Modeling and Performance Analysis for Soft Handoff Schemes in CDMA Cellular Systems

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***Abstract*—This paper investigates the features of a cellular geometry in code-division multiple-access (CDMA) systems with soft handoff and distinguishes controlling area of a cell from coverage area of a cell. Some important characteristics of the cellular configuration in soft handoff systems are used to propose a new design of efficient call admission control (CAC) in CDMA systems. Then, the paper constructs a continuous-time Markov chain (CTMC) model for CAC in CDMA with a soft handoff queue, obtains closed-form solutions, and thus develops loss formulas as performance indices such as the new blocking probability and the handoff dropping probability. In order to determine handoff traffic arrival rate, a fixed-point strategy is developed. Algorithms are also provided to stably compute loss probabilities and to determine the optimal number of guard channels. A new soft handoff scheme—eliminating pseudo handoff calls (EPHC)—is proposed to improve channel utilization efficiency based on mobility information. As an application of the loss formulas, the proposed modeling techniques are used to evaluate and compare the performance of conventional and proposed EPHC soft handoff schemes. Numerical results show the effectiveness of the proposed Markov chain models and the benefits of the new soft handoff scheme.**

***Index Terms*—Analytic modeling, Markov chain, performance, soft handoff.**

I. Introduction

SOFT HANDOFF is an important feature of cellular code-division multiple-access (CDMA) systems, wherein mobile stations (MSs) within a soft handoff region use multiple radio channels and receive their signals from multiple base stations (BSs) simultaneously. Several analytic and simulation models have been proposed for the performance analysis of such systems [2]–[6]. Specifically, combinatorial [15], Markov chain [16], [17], and stochastic reward net [3], [4] models were constructed to evaluate system performance incorporating soft handoff. However, closed-form solutions to the loss probabilities in CDMA cellular systems have yet to be reported. In order to characterize soft handoff in CDMA cellular systems, several cellular coverage mechanisms [7]–[13] were presented to illustrate distributions of BSs and calls. Since the handoff area occupies about 30%–50% of the entire cell area in general CDMA cellular systems, channel shortages may occur, and utilization efficiency of traffic channels may decrease as a soft handoff call may use several channels simultaneously. Some call admission control (CAC) schemes, such as prioritized handoff queueing [8], adaptive channel reservation [6], and parameter optimization [10], have been introduced to cope with these problems.

In order to analyze the performance of CDMA cellular systems with soft handoff, we propose new modeling strategies to evaluate the performance indices of soft handoff schemes. At first, we introduce the concept of relative mobility to divide the handoff area into two separate regions. Then, we develop a corresponding algorithm for relative mobility estimation of MSs in the system. Furthermore, we develop an analytic Markov chain model and derive closed-form solutions for various performance measures. Based on the analytic model and solutions, we also present algorithms to stably compute the loss formulas and determine the optimal number of guard channels. Our model can be seen as a direct extension of the one proposed in [1] for the channel allocation performance of hard handoff in cellular networks. Finally, we use the developed loss formulas to evaluate the performance indices of our new soft handoff scheme and compare them with those of conventional soft handoff schemes.

Analytic models of soft handoff in wireless cellular systems were also proposed in [21] under various circumstances. Note that the objective in [21] was to investigate the major factors determining the performance of soft handoff and compare the performance of soft handoff with that of hard handoff. Therefore, the concepts, such as guard channels, prioritized handoff queueing, and pseudo handoff calls, were intentionally not considered. In this paper, we focus on CDMA cellular systems, where not only hard handoff is difficult to implement but also soft handoff is required by the power control scheme. Without taking hard handoff into account, our proposed analytic models incorporate more features associated with soft handoff. Furthermore, stable computation algorithms are provided.

In Section II, some features of soft handoff in CDMA systems are presented. Then, our view of cellular geometry is described, and the mobility estimation method is illustrated. To obtain performance measures of the scheme, a continuous-time Markov chain (CTMC) model is developed in Section III.

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Consequently, a fixed-point strategy, stable computation of the loss formulas, and optimization problems are discussed. Then, a soft handoff scheme that increases system channel utilization and decreases handoff dropping probability is presented. In Section IV, the performances of the proposed scheme and that of the conventional soft handoff scheme are computed and compared using the loss formulas we developed. Finally, conclusions are made in Section V.

II. Cellular Geometry and Parameter Estimation for Soft Handoff

A. Soft Handoff in CDMA Cellular Systems

In CDMA cellular systems, each MS periodically measures and computes the received signal strength from its surrounding BSs via a pilot channel [22]. The pilot channel is the forward link channel that uses Walsh code to provide phase reference for coherent modulation of a mobile signal. The signal strength of the pilot channel can help a mobile determine which BS has the best link quality. This is the key to achieving optimum performance during the handoff procedure. The pilots identified by the mobile are partitioned into three sets: Neighborhood Set, Candidate Set, and Active Set. Neighborhood Set contains neighbor pilots that are candidates for handoff but are not currently in the Active Set or the Candidate Set. When the power received by the MS from the BS of a cell exceeds a predefined threshold T_{ADD}, the MS sends a pilot strength measurement message (PSMM) to the BS and transfers the pilot from its Neighborhood Set to its Candidate Set. If the MS receives handoff direction message (HDM) from the BS, the detected pilot is transferred from the Candidate Set to the Active Set, which is the set of BSs with which a user is communicating at any given time. Thus, the speech frames will be sent between the mobile switching center (MSC) and the mobile via the BSs in the Active Set. If the power received by the MS from the BS of the current cell decreases to below threshold T_{DROP}, the MS transfers the pilot from the Active Set to the Neighborhood Set and sends a handoff completion message to the BS. A key benefit of soft handoff is that a CDMA system can use path diversity reception, i.e., more than one BS in the Active Set is allowed during the handoff period. Multiple signals from different BSs are combined to improve the signal-to-noise ratio (SNR) and the capacity of the system.

A cell can be divided into two areas: normal area and handoff area. Each cell is assumed to be surrounded by six cells. It should be noted that the soft handoff area is mainly controlled by the handoff thresholds, such as T_{ADD} and T_{DROP}, broadcast by the serving BS. The ratio β of the handoff area to the entire cell area is defined as

$$\beta = \frac{\text{the area of the handoff region}}{\text{the area of the cell}}. \tag{1}$$

The intersection area of two cells is considered the soft handoff area, where all MSs have two channels in their Active Sets (see Fig. 1). For the soft handoff process as defined in the US IS-95, there can be more than two BSs in an Active Set. In this paper, for the purpose of illustration, we assume that there are at most two different sources in diversity reception. When the strength of one pilot in the Active Set is less than T_{DROP}, the corresponding MS will leave the handoff area for normal area after waiting for a short duration.

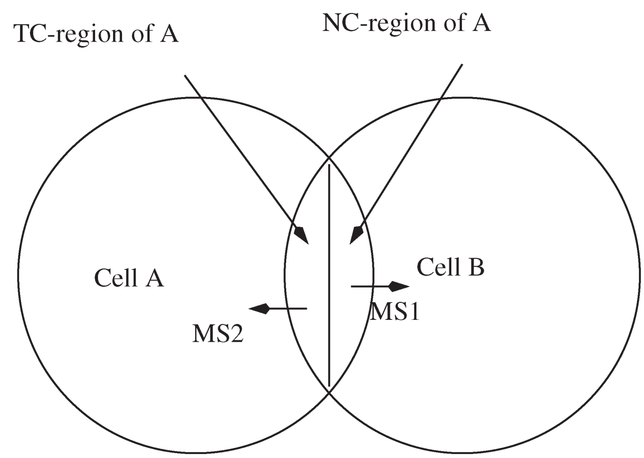

Fig. 1. Cellular system model of soft handoff.

B. Relative Mobility Estimation of MSs in Handoff Area

Accurate geometry of soft handoff in CDMA cellular system is hard to depict due to various factors, such as irregular cell boundaries, traffic conditions, and the movement of mobiles. To simplify the problem, we make the following reasonable assumptions.

1) The cellular system includes a number of cells of identical size and shape, and the coverage area of each cell can be approximated by a circle.
2) Mobiles initiating the calls are uniformly distributed throughout each cell, and one mobile unit may carry at most one call at a time.
3) The cells in the system are symmetrically located and well distributed. Each cell is surrounded by six other cells.
4) An MS in handoff area occupies at most two channels in its Active Set, i.e., there are at most two different sources in diversity reception.

Fig. 2 illustrates an example of regions and boundaries based on the assumption of a circular cell area. We can divide the coverage of a cell into normal area and handoff area. In the soft handoff area, represented by the intersection of target cell and neighborhood cell, each MS holds two channels for transmission in diversity. The handoff area can be further divided into two regions (see Fig. 1): target controlling (TC) region and neighbor controlling (NC) region. In the TC region, the BS of a target cell has stronger power than that of a neighboring cell in Active Sets of MSs. In the NC region, the BS of a neighboring cell has stronger power than that of a target cell in Active Sets of MSs. Basically, since selection diversity is used for uplink interference in CDMA systems, the BS that has a higher receiving power in the Active Set of a call plays an important role in demodulating the received signal.

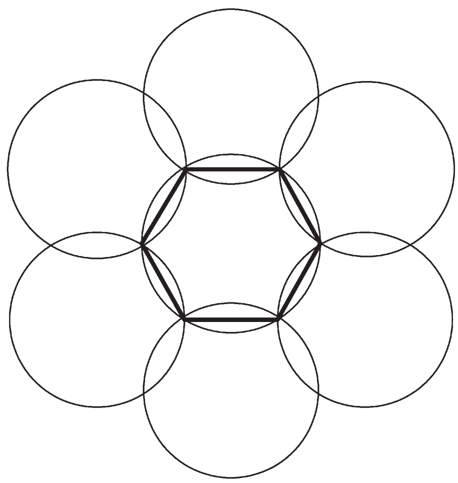

Fig. 2. Cellular structure of soft handoff.

Assume that the received pilot strength from a BS decreases when the MS moves away from the BS and increases when the MS moves toward the BS. An MS in the handoff area can detect pilot strength from the serving BS and current time t broadcast by the sync channel, which is the forward link channel used to transmit some system parameters. A mobile uses this information for time synchronization, which is crucial for the mobile to establish a forward traffic channel with the BS. Let $ps(t, i)$ be the received pilot strength from the serving BS measured at time t by MS i and $cr\_ps(t, i)$ be the rate of change of $ps(t, i)$ given by

$$cr\_ps(t, i) = \frac{ps(t + \Delta t, i) - ps(t, i)}{\Delta t} \qquad (2)$$

where Δt is the time period of information update in the cellular system.

With the pilot strength and the rate of change, MS mobility (in the handoff area) as captured by its relative position, its direction of motion, and its velocity can be estimated. It is reasonable to assume that the BS with stronger pilot strength $ps(t, i)$ in the Active Set of the MS i in the process of handoff should be nearer to the MS than the BS with weaker pilot strength. In addition, the MS undergoing handoff must be moving toward the BS if the rate of change $cr\_ps(t, i)$ detected by the BS is positive. The bigger the value of $cr\_ps(t, i)$ is, the higher the velocity is. If $|cr\_ps(t, i)| < \epsilon$, where ϵ is a suitably chosen small number, the MS is considered to be stationary.

Therefore, the defined cellular areas indicated in Figs. 1 and 2 can be identified by measuring $ps(t, i)$ and $cr\_ps(t, i)$. The coverage area of a cell is determined by checking if the pilot strength ($ps(t, i)$) of the MS in the area is greater than T_{ADD}. The soft handoff area of two cells is determined by judging if two pilot strengths from both the target BS and the neighboring BS are greater than T_{ADD}. In addition, the normal area of a target cell is determined by seeing if the $ps(t, i)$ from the target BS is greater than T_{ADD}, and the pilot strengths from all neighboring BSs are less than T_{DROP}. Furthermore, in the handoff area, the TC and NC regions can be distinguished by comparing the measured pilot strength. Let $ps_T(t, i)$ be the received power at the BS of the target cell of the signal transmitted by an MS in soft handoff area, and let $ps_N(t, i)$ be the received power at the neighboring BS of the signal transmitted by the MS. If $ps_T(t, i) > ps_N(t, i)$, the MS must be in the TC region; if $ps_T(t, i) < ps_N(t, i)$, the MS must be in the NC region.

The structure of the overall algorithm for relative mobility estimation that an MSC would execute in a CDMA system is as follows.

Step 1: Identify the position of handoff calls (with two or more channels in the Active Set)
for (m MSs in the handoff area of the target cell){
  for (q desired values of t){
  Measure pilot strength of MS i at the target BS: $ps_T(t, i)$
  Measure pilot strength of MS i at the neighboring BS: $ps_N(t, i)$
  if
    $ps_T(t, i) > ps_N(t, i)$, the MS belongs to the TC region
  else
    the MS belongs to the NC region
  }
}
Step 2: Evaluate the mobility of handoff calls
for (m MSs in the handoff area of the target cell){
  for (q desired values of t) {
  Measure the pilot strength of each call or MS i at the target BS: $ps_T(t, i)$
  Compute $cr\_ps(t, i)$
  if
    $|cr\_ps(t, i)| < \epsilon$, the MS is considered stationary
  if
    $cr\_ps(t, i) > 0$, the MS is considered moving toward the target BS
  elseif
    the MS is considered moving away from the target BS
  }
}

For instance, as shown in Fig. 1, both MS1 and MS2 have two channels in their Active Sets, which means that the pilot strengths the MSs received from both cells A and B are greater than T_{ADD}. But BS B is controlling (noncontrolling) BS for MS1 (MS2), and is noncontrolling (controlling) BS for MS2 (MS1). Besides, with respect to cell A, $cr\_ps(t, i) < 0$ for MS1 and $cr\_ps(t, i) > 0$ for MS2.

Due to the unique fading characteristics of a wireless channel, our proposed mobility estimation needs significant refinement if implemented in any commercial systems. Multiple samples of the received pilot signal strength may be used to obtain one value of $ps(t, i)$. The measurement results may be shared among different BSs to further improve estimation accuracy. Although the new soft handoff scheme proposed in the following sections is based upon user mobility information, the discussion of effective and reliable mobility estimation is out of the scope of this paper.

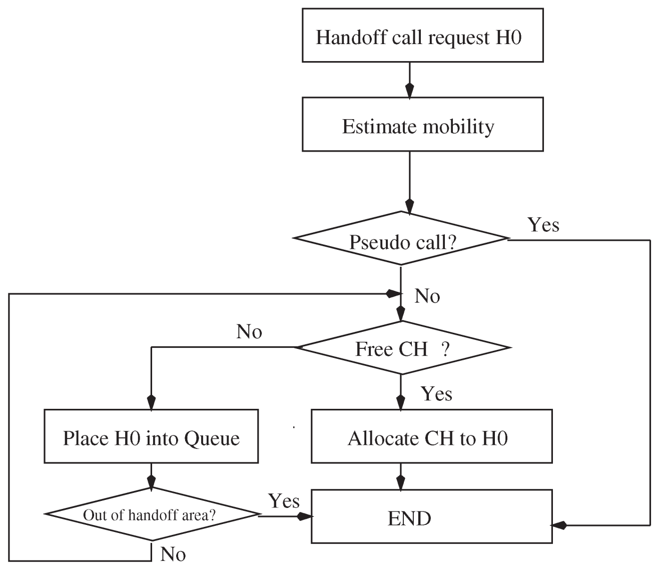

Fig. 3. Flowchart of EPHC soft handoff scheme.

C. Eliminating Pseudo Handoff Calls (EPHC) Soft Handoff Scheme

According to the features of soft handoff in a CDMA cellular system, a request for soft handoff to a cell occurs in the following two situations. The first case occurs when an MS that is an active call moves to the soft handoff area from the normal area of a neighboring cell. This will cause the MS to generate a request for a channel from the target BS. The second case occurs when a new call originating in the NC region of the soft handoff area is accepted by a neighboring BS. Then, this MS requests a channel from the target BS immediately after it is accepted as a new call by the neighboring BS. This is due to the fact that the received pilot strengths from both BSs are greater than T_{ADD}.

With respect to cell A in Fig. 1, an MS in the NC region of soft handoff area moving away from cell A, satisfying $cr\_ps(t,i) < 0$, does not need to be handed over to cell A although it is in the handoff area. In addition, the MS in the NC region of cell A satisfying $|cr\_ps(t,i)| < \epsilon$ does not need to be handed over to cell A either.

New calls in the NC region of the handoff area in the target cell that satisfy $cr\_ps(t,i) < 0$ or $|cr\_ps(t,i)| < \epsilon$ are defined as pseudo handoff calls of the target cell. Otherwise, the calls are called real handoff calls.

In order to improve the efficiency of channel assignment and the performance of soft handoff in a system, we propose a soft handoff scheme of EPHC, as described by the flowchart in Fig. 3. When a handoff request arrives, its mobility is measured first. A pseudo handoff call is ignored while a real handoff call is assigned a channel if a free channel is available. The real handoff call is placed into a queue waiting for a free channel if there is no free channel currently available. The call will be refused if the queue is full. However, the refused handoff call is not necessarily dropped. The handoff calls in or out of the handoff queue would be dropped only if the calls still fail to get channels from the target cell after moving from the handoff area into the normal area.

When our new soft handoff scheme is implemented in the current IS-95/CDMA2000 systems, the quality of voice and the total interference in the system are not significantly influenced. Since selection diversity is used for uplink interference in CDMA systems, controlling BSs have higher received power from the MS than noncontrolling BSs and thus demodulate the signal. On the other hand, the transmitting power of pseudo handoff calls, without the noncontrolling channels in its Active Set, will remain almost the same. Furthermore, the new scheme may not require hardware changes in relevant system components such as MSC, BS, and MS, although some software updates may be needed. Since computation overhead is quite low in our scheme, the performance improvement may well outweigh the cost of implementing our algorithm into CDMA systems.

III. Analytic Model

In Section III-A, we develop the CTMC for soft handoff schemes. Performance indices are defined and closed-form expressions are derived in Section III-B. In Section III-C, we introduce fixed-point iteration to determine the handoff arrival rate.

A. Markov Chain Model for Soft Handoff With a Handoff Queue

Under the condition that all neighboring cells are statistically identical and behave independently, we consider the performance model of a single cell in a CDMA cellular system. There are two kinds of calls entering a cell: new calls and handoff calls. Both call arrivals in a cell are assumed to be Poissonian with rates λ_n and λ_h, respectively. Notice that new call arrivals can only happen in the controlling (hexagonal) area of the target cell. There is a limited number of channels N in the channel pool of the cell. Each cell will reserve g channels out of the total available channels for handoff calls since dropping handoff calls is considered less desirable than blocking a new call. When a new call arrives, it is accepted if there are more than g idle channels available; otherwise, the new call is blocked. Every handoff requirement is assumed to be perfectly detected in our model and the assignment of the channel is instantaneous if it is available. A handoff queue is used for the situation in which a handoff call arrives when there are no idle channels available. The maximum handoff queue length is l_e. Also, we assume that the channel holding time T_c and the mean dwell time T_{dc} in the whole covering area of a cell follow exponential distributions with means μ_c^{-1} and μ_{dc}^{-1}, respectively. Besides, a call with a handoff request queued is forced to terminate if the call moves out of the radio coverage area of the neighboring cell. The corresponding dwell time distribution is assumed to be exponential with mean μ_l^{-1}.

Given our assumptions, the underlying model is a homogeneous CTMC of the birth–death type. Let $C(t)$ states of the CTMC denote the number of busy channels of a target cell plus the number of mobiles in the handoff queue at time t. The state diagram of the birth–death Markov chain is shown in Fig. 4.

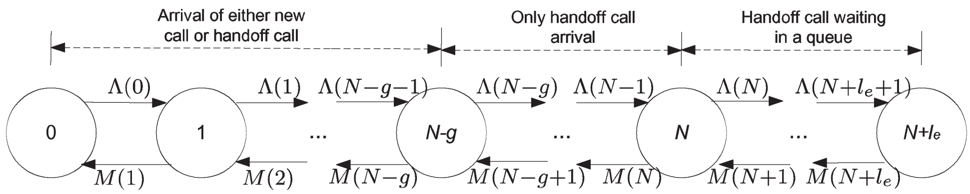

Fig. 4. Markov chain model of CDMA handoff scheme.

The birth and death rates are state dependent. Since a new call will be blocked if the number of busy channels is greater than $N-g$, the birth rate of the CTMC is

$$\Lambda(n)=\begin{cases}\lambda_{1c}+\lambda_h, & \text{if } n<N-g\\ \lambda_h, & \text{if } N-g\le n<N+l_e\end{cases} \tag{3}$$

where $\lambda_{1c}=\lambda_n(1-\beta/2)+\lambda_n(\beta/2)P_b$, β is the ratio of the NC region of the target cell, and P_b is the new call blocking probability of the cell, which will be computed later. We can see that new calls in the target cell can be divided into two parts: ones from the normal area plus TC region of the cell, and the others from the NC region of the cell if new call request is refused by the neighboring cell BSs.

The death rates of the CTMC $M(n)$ are

$$M(n)=\begin{cases}n(\mu_c+\mu_{dc}), & \text{if } n\le N\\ N(\mu_c+\mu_{dc}) \\ \quad+(n-N)(\mu_c+\mu_l), & \text{if } N<n\le N+l_e.\end{cases} \tag{4}$$

When the number of busy channels $C(t)$ is less than or equal to N, no call has to wait in the handoff queue. Channels are released mainly due to call completion and call departures from the target cell. When the number of available channels $C(t)$ is greater than N and less than $N+l_e$, N channels have been allocated, and some calls have to wait in the handoff queue. In this case, some calls in the queue would not get channels from the target cell until the calls move out of the radio coverage of the neighboring cell and are dropped.

Define the steady-state probability as

$$p_n=\lim_{t\longrightarrow\infty}\Pr\left(C(t)=n\right),\quad n=0,1,\ldots,N+l_e.$$

We define $A=(\lambda_{1c}+\lambda_h)/(\mu_c+\mu_{dc})$, $A_1=\lambda_h/(\lambda_{1c}+\lambda_h)$, and $A_2=(\mu_c+\mu_l)/(\mu_c+\mu_{dc})$. Solving the CTMC, we have

$$p_n=p_0\begin{cases}\frac{A^n}{n!}, & \text{if } n<N-g\\ \frac{A^n}{n!}A_1^{n-(N-g)}, & \text{if } N-g\le n\le N\\ \frac{A^n}{\left(N!\prod_{j=1}^{n-N}(N+jA_2)\right)}A_1^{n-(N-g)}, & \text{if } N<n\le N+l_e\end{cases}. \tag{5}$$

Clearly, $\sum_{n=0}^{N+l_e}p_n=1$. Thus, an expression for p_0 is obtained as

$$p_0=\left[\sum_{n=0}^{N-g-1}\frac{A^n}{n!}+\sum_{n=N-g}^{N}\frac{A^n}{n!}A_1^{n-(N-g)}\right.$$
$$\left.+\sum_{n=N+1}^{N+l_e}\frac{A^n}{\left(N!\prod_{j=1}^{n-N}(N+jA_2)\right)}A_1^{n-(N-g)}\right]^{-1}. \tag{6}$$

B. Performance Indices

1) Blocking Probability: We denote the blocking probability from the cell's point of view as $P_b(N,g,l_e)$ and the blocking probability from the system's point of view as P_{BS}. The expressions for the blocking probabilities of new calls are

$$P_b(N,g,l_e)=\sum_{n=N-g}^{N+l_e}p_n \tag{7}$$

and

$$P_{\mathrm{BS}}=\beta P_bP_b+(1-\beta)P_b. \tag{8}$$

In the soft handoff area, if a new call is blocked at one cell, it still has a chance in another cell. That is the reason why P_b is used twice in the above equation for system blocking probability.

2) Handoff Dropping Probability: Let P_{ds} denote the handoff dropping probability for the EPHC handoff scheme and the conventional handoff scheme from the system's point of view and is given by

$$P_{ds}(N,g,l_e)=p_{N+l_e}+\sum_{n=N+1}^{N+l_e}(n-N)\mu_l\frac{p_n}{\lambda_h}. \tag{9}$$

An incoming handoff call will be dropped under two situations: 1) The handoff queue is full (and surely no channel is available) when a mobile submits a handoff call request, which is represented by the first term of (9), or 2) the mobile with a handoff request queued moves out of the radio coverage of the neighboring cell before being allocated a channel by the BS of the target cell, which is represented by the second term of (9).

C. Fixed-Point Iteration

Note that the Markov chain in Fig. 4 fits both the conventional soft handoff scheme and our EPHC handoff scheme. The primary difference between the two schemes is that our proposed scheme distinguishes real handoff calls from all pseudo handoff calls.

In practice, the incoming handoff request rate λ_h and the real new call arrival rate λ_{1c} are unknown parameters. It is evident that $\lambda_{1c} = (1-\beta/2)\lambda_n + \lambda_n(\beta/2)P_b \approx (1-\beta/2)\lambda_n$, since the blocking probability P_b in steady state is expected to be rather small. As we have assumed that all cells are statistically identical, the following balance should be satisfied in equilibrium.

For conventional soft handoff scheme

$$\lambda_h = \mu_{dc}\sum_{n=1}^{N} np_n + \mu_{dc}\sum_{n=N+1}^{N+l_e} Np_n + \lambda_n\frac{\beta}{2}(1-P_b). \quad (10)$$

According to the intrinsic characteristics of soft handoff described before, the rate of soft handoff should include two terms: 1) the rate at which calls arrive into the target cell from a neighboring cell, which equals the throughput of outgoing calls from the target cell, and 2) the rate at which calls in the NC region of the target cell request soft handoff immediately after their new call requests are accepted by a neighboring cell BS. It equals the rate at which calls in the TC region of the target cell request soft handoff over a neighboring cell immediately after their new call requests are accepted by the target cell BS.

Similarly, for EPHC handoff scheme

$$\lambda_h = \mu_{dc}\sum_{n=1}^{N} np_n + \mu_{dc}\sum_{n=N+1}^{N+l_e} Np_n + \frac{1}{3}\lambda_n\frac{\beta}{2}(1-P_b). \quad (11)$$

Equation (11) is the same as (10) except that the second term is multiplied by one third. The reason is that in EPHC handoff some pseudo handoff calls are ignored. Here, we assume that the ratio of pseudo handoff calls (including new calls in the NC region of the target cell moving toward neighboring and being stationary) to new calls in the NC region is two thirds [4].

Let $T(x)$ denote handoff-out rate for a given handoff-in rate $\lambda_h = x$ when the other parameters are fixed. In Appendix A, we show that for a conventional soft handoff scheme

$$T(x) = \left(\frac{\mu_{dc}}{\mu} - \frac{\mu_{dc}\beta}{2\mu} + \frac{\beta}{2}\right)\lambda_n\left(1-P_b(x)\right) + x\frac{\mu_{dc}}{\mu}\left(1-P_F(x)-P_N(x)\right) + 2N\mu_{dc}P_F(x) \quad (12)$$

where $\mu = \mu_{dc} + \mu_c$, $P_F(x) = \sum_{n=N+1}^{N+l_e} p_n$ is the probability that the target cell is overloaded but the handoff queue is not full, and $P_N(x) = p_N$. If we consider $x = T(x)$, we get

$$x = \frac{(2\mu_{dc} - \mu_{dc}\beta + \beta\mu)\lambda_n\left(1-P_b(x)\right) + 2N\mu_{dc}P_F(x)}{2\mu - 2\mu_{dc}\left(1-P_F(x)-P_N(x)\right)}. \quad (13)$$

For the EPHC handoff scheme, in the same way, we get

$$x = \frac{(6\mu_{dc} - 3\mu_{dc}\beta + \beta\mu)\lambda_n\left(1-P_b(x)\right) + 2N\mu_{dc}P_F(x)}{6\mu - 6\mu_{dc}\left(1-P_F(x)-P_N(x)\right)}. \quad (14)$$

The fixed-point iteration algorithm we use to solve the Markov chain is shown as follows:

C: The fixed-point iteration
Initialization $\lambda_h^{(0)}$
$\lambda_h^{(1)} \longleftarrow \lambda_h^{(0)}$
repeat{
solve the CTMC in Fig. 4
Compute $\lambda_h^{(i+1)}$ according to (11) or (12)
$\delta \longleftarrow |\lambda_h^{(i+1)} - \lambda_h^{(i)}|/\lambda_h^{(i)}$;
until $\delta < \epsilon$;
}

D. Computational Aspects and Optimization Problems

To avoid possible computational overflow and underflow due to the direct use of (7) and (9) when the number of channels N is large, we also develop recursive methods for numerically stable computations of the loss probabilities. Let

$$E_B(A,N) = \frac{\frac{A^N}{N!}}{1 + A + \frac{A^2}{2!} + \cdots + \frac{A^N}{N!}} \quad (15)$$

be the well-known Erlang-B formula.

Given fixed N, g, A, and A_1 [1], loss formulas in a time-division multiple-access (TDMA)-type wireless cellular network with hard handoff are given as

$$P_d^L(N,g) = \frac{\frac{A^N}{N!}A_1^g}{\sum_{n=0}^{N-g-1}\frac{A^n}{n!} + \sum_{n=N-g}^{N}\frac{A^n}{n!}A_1^{n-(N-g)}} \quad (16)$$

$$P_b^L(N,g) = \frac{\sum_{n=N-g}^{N}\frac{A^n}{n!}A_1^{n-(N-g)}}{\sum_{n=0}^{N-g-1}\frac{A^n}{n!} + \sum_{n=N-g}^{N}\frac{A^n}{n!}A_1^{n-(N-g)}}. \quad (17)$$

Then, we can show that

$$P_b(N,0,0) = E_B(A,N) = P_b^L(N,0)$$

$$P_b(N,g,0) = P_b^L(N,g).$$

As recommended in [20], a much better recursion for computation of the Erlang-B formula is

$$E_B(A,k) = \frac{\frac{A}{k}E_B(A,k-1)}{1 + \frac{A}{k}E_B(A,k-1)}, \quad k = 1,2,\ldots,N \quad (18)$$

with $E_B(A,0) = 1.0$. Then, the loss formulas in a TDMA-type wireless network with hard handoff can be recursively computed [1].

Let $N_1 = N - g,\ P_d^L(N_1, 0) = E_B(A, N_1)$, then

$$P_d^L(N_1 + k, k) = \frac{P_d^L\left(N_1 + (k-1), k-1\right)}{\frac{N}{A_1} + P_d^L\left(N_1 + (k-1), k-1\right)} \qquad k = 1, 2, \ldots, g. \quad (19)$$

Similarly, let $P_d^L(N_1, 0) = E_B(A, N_1)$ and compute

$$P_b^L(N_1+k, k) = \frac{\frac{N}{A_1} P_b^L\left(N_1+(k-1), k-1\right) + P_d^L\left(N_1+(k-1), k-1\right)}{\frac{N}{A_1} + P_d^L\left(N_1+(k-1), k-1\right)} \qquad k=1, 2, \ldots, g. \quad (20)$$

Therefore, the blocking and dropping probabilities in (7) and (9) can be stably computed after recursive computation of $P_d^L(N, g)$ and $P_b^L(N, g)$ (for a proof, see Appendixes B and C) as

$$P_b(N, g, l_e) = \frac{(1 + G_1) P_b^L(N, g)}{1 + G_1 P_b^L(N, g)} \quad (21)$$

$$P_{ds}(N, g, l_e) = \frac{G_2 P_b^L(N, g)}{1 + G_1 P_b^L(N, g)} + \frac{\mu_l}{\lambda_h} \frac{G_3 P_b^L(N, g)}{1 + P_b^L(N, g) G_1} \quad (22)$$

where

$$G_1 = \frac{\sum_{n=1}^{l_e} \frac{\left(\frac{\lambda_h}{\mu}\right)^{n+g}}{\prod_{j=1}^{n}(N+jA_2)}}{\sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^n \prod_{j=1}^{g-n}(N - j + 1)} \quad (23)$$

$$G_2 = \frac{\left(\frac{\lambda_h}{\mu}\right)^{l_e+g}}{\prod_{j=1}^{l_e}(N+jA_2) \sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^n \prod_{j=1}^{g-n}(N-j+1)} \quad (24)$$

$$G_3 = \frac{\sum_{n=1}^{l_e} \frac{n\left(\frac{\lambda_h}{\mu}\right)^{n+g}}{\prod_{j=1}^{n}(N+jA_2)}}{\sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^n \prod_{j=1}^{g-n}(N - j + 1)}. \quad (25)$$

Since g and l_e are of small value (normally less than 5), it is easily seen that overflow and underflow do not occur during computations of G_1, G_2, and G_3. Equations (19)–(22) can be easily programmed in a simple loop.

In addition, we also give a solution to the following optimization problem.

O: Given A, A_1, and N, determine the optimal integer value of g so as to minimize $P_b(g)$ such that $P_{ds}(g) \leq P_{d0}$.

First, we prove that the dropping probability $P_{ds}(N, g, l_e)$ is a decreasing function of g for fixed N and l_e (for a proof, see Appendix D), i.e., $P_{ds}(N, g, l_e) < P_{ds}(N, g-1, l_e)$, so we can always determine the smallest value of g such that $P_d(g) \leq P_{d0}$. Then, from the other property $P_b(N, g, l_e) > P_b(N, g-1, l_e)$ (for a proof, see Appendix E), we see that a value of g will minimize $P_b(g)$. Thus, the optimal value of g is obtained using a simple one-dimensional (1-D) search over the range $0, 1, 2, \ldots, N-1$ for g such that

$$g^* = \min \left\{ g | P_{ds}(g) \leq P_{d0} \right\}. \quad (26)$$

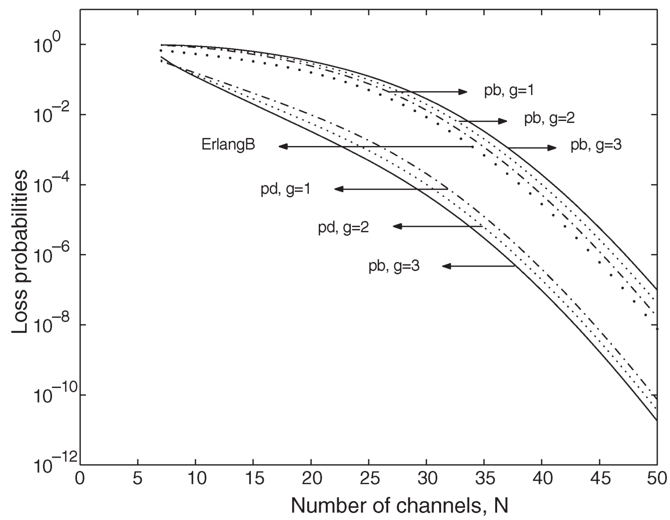

Fig. 5. Loss probability as functions on N.

TABLE I
RESULTS OF OPTIMIZATION PROBLEM **O**

P_{d0}	g^*	$P_d(g^*)$	$P_b(g^*)$
10^{-2}	0	2.794×10^{-3}	4.758×10^{-2}
10^{-3}	1	8.765×10^{-4}	8.036×10^{-2}
10^{-4}	3	9.124×10^{-5}	1.260×10^{-1}
10^{-5}	6	3.755×10^{-6}	1.827×10^{-1}
10^{-6}	8	5.336×10^{-7}	2.862×10^{-1}

IV. NUMERICAL RESULTS AND DISCUSSIONS

In Fig. 5, we have plotted the loss probabilities P_{ds} and P_{BS} as functions of the number of channels N for different values of g. We have assumed $A = 20$, $A_1 = 0.5$, $\mu_l = 0.024$, $\beta = 0.3$, $l_e = 4$, and $\mu = 0.04$. In addition, we used (21) and (22) for values of N as large as 1000 and have not encountered difficulties.

As a numerical example of the optimization problem, we take $N = 24$, $A = 20$, $A_1 = 0.3$, $\mu_l = 0.024$, $\mu = 0.04$, $\beta = 0.3$, and $l_e = 4$. Table I gives the optimal values of g^* for different values of P_{d0}.

We consider a system with parameters $N = 24$, $g = 2$, $\beta = 0.3$, $\lambda_n = 0.01$, $\mu_c = 0.01$, $\mu_l = 0.024$, $\mu_{dc} = (T_{dc})^{-1} = 0.03$, and $l_e = 4$. Some numerical results have been generated as shown in Figs. 6 and 7.

Fig. 6 shows the new call blocking probabilities of the conventional soft handoff scheme and our EPHC scheme. The new call blocking probability of the EPHC scheme is slightly lower than that of the conventional soft handoff scheme because the EPHC scheme saves some channel resources for new call requests.

Fig. 7 shows the handoff dropping probability of the conventional soft handoff scheme and that of the EPHC scheme. The improvement in handoff dropping probability achieved by the

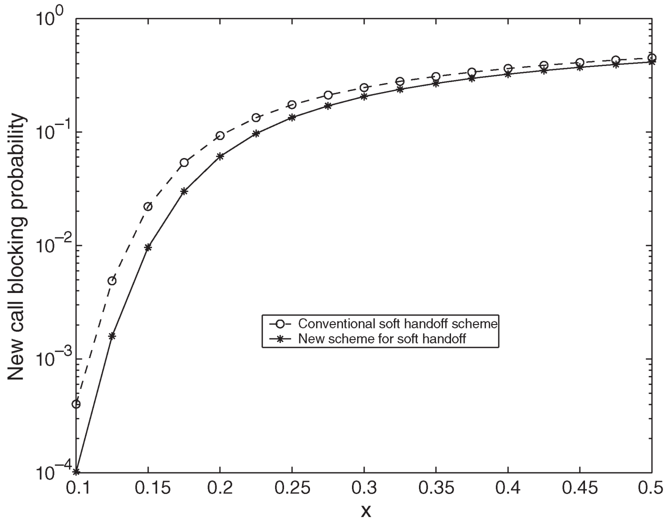

Fig. 6. New call blocking probability versus new call arrival rate (calls/s).

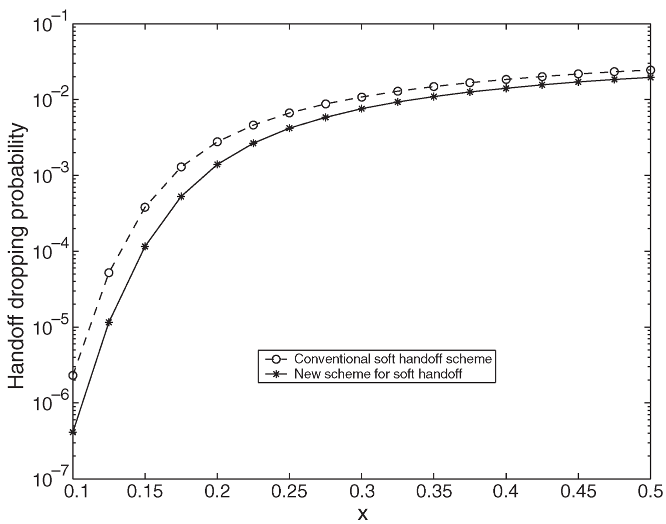

Fig. 7. Handoff dropping probability versus new call arrival rate (calls/s).

EPHC handoff scheme is significant because the EPHC scheme distinguishes pseudo handoff calls from real handoff calls and serves more handoff calls.

V. Conclusion

In this paper, a new view of cellular geometry in the CDMA system and a relative mobility algorithm for soft handoff are proposed. Then, based on relative mobility estimation, a new soft handoff scheme (EPHC), which increases system channel utilization and decreases handoff dropping probability, is presented. To analyze the performance of soft handoff schemes in CDMA cellular systems, Markov chain models are presented to obtain loss formulas for the systems. A more practical concept of call dropping in CDMA system with soft handoff is given and discussed. Effective algorithms are provided to stably compute the loss formulas and to solve the problem of determining the optimal number of guard channels. Consequently, a fixed-point strategy is developed in order to determine the handoff arrival rate into a cell.

Numerical results show that the developed loss formulas are effective, and the EPHC handoff scheme outperforms the conventional handoff scheme with respect to both the new call blocking probability and the handoff dropping probability. Future research will consider the model and analysis of the soft handoff scheme for a more general case in which the Active Set of each call could have more than two channels.

Appendix

We will use the following notation throughout the Appendix to facilitate our discussion:

$$Y_1 = \sum_{n=0}^{N-g-1} \frac{A^n}{n!}$$

$$Y_2 = \sum_{n=N-g}^{N} \frac{A^n}{n!} A_1^{n-(N-g)}$$

$$Y_3 = \sum_{n=N+1}^{N+l_e} \frac{A^n}{\left(N! \prod_{j=1}^{n-N} (N + jA_2)\right)} A_1^{n-(N-g)}.$$

A. Proof of the Expression of $T(x)$

Remember that here, λ_h is the variable, and let us denote

$$A_x = \frac{\lambda_{1c} + x}{\mu_c + \mu_{dc}}, \qquad \alpha_x = \frac{x}{\lambda_{1c} + x}$$

$$\begin{aligned}
T_1(x) &= \mu_{dc} \sum_{n=1}^{N} np_n(x) + \mu_{dc} \sum_{n=N+1}^{N+l_e} Np_n(x) \\
&= \mu_{dc} p_0(x) \left[\sum_{n=1}^{N-g-1} n \frac{A_x^n}{n!} + \sum_{n=N-g}^{N} n \frac{A_x^n}{n!} \alpha_x^{n-(N-g)} \right] \\
&\quad + N\mu_{dc} p_0(x) Y_3(x) \\
&= \frac{\mu_{dc}}{\mu} p_0(x) \lambda_{1c} Y_1(x) + x \frac{\mu_{dc}}{\mu} p_0(x) Y_1(x) \\
&\quad + \mu_{dc} p_0(x) A_x \frac{x}{\lambda_1 + x} \left(Y_2 - \frac{A_x^N}{N!} \alpha_x^g \right) \\
&\quad + N\mu_{dc} p_0(x) Y_3(x) \\
&= \frac{\mu_{dc}}{\mu} p_0(x) \lambda_{1c} Y_1(x) + x \frac{\mu_{dc}}{\mu} p_0(x) \\
&\quad \times \left(Y_1(x) + Y_2(x) - \frac{A_x^N}{N!} \alpha_x^g \right) + N\mu_{dc} p_0(x) Y_3(x) \\
&= \frac{\mu_{dc}}{\mu} p_0(x) \lambda_{1c} Y_1(x) + x \frac{\mu_{dc}}{\mu} \\
&\quad \times \left(1 - \frac{Y_3(x)}{Y_1(x) + Y_2(x) + Y_3(x)} - p_0(x) \frac{A_x^N}{N!} \alpha_x^g \right) \\
&\quad + N\mu_{dc} p_0(x) Y_3(x) \\
&= \frac{\mu_{dc}}{\mu} \lambda_n \left(1 - \frac{\beta}{2} \right) (1 - P_b) \\
&\quad + x \frac{\mu_{dc}}{\mu} (1 - P_F(x) - P_N(x)) + N\mu_{dc} P_F(x). \qquad (27)
\end{aligned}$$

Then, for the conventional soft handoff scheme

$$\begin{aligned} T(x) =& T_1(x) + \lambda_n \frac{\beta}{2}(1-P_b) \\ =& \left(\frac{\mu_{dc}}{\mu} - \frac{\mu_{dc}\beta}{2\mu} + \frac{\beta}{2}\right)\lambda_n\left(1-P_b(x)\right) \\ &+ x\frac{\mu_{dc}}{\mu}\left(1-P_F(x)-P_N(x)\right) + N\mu_{dc}P_F(x) \end{aligned}$$

and for the EPHC handoff scheme

$$\begin{aligned} T(x) =& T_1(x) + \lambda_n \frac{\beta}{6}(1-P_b) \\ =& \left(\frac{\mu_{dc}}{\mu} - \frac{\mu_{dc}\beta}{2\mu} + \frac{\beta}{6}\right)\lambda_n\left(1-P_b(x)\right) \\ &+ x\frac{\mu_{dc}}{\mu}\left(1-P_F(x)-P_N(x)\right) + N\mu_{dc}P_F(x). \end{aligned}$$

B. Stable Computation of P_b

$$\begin{aligned} P_b =& \frac{Y_2+Y_3}{Y_1+Y_2+Y_3} = \frac{1+\frac{Y_3}{Y_2}}{\frac{Y_1+Y_2}{Y_2}+\frac{Y_3}{Y_2}} \\ =& \frac{1+\frac{Y_3}{Y_2}}{\left(P_b^L\right)^{-1}+\frac{Y_3}{Y_2}} = \frac{(1+G_1)P_b^L}{1+G_1P_b^L} \end{aligned}$$

where

$$\begin{aligned} G_1 = \frac{Y_3}{Y_2} =& \frac{\sum_{n=N+1}^{N+l_e} \frac{A^n}{N!\prod_{j=1}^{n-N}(N+jA_2)} A_1^{n-(N-g)}}{\sum_{n=N-g}^{N} \frac{A^n}{n!} A_1^{n-(N-g)}} \\ =& \frac{\sum_{n=1}^{l_e} \frac{A^{N+n}}{\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{\sum_{n=0}^{g} \frac{\frac{A^{n+N-g}}{(n+N-g)!}}{N!} A_1^{n}} \\ =& \frac{\sum_{n=1}^{l_e} \frac{A^n}{\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{\sum_{n=0}^{g} A^{n-g}A_1^n \prod_{j=1}^{g-n}(N-j+1)} \\ =& \frac{\sum_{n=1}^{l_e} \frac{\left(\frac{\lambda_h}{\mu}\right)^{n+g}}{\prod_{j=1}^{n}(N+jA_2)}}{\sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^{n} \prod_{j=1}^{g-n}(N-j+1)}. \end{aligned}$$

C. Stable Computation of P_{ds}

From (9), we have $P_{ds} = p_{N+l_e} + \sum_{n=N+1}^{N+l_e}(n-N)$ $(\mu_l/\lambda_h)p_n$

$$\begin{aligned} p_{N+l_e} =& \frac{\frac{A^{N+l_e}}{N!\prod_{j=1}^{l_e}(N+jA_2)} A_1^{l_e+g}}{Y_1+Y_2+Y_3} \\ =& \frac{\frac{A^{N+l_e}}{Y_2 N!\prod_{j=1}^{l_e}(N+jA_2)} A_1^{l_e+g}}{\frac{Y_1+Y_2}{Y_2}+\frac{Y_3}{Y_2}} \\ =& \frac{G_2P_b^L}{1+G_1P_b^L} \end{aligned}$$

where

$$\begin{aligned} G_2 =& \frac{\frac{A^{N+l_e}}{N!\prod_{j=1}^{l_e}(N+jA_2)} A_1^{l_e+g}}{\sum_{n=0}^{g} \frac{A^{n+N-g}}{(n+N-g)!} A_1^{n}} \\ =& \frac{A^{l_e}A_1^{l_e+g}}{\prod_{j=1}^{l_e}(N+jA_2)\sum_{n=0}^{g} A^{n-g}A_1^n \prod_{j=1}^{g-n}(N-j+1)} \\ =& \frac{\left(\frac{\lambda_h}{\mu}\right)^{l_e+g}}{\prod_{j=1}^{l_e}(N+jA_2)\sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^{n} \prod_{j=1}^{g-n}(N-j+1)} \end{aligned}$$

$$\begin{aligned} \sum_{n=N+1}^{N+l_e}(n-N)\frac{\mu_l}{\lambda_h}p_n =& \frac{\mu_l}{\lambda_h}\sum_{n=1}^{l_e} np_{n+N} \\ =& \frac{\mu_l}{\lambda_h}\frac{\sum_{n=1}^{l_e} n\frac{A^{N+n}}{N!\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{Y_1+Y_2+Y_3} \\ =& \frac{\mu_l}{\lambda_h}\frac{\sum_{n=1}^{l_e} n\frac{A^{N+n}}{Y_2N!\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{\frac{Y_1+Y_2}{Y_2}+\frac{Y_3}{Y_2}} \\ =& \frac{\mu_l}{\lambda_h}\frac{G_3P_b^L}{1+G_1P_b^L} \end{aligned}$$

$$\begin{aligned} G_3 =& \frac{\sum_{n=1}^{l_e} n\frac{A^{N+n}}{N!\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{\sum_{n=0}^{g} \frac{A^{n+N-g}}{(n+N-g)!} A_1^{n}} \\ =& \frac{\sum_{n=1}^{l_e} \frac{nA^{n}}{\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{\sum_{n=0}^{g} A^{n-g}A_1^n \prod_{j=1}^{g-n}(N-j+1)} \\ =& \frac{\sum_{n=1}^{l_e} \frac{n\left(\frac{\lambda_h}{\mu}\right)^{n+g}}{\prod_{j=1}^{n}(N+jA_2)}}{\sum_{n=0}^{g} \left(\frac{\lambda_h}{\mu}\right)^{n} \prod_{j=1}^{g-n}(N-j+1)}. \end{aligned}$$

D. Proof of $P_{ds}(N,g,l_e) < P_{ds}(N,g-1,l_e)$

Since the dropping probability for handoff, calls can be written as

$$\begin{aligned} P_{ds}(N,g,l_e) =& p_{N+l_e} + \sum_{n=N+1}^{N+l_e}(n-N)\frac{\mu_l}{\lambda_h}p_n \\ =& \frac{\frac{A^{N+l_e}}{N!\prod_{j=1}^{l_e}(N+jA_2)} A_1^{l_e+g}}{Y_1(g)+Y_2(g)+Y_3(g)} \\ &+ \frac{\mu_l}{\lambda_h}\frac{\sum_{n=1}^{l_e} n\frac{A^{N+n}}{N!\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g}}{Y_1(g)+Y_2(g)+Y_3(g)} \end{aligned}$$

$$\begin{aligned} P_{ds}(N,g-1,l_e) =& \frac{\frac{A^{N+l_e}}{N!\prod_{j=1}^{l_e}(N+jA_2)} A_1^{l_e+g-1}}{Y_1(g-1)+Y_2(g-1)+Y_3(g-1)} \\ &+ \frac{\mu_l}{\lambda_h}\frac{\sum_{n=1}^{l_e} n\frac{A^{N+n}}{N!\prod_{j=1}^{n}(N+jA_2)} A_1^{n+g-1}}{Y_1(g-1)+Y_2(g-1)+Y_3(g-1)}. \end{aligned}$$

It is easily deduced that if

$$A_1\left[Y_1(g-1)+Y_2(g-1)+Y_3(g-1)\right] < Y_1(g)+Y_2(g)+Y_3(g) \quad (28)$$

then $P_{ds}(N,g,l_e) < P_{ds}(N,g-1,l_e)$. It is equivalent to show that

$$\Leftrightarrow A_1\left[Y_1(g)+\frac{A^{N-g}}{(N-g)!}\right]+\sum_{n=N-g+1}^{N}\frac{A^n}{n!}A_1^{n-(N-g)} + \sum_{n=N+1}^{N+l_e}\frac{A^n}{N!\prod_{j=1}^{n-N}(N+jA_2)}A_1^{n-(N-g)} < Y_1(g)+Y_2(g)+Y_3(g)$$

$$\Leftrightarrow A_1Y_1(g) < Y_1(g)$$

which is always true since $0 < A_1 < 1$ and $Y_1(g) > 0$.

E. Proof of $P_b(N,g,l_e) > P_b(N,g-1,l_e)$

From Appendix B, we can write

$$\begin{aligned} P_b(N,g,l_e) &= \frac{Y_2+Y_3}{Y_1+Y_2+Y_3} \\ &= \frac{(1+G_1)P_b^L}{1+G_1P_b^L} \\ &= 1-\frac{1-P_b^L}{1+G_1P_b^L} \\ D(g) &= G_1P_b^L \\ &= \frac{Y_3(g)}{Y_1(g)+Y_2(g)} \\ &= \frac{\sum_{n=N+1}^{N+l_e}\frac{A^n}{N!\prod_{j=1}^{n-N}(N+jA_2)}A_1^{n-(N-g)}}{Y_1(g)+Y_2(g)} \\ &= \frac{A_1^g\sum_{n=N+1}^{N+l_e}\frac{A^n}{N!\prod_{j=1}^{n-N}(N+jA_2)}A_1^{n-N}}{Y_1(g)+Y_2(g)}. \end{aligned} \quad (29)$$

As we know from [1, App. C], $A_1[Y_1(g-1)+Y_2(g-1)] < Y_1(g)+Y_2(g)$. It can be seen that $D(g) < D(g-1)$. Also, it has been proved [1] that $P_b^L(g) > P_b^L(g-1)$. Therefore, from (29), we can show that $P_b(N,g,l_e) > P_b(N,g-1,l_e)$.

References

[1] G. Haring, R. Marie, R. Puigjaner, and K. S. Trivedi, "Loss formulae and their optimization for cellular networks," *IEEE Trans. Veh. Technol.*, vol. 50, no. 3, pp. 664–673, May 2001.

[2] D. Wong and T. J. Lim, "Soft handoff in CDMA mobile system," *IEEE Pers. Commun.*, vol. 4, no. 6, pp. 6–17, Dec. 1997.

[3] Y. Ma, J. J. Han, and K. S. Trivedi, "Call admission control for reduced dropped calls in code division multiple access (CDMA) cellular systems," in *Proc. IEEE Int. Conf. Computer Communications (INFOCOM)*, Tel-Aviv, Israel, Mar. 26–30, 2000, vol. 3, pp. 1481–1490.

[4] X. Ma, Y. Liu, K. S. Trivedi, Y. Ma, and J. J. Han, "A new handoff scheme for decreasing both dropped calls and blocked calls in CDMA system," in *Proc. IEEE Int. Conf. Trends in Communications (EURONCON)*, Jul. 4–7, 2001, vol. 1, pp. 115–119.

[5] D.-J. Lee and D.-H. Cho, "Channel-borrowing handoff scheme based on user mobility in CDMA cellular systems," in *Proc. IEEE Int. Conf. Communications*, New Orleans, LA, 2000, vol. 2, pp. 685–689.

[6] J. W. Chang, D. K. Sung, J. H. Ahn, and J. H. Kim, "An adaptive channel reservation scheme for soft handoff in cellular DS-CDMA systems," in *Proc. IEEE 49th Vehicular Technology Conf.*, Houston, TX, 1999, vol. 3, pp. 2481–2485.

[7] C. Gang and Y. Dacheng, "Soft handoff design and realization for C-CDMA systems," in *Proc. IEEE TENCON Conf.*, Cheju, Korea, 1999, vol. 2, pp. 1216–1219.

[8] H.-G. Jeon, S.-K. Kwon, S. R. Kim, and C.-E. Kang, "A call control scheme for soft handoff in CDMA cellular systems," in *Proc. IEEE Int. Conf. Communications (ICC)*, Atlanta, GA, 1998, vol. 2, pp. 999–1003.

[9] B. H. Cheung and C. M. Leung, "Network configurations for seamless support of CDMA soft handoffs between cell clusters," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 7, pp. 1276–1288, Jul. 1997.

[10] D. J. Lee and D. H. Cho, "Soft handoff initiation control in CDMA cellular system," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Amsterdam, The Netherlands, 1999, pp. 2143–2147.

[11] A. J. Viterbi, A. M. Viterbi, K. S. Gilhousen, and E. Zehavi, "Soft handoff extends CDMA cell coverage and increases reverse link capacity," *IEEE J. Sel. Areas Commun.*, vol. 12, no. 8, pp. 1281–1288, Oct. 1994.

[12] C. William and Y. Lee, "Overview of cellular CDMA," *IEEE Trans. Veh. Technol.*, vol. 40, no. 2, pp. 291–302, Feb. 1991.

[13] D. K. Kim and D. K. Sung, "Characterization of soft handoff in CDMA systems," *IEEE Trans. Veh. Technol.*, vol. 48, no. 4, pp. 1195–1202, Jul. 1999.

[14] N. Shinagawa, T. Kobayashi, K. Nakono, and M. Sengoku, "Teletraffic evaluation between a switch and base stations in cellular systems with multiple-connection capability for soft handoff," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Amsterdam, The Netherlands, 1999, vol. 2, pp. 1243–1247.

[15] N. Zhang and J. M. Holtsman, "Analysis of a CDMA soft-handoff algorithm," *IEEE Trans. Veh. Technol.*, vol. 47, no. 2, pp. 710–714, May 1998.

[16] S.-L. Su, J.-Y. Chen, and J. H. Huang, "Performance analysis of soft handoff in CDMA cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 14, no. 9, pp. 1762–1769, Dec. 1996.

[17] L. L. Andrew, D. J. Payne, and S. V. Hanly, "Queuing model for soft-blocking CDMA system," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Amsterdam, The Netherlands, 1999, vol. 1, pp. 436–440.

[18] V. M. Jovanovic and D. Cuberovic, "Theoretical and experimental analysis of the new soft handoff algorithm for CDMA systems," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Tokyo, Japan, 2000, vol. 3, pp. 1757–1762.

[19] K. S. Trivedi, *Probability and Statistics With Reliability, Queuing, and Computer Science Applications*, 2nd ed. New York: Wiley, 2001.

[20] H. Akinaru and K. Kawashima, *Teletraffic: Theory and Applications*. Heidelberg, Germany: Springer-Verlag, 1993.

[21] Y. B. Lin and A. C. Pang, "Comparing soft and hard handoffs," *IEEE Trans. Veh. Technol.*, vol. 49, no. 3, pp. 792–798, May 2000.

[22] V. K. Garg, *IS-95 CDMA and cdma2000: Cellular/PCS Systems Implementation*. Englewood Cliffs, NJ: Prentice-Hall, 1999.

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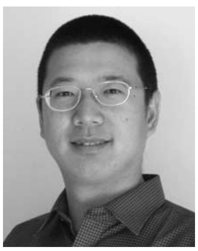

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