k = \sum_{n_{IT} \geq k} b(k; n_{IT}, \rho) P_S \tag{15}$$

The weighted cost and the loss probability of communication quality P_{loss} can be calculated in the same way as in NCAC.

2.5 PDF of Other Cell Interference

As mentioned above, the calculations for P_{block} and P_{loss} require a pdf model for $p_{\text{int}}(m)$. It has been shown that the mean and variance of the other-cell interference can be approximated by the same-cell interference multiplied by a constant coefficient f. In this paper, user mobility and thus both P_{block} and P_h are taken into account while applying these approximations. Specifically, other-cell interference is approximated by a gamma distribution as in [5] with mean and variance as follows:

$$E[m] = \rho\left(\frac{\lambda_c(1-P_{block}) + \lambda_h(1-P_h)}{\mu_c + \mu_d}\right) f_1$$

$$\text{var}[m] = \rho\left(\frac{\lambda_c(1-P_{block}) + \lambda_h(1-P_h)}{\mu_c + \mu_d}\right) f_2 \tag{16}$$

where coefficients f_1 and f_2 are determined via simulation to be 0.57 and 0.22, respectively, for a distance attenuation constant α of four and standard deviation for shadowing σ of 8 dB.

3 Numerical Results and Analysis

A homogeneous DS/CDMA system is considered, where each cell is statistically identical. Some of the system and traffic parameters used are shown in Table 1. Due to lack of space, only results for NCAC are presented.

3.1 Burstiness of call holding time and cell dwell time

In order to vary the burstiness or coefficient of variations of both the call holding time and cell dwell time distributions, let $\mu_{c1} = 5 \times 10^{-3} x$, $\alpha_c = \frac{x}{1+x}$, $\mu_{c2} = 5 \times 10^{-3} / x$; and $\mu_{d1} = 5 \times 10^{-3} x$, $\alpha_d = \frac{x}{1+x}$; $\mu_{d2} = 5 \times 10^{-3} / x$. It is noted, as x increases, the burstiness of call holding time and cell dwell time distributions increases. It is worth mentioning that x being equal to 1 implies that the call holding time and cell dwell time are exponentially distributed. Then the effect of x on the performance is studied. Let us focus on NCAC. The performance measures of interest for different CAC threshold C and x with $\lambda_c = 0.1333$ and $R = 0$ are shown in Figs. 1 to 3. As expected, as the CAC threshold C increases, all GoS measures, i.e., new call blocking probability P_{block}, handoff failure probability P_h, and weighted cost C_w, improve but QoS, i.e., loss probability of communication quality P_{loss}, deteriorates. Obviously, a balance must be striked between GoS and QoS while determining the optimal CAC threshold. More interestingly, it is observed that all performance measures of interest deteriorate when x decreases. This is due to the fact that call holding time distributions with large variance produce many short calls and few quite long calls. Long calls undergo blocking with higher probability. Once a long call is blocked, the amount of work provided to users is significantly decreased and it results in a lower system load and thus better both GoS and QoS. For ICAC, similar results are observed.

Table 1 System and traffic parameters

Parameters	Symbol	Value
Transmission bandwidth	W	1.2288Mbps
Data rate	R_v	9.6kbps
Required bit energy to interference power spectral ratio	$E_b / I_{0,req}$	7dB
Processing gain	pg	128
Voice activity factor	ρ	0.4
Interference to noise ratio	η	10dB
Average call holding time	$1/\mu_c$	200sec
Average cell dwell time	$1/\mu_d$	200sec
Maximum acceptable number	$C_{\max}$	24

3.2 Guard channels

The performance measures of interest with different guard channels R under NCAC with x=2 are shown in Figs. 4 to 7, where HE (E) stands for hyper-exponential (exponential) call holding time distributions. As expected, with hyper-exponential call holding time and cell dwell time distributions, increasing the guard channels results in higher new call probability, but lower handoff failure probability and weighted cost. Interestingly, increasing the guard channels results in lower packet loss probability. This is due to the fact that increasing the guard channels increases the new call blocking probability and less calls are admitted into the system and the interference level decreases, and thus the QoS improves. For

ICAC, similar results are observed.

3.3 Maximum allowable new call arrival rate

It is also valuable to determine the maximum allowable new call arrival rate under different CAC schemes while satisfying both GoS and QoS requirements. The GoS and QoS requirements are $P_{block} = 10^{-2}$, $P_h = 10^{-2}$ and $P_{loss} = 10^{-3}$, respectively. The maximum new call arrival rate for different x's are shown in Fig. 8. It is observed that the maximum new call arrival rate increases as x increases for R = 0 or 2. Furthermore, it is observed that the maximum new call arrival rate decreases as guard channel increases.

4 Conclusion

In this paper, two types of CAC schemes for CDMA systems are studied to guarantee both grade of service (GoS) at the call level and quality of service (QoS) at the packet level: number-based CAC (NCAC) and interference-based CAC (ICAC). For both NCAC and ICAC, the issue of how to design a CAC scheme satisfying both QoS and GoS requirements is studied. Unlike some previous studies assuming that handoff arrival rate is independent of the new call arrival rate, the handoff call arrival rate is allowed to depend on the new call arrival rate and other system parameters. The distributions of both cell dwell times and call durations are assumed to be hyper-exponential distributions. Appropriate multi-dimensional Markov chain models and analytical methods are derived to compute the performance measures of interest for the considered CAC schemes. It is shown that both GoS and QoS improve as the burstiness of cell dwell time and call holding time increases. It is also shown that guard channels can lower handoff failure probability and improve weighted cost.

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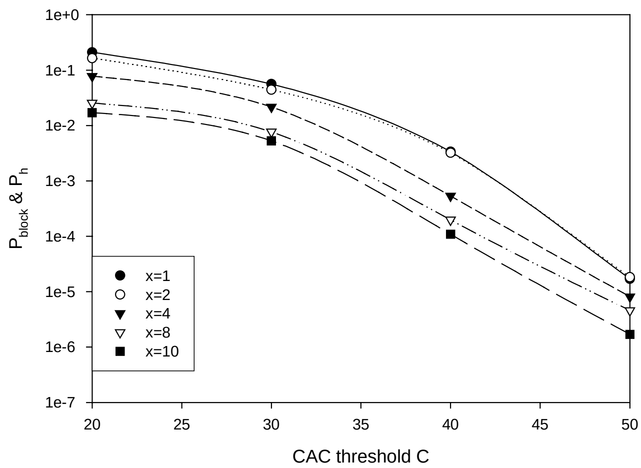

Figure 1: New call blocking and handoff failure prob. vs. CAC threshold and burstiness with NCAC

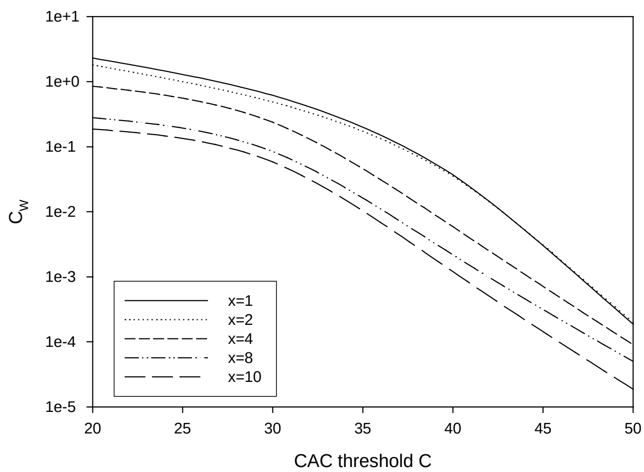

Figure 2: Weighted cost vs. CAC threshold and burstiness with NCAC

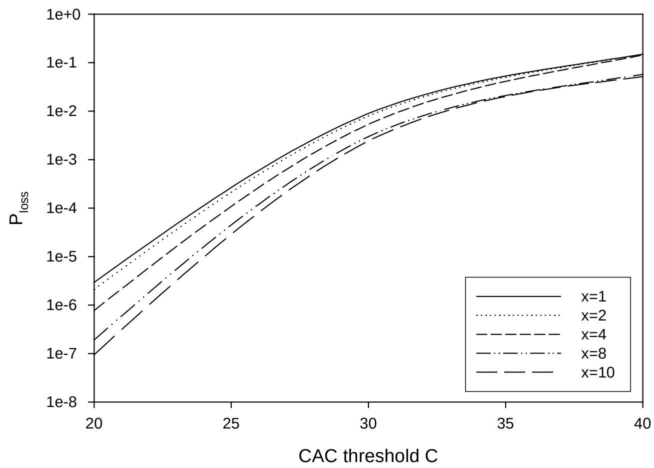

Figure 3: Packet loss prob. vs. CAC threshold and burstiness with NCAC

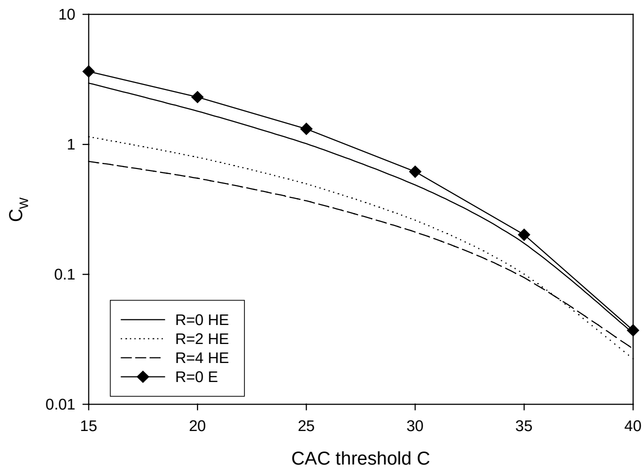

Figure 6: Weighted cost vs. CAC threshold and guard channels with NCAC

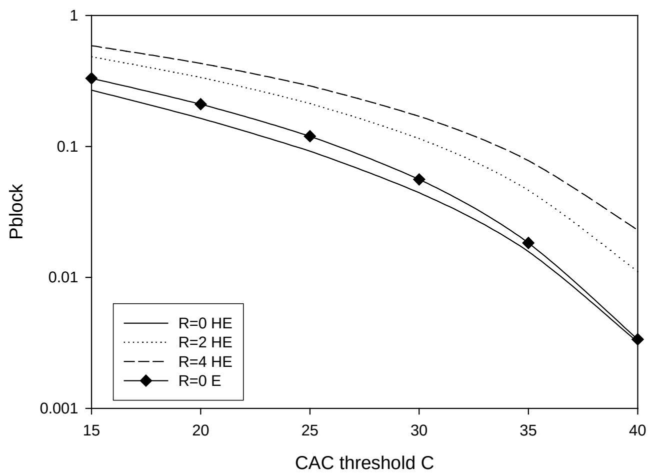

Figure 4: New call blocking prob. vs. CAC threshold and guard channels with NCAC

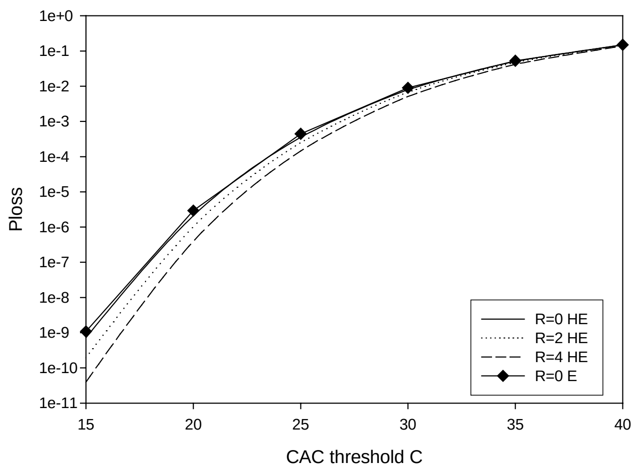

Figure 7: Packet loss probability vs. CAC threshold and guard channels with NCAC

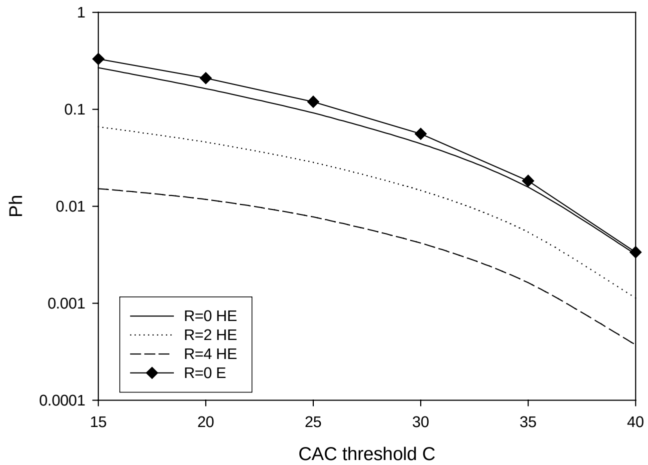

Figure 5: Handoff failure prob. vs. CAC threshold and guard channels with NCAC

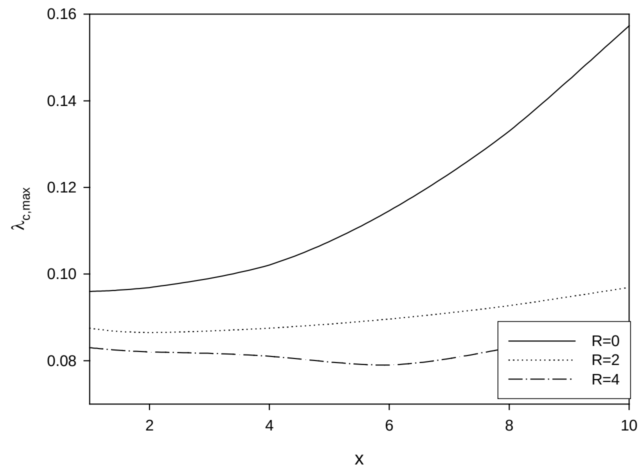

Figure 8: Maximum new call arrival rate vs. x and R with NCAC