Adaptive Channel Reservation Scheme for Soft Handoff in DS-CDMA Cellular Systems

Jin Weon Chang, *Student Member, IEEE*, and Dan Keun Sung, *Senior Member, IEEE*

***Abstract*—Soft handoff techniques in direct-sequence code-division multiple-access (DS-CDMA) systems provide mobile calls with seamless connections between adjacent cells. Channel reservation schemes are used to give high priority to more important soft handoff attempts over new call attempts. However, since the number of soft handoff attempts varies according to environmental conditions, fixed reservation schemes for handoff attempts can be inefficient. An adaptive channel reservation scheme is herein proposed to control the size of reservation capacity according to varying the number of soft handoff attempts. The proposed scheme also includes a balancing procedure between soft handoff failure and new call blocking to maximize the system capacity. To evaluate the performance of the proposed scheme, a Markovian model is developed that considers the interference-limited capacity effect of DS-CDMA systems. Analytical result shows that the proposed scheme yields a considerable enhancement in terms of new call blocking and soft handoff failure probabilities when compared with the conventional fixed channel reservation scheme.**

***Index Terms*—Call admission control, direct sequence code division multiple access (DS-CDMA), soft handoff.**

I. Introduction

CHANNEL reservation schemes have been a preferred choice among various handoff prioritization schemes because they can reduce handoff failures with a minimum of overhead [1]–[5]. However, the studies on channel reservation schemes have focused mainly on time- and frequency-division multiple-access systems.

Most previous studies on call admission control (CAC) in direct-sequence code-division multiple-access (DS-CDMA) systems have concentrated on capacity management. Gilhousen *et al.* [6] and Viterbi and Viterbi [7] determined the capacity of DS-CDMA systems without considering user mobility and variation in the other cell interference. Liu and Zarki [8] and Shin and Sung [9] proposed CAC schemes that adapted to varying other cell interference. However, none of these studies considered user mobility. Ishikawa and Umeda [10] considered call dropping in a cell in addition to call blocking, but they did not take user mobility into consideration. Su *et al.* [12] considered a soft handoff process when a fixed reservation capacity is used to reduce soft handoff failures. However, a fixed reservation capacity can cause a waste of resources because the soft handoff attempt rate varies according to factors such as variation in call arrivals and user mobility. Priscoli and Sestini [11] proposed an adaptive scheme to find an optimum balance between the call blocking and dropping probabilities. Calls are accepted by a threshold that is adaptively determined by monitoring the frequency of new call blocking and ongoing call dropping in a cell. Unfortunately, they did not consider soft handoff attempts when the dropping of ongoing calls was estimated. Soft handoff attempts should be considered differently from new call attempts because the blocking of soft handoff attempts from other cells could cause call dropping.

An adaptive channel reservation scheme for soft handoff attempts is proposed in a DS-CDMA system. The proposed scheme reserves a minimum amount of capacity and makes a reservation only if a candidate for soft handoff triggers a capacity reservation through a threshold mechanism sensing pilot signal strengths. Thus, the size of reservation capacity is efficiently controlled according to variations in the soft handoff attempt rate. In addition to this pilot-sensing mechanism, the minimum reservation capacity is controlled to find an optimal balance between new call blocking and soft handoff failures. This scheme requires an additional overhead for managing the size of reservation capacity and for measuring the rates of new call blocking and soft handoff failures. However, the overhead is small because the proposed scheme can be implemented by extending the conventional procedures for soft handoff and new calls.

The performance of the proposed scheme is analytically evaluated in terms of new call blocking probability and soft handoff failure probability. This analytical approach is based on an existing traffic model [13] and considers the interference-limited capacity of DS-CDMA systems. This capacity was previously limited by the number of channels [10]. Numerical examples show that the proposed scheme can significantly reduce the weighted sum of new call blocking and soft handoff failure probabilities, which is introduced as a measure when simultaneously considering both of the probabilities.

II. An Adaptive Channel Reservation Scheme

A. A Cellular DS-CDMA System Model

The link capacity of cellular DS-CDMA systems is determined by interference from users in the same (home) and other cells. Interference in the home cell is proportional to the number of communicating users in the home cell. However, interference from a user in soft handoff can be reduced because transmission power is controlled by the BS that receives the highest power from the user among the BSs involved in the soft handoff.

Manuscript received June 5, 1999; revised August 18, 2000.

J. W. Chang is with Samsung Electronics Co., Ltd., Sungnam-si, Kyunggi-do 463-050, Korea (e-mail: jwchang1@samsung.com).

D. K. Sung is with the Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea (e-mail: dksung@ee.kaist.ac.kr).

Publisher Item Identifier S 0018-9545(01)03067-5.

It is assumed that the transmission power of each MS is perfectly controlled so that the signal-to-interference ratio (SIR) in a home BS remains constant. If an MS is in soft handoff, its transmission power is perfectly controlled by the BS that receives the highest power from the MS.

Let g_{sh} denote the average power ratio of a soft handoff user to a nonsoft handoff user. Then the equivalent number of nonsoft handoff users in a home cell can be expressed as

$$N(n_0, n_{\mathrm{sh}}) = \begin{cases} n_0 + g_{\mathrm{sh}} n_{\mathrm{sh}} - g_{\mathrm{sh}}, & \text{if a soft handoff user is a reference user} \\ n_0 + g_{\mathrm{sh}} n_{\mathrm{sh}} - 1, & \text{otherwise} \end{cases} \quad (1)$$

where n_0 is the number of nonsoft handoff users and n_{sh} is the number of soft handoff users. Thus, the ratio of bit energy E_b to total noise power spectral density N_0 can be expressed as

$$\frac{E_b}{N_0} = \frac{S_N/R}{N_t + N(n_0, n_{\mathrm{sh}})\nu S_N/W + I_O/W} \quad (2)$$

where

S_N received signal power from an MS;
R information data rate;
ν voice activity factor;
N_t thermal noise spectral density;
W transmission bandwidth;
I_O other-cell interference.

If a required value of E_b/N_0 is given, then the condition meeting the communication quality is derived as

$$N(n_0, n_{\mathrm{sh}}) + \frac{I_O}{\nu S_N} < \frac{W/(R\nu)}{(E_b/N_0)_{\mathrm{required}}} - \frac{N_t W}{\nu S_N}. \quad (3)$$

In general, CDMA systems use the interference level in call admission control [8]–[11] in which a call attempt is admitted if the sum of the newly assigned channel power P_{new} and the current interference $I_c(t)$ is less than a total allowable interference level (TAIL). We consider the normalized other cell interference $I'_O\ (= I_O/\nu S_N)$ using its probability density function (pdf) $f_{I_{O'}}(z)$ [7], [10]. If the capacity C_R is reserved for soft handoff attempts with given n_o and n_{sh}, then the probability that a new call attempt is blocked is given by

$$\alpha(n_o, n_{\mathrm{sh}}, C_R) = \int_{\mathrm{TAIL}-C_R-n_o-g_{\mathrm{sh}}n_{\mathrm{sh}}-P_{\mathrm{new}}}^{\infty} f_{I_{O'}}(z)\, dz. \quad (4)$$

Similarly, the handoff failure probability $\alpha_{\mathrm{sh}}(n_o, n_{\mathrm{sh}})$ is obtained by deleting C_R from (4). Admission of a call attempt in a DS-CDMA system depends on the maximum allowable interference TAIL, the numbers of active users n_o, n_{sh} in a home cell, the reserved capacity C_R, and other-cell interference.

B. An Adaptive Channel Reservation Scheme

In order to guarantee the quality of service (QoS) of soft handoff attempts, some reservation capacity is required. However, a considerable amount of reserved capacity can be wasteful for a fixed value of the reservation capacity C_R because the capacity required by soft handoff is time-variant. A reservation method that adapts to variations in the soft handoff attempt rate is required.

If an MS finds a neighboring BS with a pilot signal higher than a predetermined threshold (T_{ADD}), then a new link to the BS is established while the existing link is maintained. In this case, the call is said to be in soft handoff. If the pilot signal from either the old BS or the new BS drops below a predetermined threshold T_{DROP}, the corresponding link is released [14]. We propose a new parameter T_{Rsrv}, which is a threshold of channel reservation requests. This value is less than T_{ADD}. Fig. 1 illustrates typical pilot strength variation as an MS moves from one base station area to another area. If an MS finds any neighboring BS with pilot strength exceeding T_{Rsrv}, the MS sends a channel reservation request message to the associated BS controller. Afterwards, if the pilot strength drops and stays below T_{Rsrv} during a predetermined period, the MS asks the associated BS controller to release the reservation capacity. On the other hand, if the pilot strength reaches T_{ADD}, then the MS initiates soft handoff using the reserved capacity. Thus, the reserved capacity decreases with an initiation of soft handoff. The threshold T_{Rsrv} is not an absolute value but rather is a relative value to T_{ADD}. When T_{ADD} is dynamically determined according to the current link status, T_{Rsrv} also is adaptively modified, and thus the proposed scheme is applicable to dynamic soft handoff threshold [15].

T_{Rsrv} should be less than T_{ADD} so that the reserved capacity is exclusively available when the MS with the reserved capacity actually requests the capacity for the soft handoff. However, if T_{Rsrv} is too low, excessive unnecessary reservations can occur. The reservation process can be divided into two cases depending on whether T_{Rsrv} is greater or less than T_{DROP}. If T_{Rsrv} is less than T_{DROP} (Case B), an MS requires a channel reservation as soon as it gets out of soft handoff. Otherwise (Case A), no reservation is requested by an MS that has just moved out of soft handoff.

Fig. 2 shows channel reservation and release algorithms in a BS controller. The reserved capacity $C_R(K)$ is initially set at β_0 and a BS controller waits for a reservation request. When a channel reservation is requested by an MS, the associated BS controller accepts the request if the number of reservations K in the BS is smaller than a predetermined maximum of K, K_{max}. In the case of acceptance of the reservation request, the BS controller increases K by one and increases $C_R(K)$ by β_K, which can be properly set at a different value for each K if the reserved capacity $C_R(K)$ is less than C_{R_max}. Otherwise, $C_R(K)$ is set at C_{R_max}. When the release of a reserved channel capacity is requested, the BS controller decreases K by one and $C_R(K)$ by β_{K+1} if $C_R(K)$ is less than C_{R_max}. Otherwise, $C_R(K)$ remains at C_{R_max}.

The proposed pilot-sensing reservation mechanism will reduce unnecessary blocking of new calls with priority on soft handoff calls. However, the system capacity also depends on the QoS difference between new call blocking and soft handoff failures, i.e., a weight on the soft handoff failures [16], [17]. For a given weighting factor, system capacity is limited by new call blocking if the new call blocking probability is higher than the weighted soft handoff failure probability. On the other hand, if the weighted soft handoff failure probability is higher than the

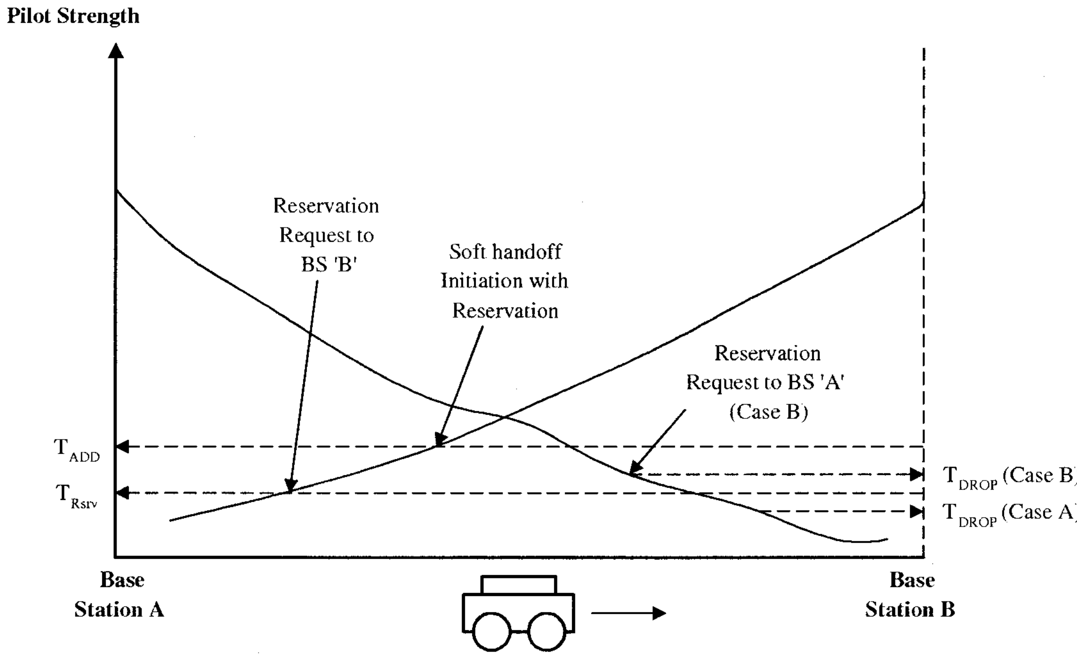

Fig. 1. Reservation of channel capacity for soft handoff calls by a threshold mechanism of pilot strength.

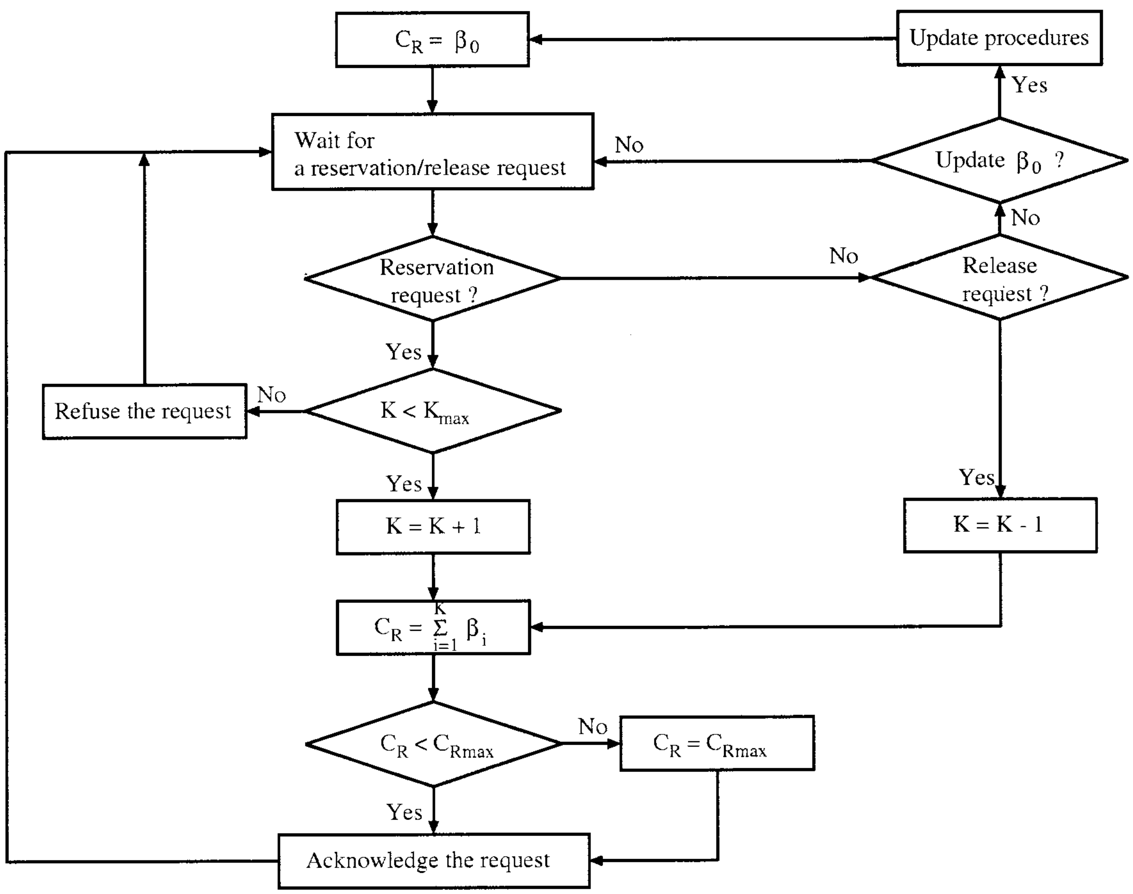

Fig. 2. Channel reservation/release algorithms.

new call blocking probability, the excessive soft handoff failure probability limits the system capacity. Thus, the system capacity is maximal when the new call blocking probability is equal to the weighted soft handoff failure probability.

To keep a balance between the new call blocking and the soft handoff failure probabilities, the proposed scheme controls the size of minimum reservation capacity β_0 by counting the numbers of new call blocking and soft handoff failures. A moving window method is used in order to estimate the frequencies of new call blocking and soft handoff failures, as shown in Fig. 3(a). $N_{\rm win}$ windows are simultaneously managed with a time interval of $T_{\rm win}$. At the ith window, the number of new call requests $N_{nc}(i)$, the number of blocked new call requests $N_{nb}(i)$, the number of soft handoff requests $N_{hc}(i)$, and the number of failed handoff requests $N_{\rm hf}(i)$ are counted in a time interval of $(t_0 + iT_{\rm win},\, t_0 + (N_{\rm win} + i)T_{\rm win})$ and in the successive time intervals of $N_{\rm win}T_{\rm win}$ where t_0 is an initial time. The size of minimum reservation capacity β_0 is updated at a time interval $T_{\rm win}$ as $\beta_0+\Delta$ if $f_wN_{\rm hf}(i)/N_{hc}(i)$ is larger than $N_{nb}(i)/N_{nc}(i)$, where f_w is the weighting factor representing the relative importance of soft handoff failure to new call blocking. Otherwise, β_0 is updated as $\beta_0 - \Delta$. Fig. 3(b) shows an update algorithm of the minimum reservation capacity β_0.

It is a very difficult problem to choose an appropriate size $T_{\rm win}$ of the window monitoring interval. Since the offered traffic is time-variant, a short interval may not support a sufficient estimation for determining the size of reservation capacity [11]. On the other hand, the dynamic variation of the offered traffic makes the reservation process inefficient if the monitoring interval is too long. The proposed balancing algorithm for the QoS difference between new call blocking and soft handoff failures updates the value of β_0 at a sufficiently long interval. Thus, it finds gradually only the long-term balance while the required reservation capacity according to the dynamic variation of the offered traffic is managed by the pilot-sensing reservation mechanism.

III. Performance Analysis

Two measures are derived in order to investigate the performance of the adaptive channel reservation scheme. These are the blocking probability P_B for new calls and the handoff failure probability $P_{\rm hf}$ for soft handoff attempts. The exact model for the proposed scheme is complex because of the effect of the interference-limited capacity in DS-CDMA systems and the process for channel capacity reservations. The processes for new calls and soft handoff calls should also be taken into account. A Markovian model can reduce the complexity under the assumption that residual times in regions, which will be specified later, follow exponential distributions. In Section III-A, a traffic model for the proposed scheme is derived. The performance of the proposed scheme is evaluated using a Markovian model in Section III-B.

A. Traffic Model

In order to find traffic rates for the adaptive channel reservation scheme, the approach of [13] is used with the following assumptions:

1) the cell is square-shaped [13], [18], [19];
2) mobile stations initiating calls are uniformly distributed throughout all cells;
3) new call arrivals follow a Poisson process with a rate of λ_o;
4) the call holding time T_c is exponentially distributed with a mean of $1/\mu_c$;
5) the residual times are exponentially distributed.

Fig. 4 illustrates an example of regions and boundaries based on a square cell structure. To account for the reservation process as well as the soft handoff process, one cell area is divided into six regions. These regions are:

1) the innermost cell region (IMR);
2) the reservation region (RSR);
3) the inner cell region;
4) the soft handoff region by the threshold $T_{\rm ADD}$ (SHR$_{\rm ADD}$);
5) the soft handoff region by the threshold $T_{\rm DROP}$ (SHR$_{\rm DROP}$);
6) the outer cell region.

An MS initiating a call in an IMR attempts to reserve channel capacity for a soft handoff attempt when entering an RSR (point "i" in Fig. 4). The MS attempts a soft handoff when crossing the inner cell region boundary into an SHR$_{\rm ADD}$ region (point "ii" in Fig. 4). Soft handoff is ended when the MS leaves the SHR$_{\rm DROP}$ region (point "iii" in Fig. 4). Thus, the SHR$_{\rm DROP}$ region includes the SHR$_{\rm ADD}$ region. Even when an MS is in soft handoff, another handoff may occur if the pilot signal from a third BS becomes stronger than either one of the two previously received pilot signals. Another reservation request for channel capacity occurs for a candidate handoff MS in an RSR if the pilot signal from a third BS becomes stronger. Thus, we here introduce an overlap region and a sub-RSR region to divide the SHR$_{\rm DROP}$ and the RSR into four parts.

1) Soft Handoff Attempt Rate: The soft handoff attempt rate $\lambda_{\rm sh}$ is derived as follows [13]:

$$\lambda_{\rm sh} = \overline{K}_{\rm sh}\lambda_o \quad (5)$$

where $\overline{K}_{\rm sh}$ is the average number of handoff attempts during the call holding time T_c. $\overline{K}_{\rm sh}$ is composed of two terms originated by a call occurring in an SHR$_{\rm ADD}$ and an inner cell region

$$\overline{K}_{\rm sh} = P_{\rm NS}\overline{K}_{\rm sh\_NS} + P_S\overline{K}_{\rm sh\_S} \quad (6)$$

where $P_{\rm NS}$ is the probability that a new call arrives in the inner cell region (an inner region area/a cell area) and P_S is the probability that a new call arrives in the SHR$_{\rm ADD}$. For $K_{\rm sh\_NS}$, the same expression as [13] can be used

$$\overline{K}_{\rm sh\_NS} = \frac{(1-P_B)P_Ix}{\{1-(1-P_{\rm hf})y\}^2} \quad (7)$$

where x is the probability that a call that requested a handoff request (HOR) does not request any more HORs, $x = P_{\rm hf} + (1 - P_{\rm hf})\{1 - P_V + P_VP_a(1-P_I)\}$; y is the probability that a call makes another HOR, $y = P_V(P_b + P_aP_I)$; P_I (P_V) denotes the probability that a caller leaves an inner cell (an overlap region) before call completion, and P_a and P_b are the conditional probabilities that an MS moves from an overlap region to an inner cell and to another overlap region, respectively, under the condition that the MS leaves the overlap region. For the term originated

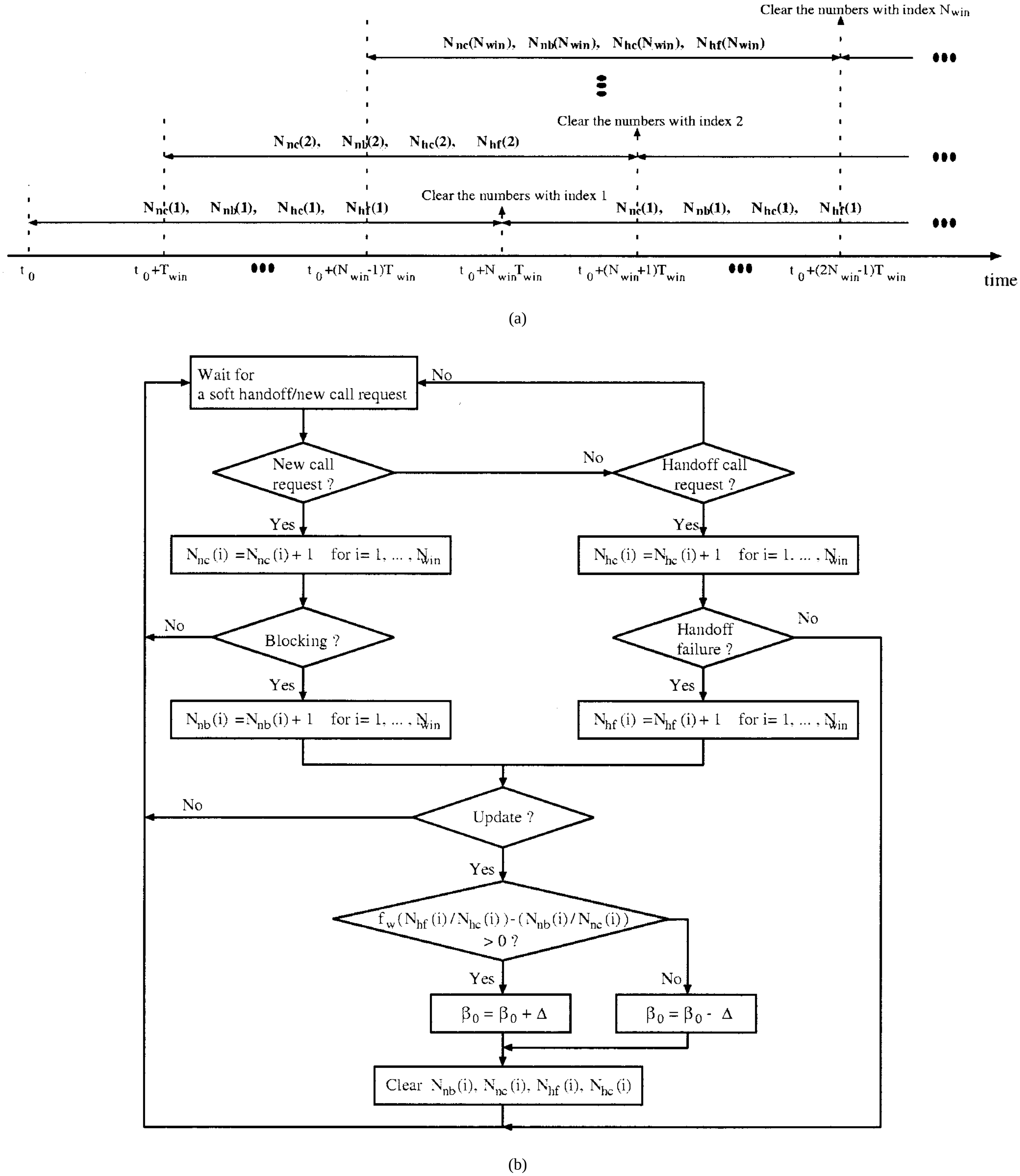

Fig. 3. An update procedure for the minimum reservation capacity β_0. (a) A moving window method for the estimation of the new call blocking and the soft handoff failure probabilities. (b) An algorithm for updating β_0.

by a call occurring in an $\mathrm{SHR_{ADD}}$, one assumption is different from [13]. This different assumption is that all attempts from a call that originates in the $\mathrm{SHR_{ADD}}$ region are regarded as new call attempts even for the second associated BS. This is because call attempts to the associated BSs are made almost simultaneously, and thus the attempt does not cause disconnection of an ongoing call. However, these calls, if they are admitted from all the associated BSs, are put into soft handoff from the beginning of call connection. Therefore, a different expression for $\overline{K}_{\mathrm{sh\_S}}$ is derived with a slight change from [13] as

$$\overline{K}_{\mathrm{sh\_S}} = \frac{(1-P_B)^2\, y(1-P_{\mathrm{hf}})\, x}{[1-(1-P_{\mathrm{hf}})y]^2}. \tag{8}$$

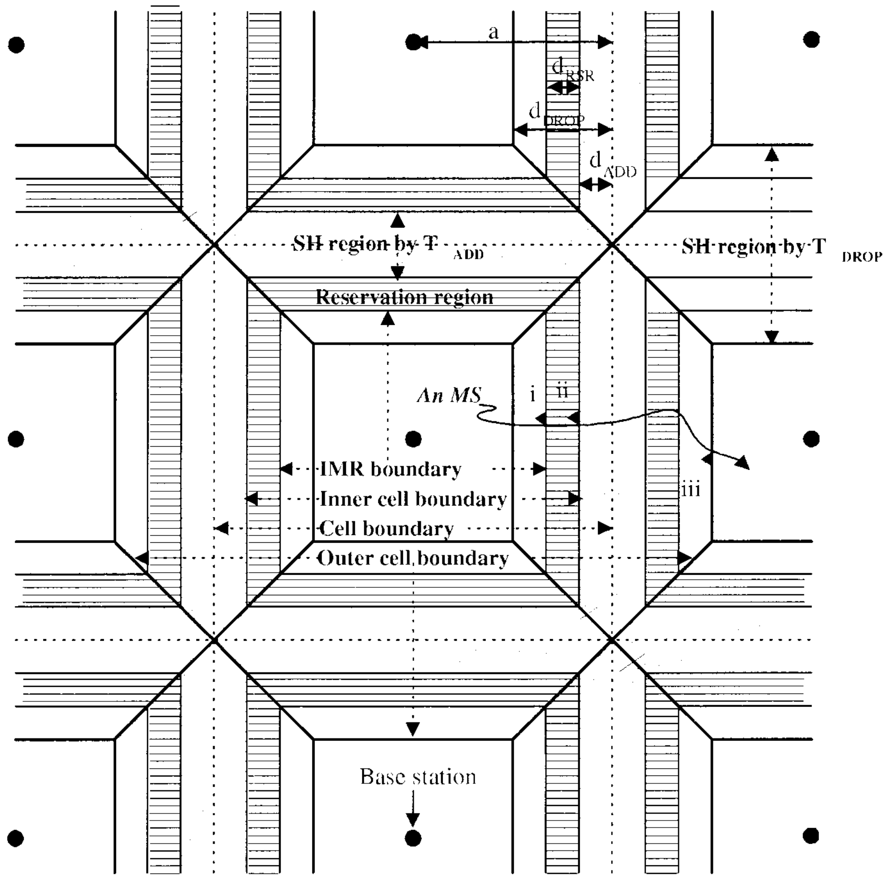

Fig. 4. An example of regions and boundaries based on a square cell structure.

An MS makes a reservation request for channel capacity if it moves from an IMR region to an RSR region or from a sub-RSR region to another sub-RSR. It is assumed that calls in soft handoff do not require reservation requests. Thus, a soft handoff attempt without reserved capacity occurs either if a new call arrives in the $\mathrm{SHR_{ADD}}$ region and is not blocked or if a communicating MS moves from its overlap region to another overlap region. Thus, if $\overline{K}_{\mathrm{DRC}}$ denotes the average number of soft handoff attempts without reservation requests, the arrival rate of soft handoff attempts without its reservation request $\lambda_{\mathrm{sh\_DRC}}$ can be written as

$$\lambda_{\mathrm{sh\_DRC}} = \overline{K}_{\mathrm{DRC}}\lambda_o. \tag{9}$$

The arrival rate of soft handoff attempts with a reservation request $\lambda_{\mathrm{sh\_R}}$ is given by

$$\lambda_{\mathrm{sh\_R}} = (\overline{K}_{\mathrm{sh}} - \overline{K}_{\mathrm{DRC}})\lambda_o. \tag{10}$$

$\overline{K}_{\mathrm{DRC}}$ (derived in the Appendix) is given by

$$\begin{aligned}\overline{K}_{\mathrm{DRC}} =& P_S\overline{K}_{\mathrm{sh\_S}}P_b/(P_b + P_aP_I)\\ &+ P_{\mathrm{NS}}\{[\overline{K}_{\mathrm{sh\_NS}} - (1 - P_B)P_I]P_b/(P_b + P_aP_I)\}.\end{aligned} \tag{11}$$

2) Channel Reservation Request Rate: To find the channel reservation request rate λ_R, Cases A and B are considered. For Case A, the $\mathrm{SHR_{DROP}}$ region includes an RSR region. Thus, an MS that has just moved out of $\mathrm{SHR_{DROP}}$ does not immediately require a reservation. In Case B, a reservation is required because an MS that has just moved out of $\mathrm{SHR_{DROP}}$ is in RSR for Case B.

A channel reservation in Case A is required by a communicating MS that moves from an IMR to an RSR or by an MS that originates a call in the RSR and the call is not blocked. A communicating MS in a sub-RSR region does not require any further reservation if the following conditions are satisfied.

1) The call of a communicating MS is terminated within the sub-RSR.
2) The mobile call is terminated within the IMR after the caller moves from the sub-RSR to the IMR.
3) The communicating MS moves from the sub-RSR to the $\mathrm{SHR_{ADD}}$ and a handoff attempt fails. If the handoff attempt succeeds the following conditions are satisfied.
    a) The mobile call is terminated within the overlap region.
    b) The communicating MS moves from the overlap region to the IMR and the call is terminated within the IMR.
    c) The communicating MS moves from the overlap region to another overlap region and condition 3) is satisfied.

A communicating MS in a sub-RSR region requires another reservation if the following conditions are satisfied.

1) A communicating MS moves from the sub-RSR to the IMR and moves back into a sub-RSR again.

2) A communicating MS moves from the sub-RSR to another sub-RSR.
3) A communicating MS moves from the sub-RSR to the $\mathrm{SHR}_{\mathrm{ADD}}$, the handoff attempt succeeds, and the following two conditions are satisfied.
   a) The communicating MS moves from the overlap region to the IMR and then moves back into a sub-RSR again.
   b) The communicating MS moves from the overlap region to another overlap region and condition 3) is satisfied.

When a new call arrives in an RSR region with P_{Rsrv}, it requires immediate channel reservation if it is not blocked. Assuming a uniform distribution of new calls, the probability P_{Rsrv} can be written as $P_{\mathrm{Rsrv}} =$ (RSR area)/(Cell area).

Let T_{RSR} and T_{IMR} denote the residual times in a sub-RSR and an IMR, respectively, both for a new call that originates in the corresponding region and for an ongoing call that moves from the corresponding neighbor region. The same distribution of residual times can be applied to both new calls and ongoing calls. These residual times depend largely on cell size and terminal mobility factors, such as terminal speed and direction. If P_{RSR} and P_{IMR} denote the probabilities that a call leaves the RSR and the IMR, respectively, then the probabilities can be expressed as

$$\begin{aligned} P_{\mathrm{RSR}} &= \Pr\{T_c > T_{\mathrm{RSR}}\} \\ &= \int_0^\infty e^{-\mu_c t} f_{T_{\mathrm{RSR}}}(t)\,dt \\ &= \mu_{\mathrm{RSR}}/(\mu_c + \mu_{\mathrm{RSR}}) \end{aligned} \tag{12}$$

and

$$\begin{aligned} P_{\mathrm{IMR}} &= \Pr\{T_c > T_{\mathrm{IMR}}\} \\ &= \int_0^\infty e^{-\mu_c t} f_{T_{\mathrm{IMR}}}(t)\,dt \\ &= \mu_{\mathrm{IMR}}/(\mu_c + \mu_{\mathrm{IMR}}) \end{aligned} \tag{13}$$

where $1/\mu_{\mathrm{RSR}}$ and $1/\mu_{\mathrm{IMR}}$ are the average residual times in the RSR and IMR region, respectively.

If M_A is the number of reservation requests during the call holding time T_c for Case A, the probability $\Pr\{M_A = m\}$ can be derived as

$$\begin{aligned} &\Pr\{M_A = 0\} \\ &\quad = (P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)(1-P_{\mathrm{IMR}}) + P_{\mathrm{NS}}P_B + P_S \\ &\qquad \cdot \{P_B + (1-P_B)P_B + (1-P_B)^2(1-P_V) \\ &\qquad\quad + (1-P_B)^2\{P_V P_a(1-P_{\mathrm{IMR}}) + P_V P_b(1-P_V)\} \\ &\qquad\quad /\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} \end{aligned} \tag{14}$$

$$\begin{aligned} &\Pr\{M_A = 1\} \\ &\quad = (P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)P_{\mathrm{IMR}} z_{\mathrm{NR}} \\ &\qquad + P_{\mathrm{Rsrv}}(1-P_B)z_{\mathrm{NR}} + P_S(1-P_B)^2 \\ &\qquad \cdot \{P_V P_a P_{\mathrm{IMR}}/\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} z_{\mathrm{NR}} \end{aligned} \tag{15}$$

$$\begin{aligned} &\Pr\{M_A = 2\} \\ &\quad = (P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)P_{\mathrm{IMR}} z_R z_{\mathrm{NR}} \\ &\qquad + P_{\mathrm{Rsrv}}(1-P_B)z_R z_{\mathrm{NR}} + P_S(1-P_B)^2 \\ &\qquad \cdot \{P_V P_a P_{\mathrm{IMR}}/\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} z_R z_{\mathrm{NR}} \end{aligned} \tag{16}$$

$$\vdots \quad = \quad \vdots$$

$$\begin{aligned} &\Pr\{M_A = m\} \\ &\quad = (P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)P_{\mathrm{IMR}} z_R^{m-1} z_{\mathrm{NR}} \\ &\qquad + P_{\mathrm{Rsrv}}(1-P_B)z_R^{m-1} z_{\mathrm{NR}} + P_S(1-P_B)^2 \\ &\qquad \cdot \{P_V P_a P_{\mathrm{IMR}}/\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} z_R^{m-1} z_{\mathrm{NR}} \end{aligned} \tag{17}$$

where z_R and z_{NR} denote the probabilities that a communicating MS in a sub-RSR requires another reservation and does not require another reservation, respectively. These values are given by

$$\begin{aligned} z_R &= P_{\mathrm{RSR}}P_d P_{\mathrm{IMR}} + P_{\mathrm{RSR}}P_e + P_{\mathrm{RSR}}P_c \\ &\qquad \cdot (1-P_{\mathrm{hf}})P_V P_a P_{\mathrm{IMR}}/\{1-(1-P_{\mathrm{hf}})P_V P_b\} \end{aligned} \tag{18}$$

$$\begin{aligned} z_{\mathrm{NR}} &= (1-P_{\mathrm{RSR}}) + P_{\mathrm{RSR}}P_d(1-P_{\mathrm{IMR}}) + P_{\mathrm{RSR}} \\ &\qquad \cdot P_c\{P_{\mathrm{hf}} + (1-P_{\mathrm{hf}})(1-P_V) + (1-P_{\mathrm{hf}}) \\ &\qquad\quad \cdot P_V P_a(1-P_{\mathrm{IMR}})\}/\{1-(1-P_{\mathrm{hf}})P_V P_b\} \end{aligned} \tag{19}$$

where P_c, P_d, and P_e are the conditional probabilities that an MS moves from a sub-RSR region to an overlap region, to an IMR, and to another sub-RSR, respectively, under the condition that the MS leaves the sub-RSR. Since $P_c + P_d + P_e = 1$, z_R equals to $1 - z_{\mathrm{NR}}$. The expected value of M_A is given by

$$\begin{aligned} \overline{M}_A &= \sum_{m=0}^{\infty} m \Pr\{M_A = m\} \\ &= \{(P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)P_{\mathrm{IMR}} + P_{\mathrm{Rsrv}}(1-P_B) \\ &\qquad + P_S(1-P_B)^2 P_V P_a P_{\mathrm{IMR}}/\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} \\ &\qquad \cdot z_{\mathrm{NR}}(1-z_R)^{-2}. \end{aligned} \tag{20}$$

For Case B, an MS, if it has left an SHR_{ADD} region and is in an RSR region, requires a channel reservation immediately. Therefore, the condition that a communicating MS in a sub-RSR does not require any additional reservation is the same as the condition for Case A. However, the case for condition 3b) of Case A is excluded. The condition that a communicating MS in a sub-RSR requires another reservation is also the same as the condition for Case A, but changes in the case of condition 3a) for Case A. The subcondition is required that a communicating MS moves to the $\mathrm{SHR}_{\mathrm{ADD}}$ and, if a handoff attempt succeeds, the MS then moves from the overlap region directly to a sub-RSR. Similar to Case A, the expected number of reservation requests during a call holding time can be written as

$$\begin{aligned} \overline{M}_B &= \{(P_{\mathrm{NS}} - P_{\mathrm{Rsrv}})(1-P_B)P_{\mathrm{IMR}} + P_{\mathrm{Rsrv}} \cdot (1-P_B) \\ &\qquad + P_S(1-P_B)^2 P_V P_a/\{1-(1-P_{\mathrm{hf}})P_V P_b\}\} \\ &\qquad \cdot z'_{\mathrm{NR}}(1-z'_R)^{-2} \end{aligned} \tag{21}$$

where z'_R $(= 1 - z'_{\mathrm{NR}})$ is the probability that a communicating MS in a sub-RSR requires another reservation. This probability is given by

$$\begin{aligned} z'_R &= P_{\mathrm{RSR}}P_d P_{\mathrm{IMR}} + P_{\mathrm{RSR}}P_e + P_{\mathrm{RSR}}P_c(1-P_{\mathrm{hf}})P_V P_a \\ &\qquad /\{1-(1-P_{\mathrm{hf}})P_V P_b\}. \end{aligned} \tag{22}$$

Finally, the average channel reservation request rate is given by

$$\lambda_R = \begin{cases} \lambda_o \overline{M}_A, & \text{if } T_{\mathrm{Rsrv}} > T_{\mathrm{DROP}} \\ \lambda_o \overline{M}_B, & \text{otherwise.} \end{cases} \tag{23}$$

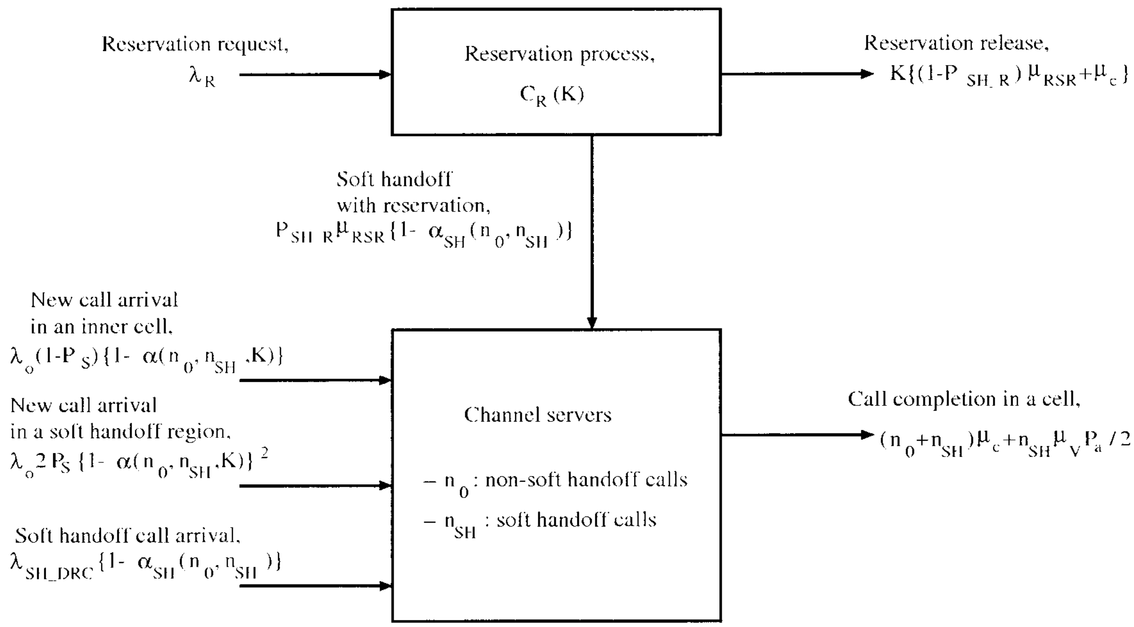

Fig. 5. A state transition diagram for the Markovian model.

B. Markovian Model

New call arrivals, soft handoff arrivals, and reservation request arrivals are based on the Markovian model for the adaptive channel reservation scheme. Fig. 5 shows a call flow diagram for the proposed scheme. New call arrivals in an inner region with a rate of $\lambda_o(1-P_S)$, in a soft handoff region with $\lambda_o 2P_S$, and soft handoff arrivals without reserved capacity with a rate of $\lambda_{\text{sh\_DRC}}$ all cause call attempts directly to channel servers. New call arrivals in a soft handoff region are admitted only if both of the associated BSs accept, and, if they are admitted, the calls go into soft handoff. A soft handoff arrival with a channel reservation enters the system as a reservation request arrival. When the reservation is released, it is assumed that the release is caused by a soft handoff attempt with a probability of $P_{\text{sh\_R}}$ in (24), shown at the bottom of the page.

Service for a reservation request arrival is completed either if the call of the MS that requested the reservation is terminated or if the MS moves out of an RSR region. When the MS moves to an SHR_{ADD} region without a call termination, soft handoff attempt is terminated. The attempt rate is equal to $\lambda_{\text{sh\_R}}$. Thus, $P_{\text{sh\_R}}$ is the ratio of $\lambda_{\text{sh\_R}}$ to $\lambda_R \cdot P_{\text{RSR}}$. New call arrivals are blocked with a probability of $\alpha(n_o, n_{\text{sh}}, k)$, which depends on the number of reservations k in a cell. Soft handoff arrivals are blocked with a probability of $\alpha_{\text{sh}}(n_o, n_{\text{sh}})$.

The state in the Markovian model is defined as $s = (n, n_{\text{sh}}, k)$, where n is the number of active calls in a cell, and thus is equal to $n_o + n_{\text{sh}}$. There are 11 conditions that cause state transitions:

1) a new call arrival in an inner region if it is not blocked;
2) a new call arrival in a soft handoff region if it is not blocked;
3) a soft handoff attempt arrival without reservation if it is not blocked;
4) a reservation request arrival;

$$Q_{ss'} = \begin{cases} \lambda_o(1-P_S)(1-\alpha(n, n_{\text{sh}}, k)), & \text{if } s' = (n+1, n_{\text{sh}}, k) \\ \lambda_o 2P_S(1-\alpha(n, n_{\text{sh}}, k))^2, & \text{if } s' = (n+1, n_{\text{sh}}+1, k) \\ \lambda_{\text{sh\_DRC}}(1-\alpha_{\text{sh}}(n, n_{\text{sh}})), & \text{if } s' = (n+1, n_{\text{sh}}+1, k) \\ \lambda_R, & \text{if } s' = (n, n_{\text{sh}}, k+1) \\ k\mu_{\text{RSR}}(1-P_{\text{sh\_R}}+P_{\text{sh\_R}}\alpha_{\text{sh}}(n, n_{\text{sh}}))+k\mu_c, & \text{if } s' = (n, n_{\text{sh}}, k-1) \\ k\mu_{\text{RSR}}P_{\text{sh\_R}}(1-\alpha_{\text{sh}}(n, n_{\text{sh}})), & \text{if } s' = (n+1, n_{\text{sh}}+1, k-1) \\ (n-n_{\text{sh}})\mu_c, & \text{if } s' = (n-1, n_{\text{sh}}, k) \\ n_{\text{sh}}\mu_c, & \text{if } s' = (n-1, n_{\text{sh}}-1, k) \\ n_{\text{sh}}\mu_V/2, & \text{if } s' = (n-1, n_{\text{sh}}-1, k) \\ (n-n_{\text{sh}})\mu_I, & \text{if } s' = (n, n_{\text{sh}}+1, k) \\ n_{\text{sh}}\mu_V P_a/2, & \text{if } s' = (n, n_{\text{sh}}-1, k) \end{cases} \quad (24)$$

5) for given k reservations, a mobile call termination or reservation release that is not caused by a successful soft handoff attempt;
6) for given k reservations, a reservation release due to a successful soft handoff attempt;
7) completion of an active call that is not in soft handoff.
8) completion of an active call in soft handoff;
9) crossing the outer cell boundary of an $\mathrm{SHR_{DROP}}$ region;
10) crossing the boundary of an $\mathrm{SHR_{ADD}}$ region from an inner region;
11) crossing the boundary of an $\mathrm{SHR_{ADD}}$ region from an $\mathrm{SHR_{DROP}}$ region.

A state transition diagram for these transition conditions is shown in Fig. 6. The corresponding infinitesimal generator matrix $Q_{ss'}$ is given by (24), where $1/\mu_I$ and $1/\mu_V$ are the average residual times in an inner region and in an RSR region, respectively. The blocking probability of new call attempts can be obtained as the sum of terms of the inner and the soft handoff regions

$$P_B = \sum_{n=0}^{\infty}\sum_{n_{\mathrm{sh}}=0}^{n}\sum_{k=0}^{K_{\max}} \{\alpha(n_o, n_{\mathrm{sh}}, k)(1-P_S)/(1+P_S) + \{2\alpha(n_o, n_{\mathrm{sh}}, k) - \alpha^2(n_o, n_{\mathrm{sh}}, k)\} \cdot 2P_S/(1+P_S)\} P_s(n, n_{\mathrm{sh}}, k) \quad (25)$$

where $P_s(n, n_{\mathrm{sh}}, k)$ is the steady-state probability of state $s = (n, n_{\mathrm{sh}}, k)$. Soft handoff attempts with/without reservation fail if the other-user interference exceeds the interference limit TAIL. The handoff failure probability for soft handoff attempts without reservation can be obtained by simply summing all possible states multiplied by the probability of $\alpha_{\mathrm{sh}}(n_o, n_{\mathrm{sh}})$. The handoff failure probability for soft handoff attempts with reservation can be derived by calculating the blocking rate of handoff attempts with reservation over the total soft handoff arrival rate. Thus, the total probability of the soft handoff failure can be derived as

$$P_{\mathrm{hf}} = \sum_{n=0}^{\infty}\sum_{n_{\mathrm{sh}}=0}^{n}\sum_{k=0}^{K_{\max}} \alpha_{\mathrm{sh}}(n_o, n_{\mathrm{sh}}) P_s(n, n_{\mathrm{sh}}, k) \cdot \{\lambda_{\mathrm{sh\_DRC}} + k\mu_{\mathrm{RSR}} P_{\mathrm{sh\_R}}\}/\lambda_{\mathrm{sh}}. \quad (26)$$

The rate of handoff attempt with reservation increases with the number of reservations, which means that larger capacity is reserved when handoff attempts rate is high. The state probabilities P_B and P_{hf} can be obtained recursively by solving the matrix $Q_{ss'}$ from (4), (5), (9), (10), and (23)–(26).

IV. NUMERICAL EXAMPLES

The performance of the adaptive channel reservation scheme is compared with a scheme using a fixed amount of reserved capacity.

A. Assumptions

In a square cell structure shown in Fig. 4, $2a$ is the length of a square cell, $2d_{\mathrm{ADD}}$ is the width of an $\mathrm{SHR_{ADD}}$, $2d_{\mathrm{DROP}}$ is the width of the overlap region, and d_{RSR} is the width of an RSR. Let k_{IM}, k_{ADD}, and k_{DROP} denote $(d_{\mathrm{RSR}} + d_{\mathrm{ADD}})/a$, d_{ADD}/a, and d_{DROP}/a, respectively. Then P_S and P_{Rsrv} can be expressed as

$$P_S = 1 - P_{\mathrm{NS}} = k_{\mathrm{ADD}}(2 - k_{\mathrm{ADD}}) \quad (27)$$

$$P_{\mathrm{Rsrv}} = \frac{d_{\mathrm{RSR}}}{a}(2 - k_{\mathrm{ADD}} - k_{\mathrm{IM}}). \quad (28)$$

To determine the values of parameters and variables, the following assumptions are made.

1) In general, mobile stations tend to reside for a longer time in a larger cell. The average residual time in a cell is known to be proportional to the cell radius and inversely proportional to the speed of a mobile station [20]. It is assumed that the average residual times in an innermost cell, in an inner cell, in an ordinary cell, and in an outer cell are proportional to the shortest distances (d_{short}) from the center to the boundary. Since the ratios of (d_{short}) for the innermost cell, the inner cell, the ordinary cell, and the outer cell are $(1 - k_{\mathrm{IM}}) : (1 - k_{\mathrm{ADD}}) : 1 : (1+k_{\mathrm{DROP}})$, the following relations among $1/\mu_{\mathrm{IM}}$, $1/\mu_I$, $1/\mu_{\mathrm{cell}}$, and $1/\mu_O$ are also assumed, where $1/\mu_{\mathrm{cell}}$ is the average residual time in an ordinary cell

$$1/\mu_{\mathrm{IM}} = 1/\mu_{\mathrm{cell}}(1 - k_{\mathrm{IM}}) \quad (29)$$

$$1/\mu_I = 1/\mu_{\mathrm{cell}}(1 - k_{\mathrm{ADD}}) \quad (30)$$

$$1/\mu_O = 1/\mu_{\mathrm{cell}}(1 + k_{\mathrm{DROP}}). \quad (31)$$

2) P_a $(= 1 - P_b)$, P_c, P_d $(P_e = 1 - P_c - P_d)$, and the average residual times in an overlap region and a reservation region depend on the region's shape and size and the mobility model. If a mobile station passes through an overlap region boundary and a reservation region boundary with equal probability, then P_a, P_c, and P_d are given by

$$P_a = (a - d_{\mathrm{DROP}}) \Big/ \left\{a + \left(\sqrt{2} - 1\right) d_{\mathrm{DROP}}\right\} \quad (32)$$

$$P_c = (a - d_{\mathrm{ADD}}) \Big/ \left\{2(a - d_{\mathrm{ADD}}) + \left(\sqrt{2} - 1\right) d_{\mathrm{RSR}}\right\} \quad (33)$$

$$P_d = (a - d_{\mathrm{ADD}} - d_{\mathrm{RSR}}) \Big/ \left\{2(a - d_{\mathrm{ADD}}) + \left(\sqrt{2} - 1\right) d_{\mathrm{RSR}}\right\}. \quad (34)$$

Without loss of generality, the average residual times in an overlap region and a sub-RSR region can be expressed as

$$1/\mu_V = \text{overlap\_ratio}(1/\mu_O - 1/\mu_I) \quad (35)$$

$$1/\mu_{\mathrm{RSR}} = \text{sub–RSR\_ratio}(1/\mu_I - 1/\mu_{\mathrm{IM}}) \quad (36)$$

where the overlap_ratio and the sub-RSR_ratio are not constant but depend largely on the shapes and the sizes of the overlap region and the sub-RSR region and the mobility model.

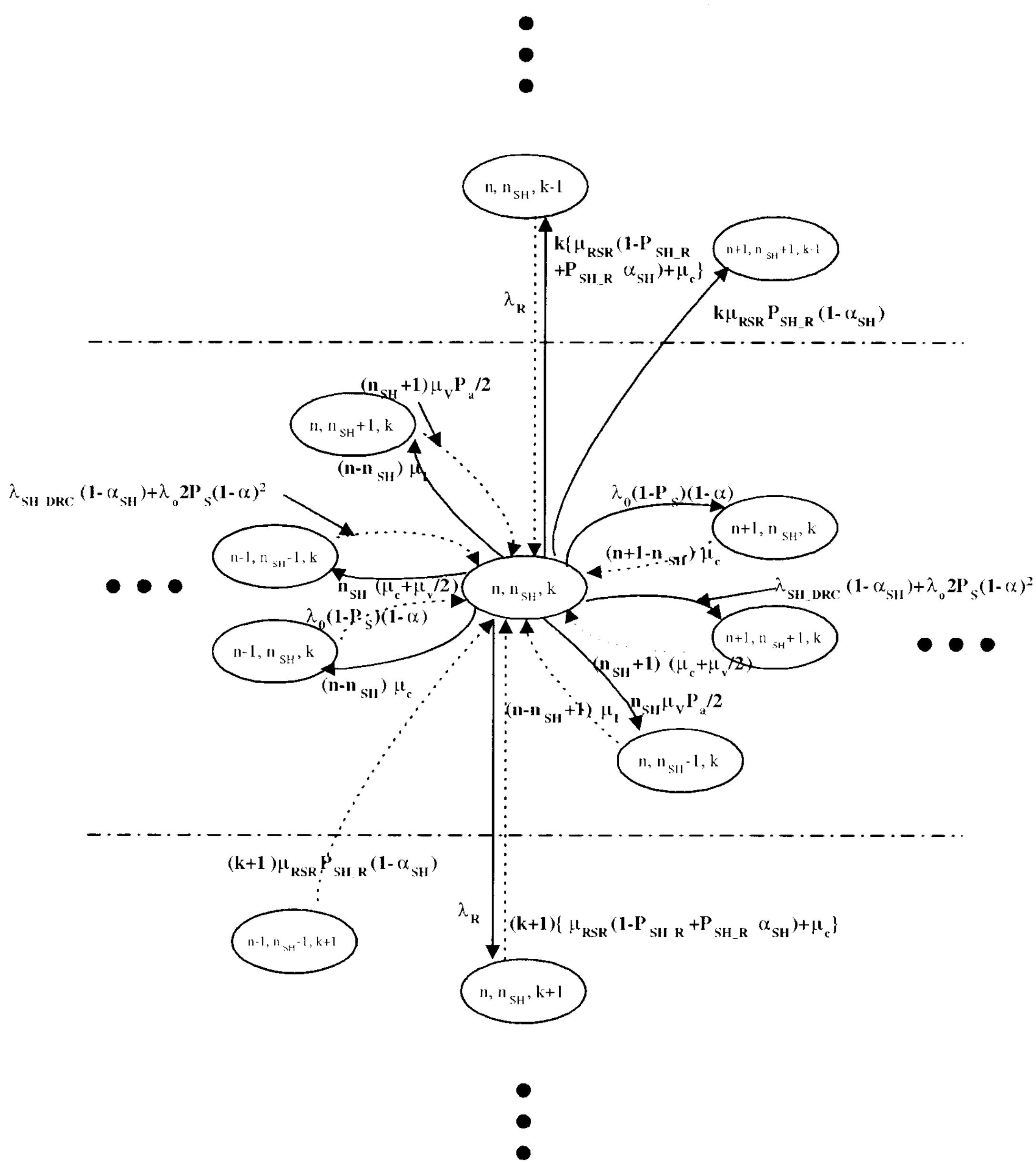

Fig. 6. A state transition diagram for the Markovian model.

3) To find the average power ratio $g_{\rm sh}$ of a soft handoff call, the received signal power from a user located at (u, v) in an SHR_{DROP} region is given by

$$g_{\rm sh}(u, v, \xi_I - \xi_O) = \begin{cases} (r_O/r_I)^{n_{\rm pc}} 10^{(\xi_I - \xi_O)/10}, & \text{if } \xi_I - \xi_O < 10 n_{\rm pc} \log_{10}(r_I/r_O) \\ 1, & \text{if } \xi_I - \xi_O > 10 n_{\rm pc} \log_{10}(r_I/r_O) \end{cases} \quad (37)$$

where

r_I and r_O distances to the two BSs from an MS, respectively;

ξ_I and ξ_O Gaussian random variables representing log-normal fading of the two channels between an MS and the BSs;

$n_{\rm pc}$ propagation constant.

The two Gaussian random variables are assumed to have zero mean and identical variance equal to σ. Thus, $g_{\rm sh}$ can be obtained as

$$g_{\rm sh} = (1/\overline{S}_{\rm or}) \iint_{S_{\rm or}} \int g_{\rm sh}(u, v, \xi_I - \xi_O) d(\xi_I - \xi_O)\, dS_{\rm or} \quad (38)$$

where $S_{\rm or}$ and $\overline{S}_{\rm or}$ denote the overlap region and the size of the overlap region, respectively. As $d_{\rm DROP}$ varies with $a = 1$, the values of $g_{\rm sh}$ are obtained by a numerical integration for $n_{\rm pc} = 4$ and $\sigma = 8$, and the result is shown in Table I.

4) The pdf of the normalized other-cell interference is assumed to follow a gamma distribution, which is expressed as

$$f_{I'_O}(z) = \frac{1}{\Gamma(\nu)} h^{\nu} z^{\nu-1} e^{-hz} \quad (39)$$

where $\Gamma(x)$ is a gamma function. The mean and the variance of the normalized other-cell interference can be translated into the parameters of the gamma distribution using $E\{I'_O\} = \nu/h$ and $\text{var}\{I'_O\} = \nu/h^2$. The mean and variance of I'_O are assumed to be proportional to home-cell interference with two coefficients f_m and f_v as $E\{I'_O\} = f_m n_o$ and $\text{var}\{I'_O\} = f_v n_o$. The factors of f_m and f_v are assumed to be 0.57 and 0.22, respectively, from [10]. The gamma distribution is a better model than the Gaussian distribution because of a better fit to simulation results [10].

B. Numerical and Simulation Results

Analytical results in steady traffic conditions and simulation results in both steady and dynamic traffic conditions are provided in the following presentation. For a steady condition of the offered load, the performance of the proposed scheme is found based on the analytical derivation of Section III. Simulation for the proposed scheme in a cell is made in order to verify the analytical results and to find the performance in a nonsteady condition, i.e., for the offered load with varying means. It is assumed that a cell can support a TAIL value of 15.8 in a homogeneous cell structure in steady state with parameter values of $W = 1.2288$ Mcps, $R = 14.4$ kbps, $\nu = 1$, $N_t W/\nu \max(S_N) = 1$ dB, and $(E_b/N_0)_{\text{req}} = 7$ dB [see (3)]. Additional parameter values are $a = 1$, $d_{\text{ADD}} = 0.1$, $d_{\text{DROP}} = 0.2$, overlap_ratio $= 1$, sub–RSR$_ratio = 1$, $1/\mu_c = 1/\mu_{cell} = 100$ s, $N_{\text{win}} = 10$, $T_{\text{win}} = 20\,000$ s, and $\Delta = 0.01$.

1) Capacity Comparison in Steady Conditions: System capacity is defined as the maximum value of the offered load in Erlangs at which both the blocking probability is less than 10^{-2} and the soft handoff failure probability is less than 10^{-3}. Fig. 7 shows the system capacities of the proposed and fixed reservation schemes by both numerical analysis and simulation. The simulation results agree very well with the analytical ones. The capacity of the fixed scheme increases with values of C_R less than 2.4 because the soft handoff failure probability decreases and, when the value of C_R is larger than 2.4, the capacity decreases because an increase in the new call blocking probability limits the capacity. The value of C_R at which the fixed scheme has the maximum capacity can vary as the handoff call rate and the size of handoff region vary. The capacity of the proposed scheme is always larger than for the fixed scheme because it is maximally managed by the proposed balancing algorithm in Fig. 3.

2) Grade of Service Comparison: To compare the adaptive scheme with the fixed reservation scheme, the weighted sum of the new call blocking and handoff failure probabilities is introduced as a measure of grade of service (GoS), referring to the digital European cordless telecommunication (DECT) specifications [16], [17]

TABLE I
THE VALUES OF AVERAGE POWER RATIO g_{sh} BY SOFT HANDOFF

d_{DROP}	0.1	0.2	0.3	0.4	0.5
g_{sh}	0.21452	0.19166	0.17363	0.16202	0.15541

$$\text{GoS} = P_B + f_w P_{\text{hf}}. \quad (40)$$

From a GoS comparison, the performance of the proposed and the fixed schemes is evaluated when the fixed reservation size is set such that the capacity of the fixed scheme is maximal. Thus, the comparison shows the effect of the pilot-sensing reservation mechanism of the proposed scheme on the system performance at the balanced point of the new call blocking and soft handoff failure probabilities.

Fig. 8 shows the GoS reduction in percentage of the adaptive reservation scheme compared to the fixed reservation scheme for varying the size of reservation region (d_{RSR}). Since the value of C_R in the fixed reservation scheme is adjusted to have maximum capacity, the GoS reduction of the proposed scheme is small when the offered load is the system capacity, i.e., approximately 5 Erlangs in this example. However, the percentage reduction in GoS becomes steeply larger as the offered load decreases. This reduction is significant because cellular systems hardly experience offered loads larger than the system capacity. In Fig. 8, a difference in GoS between Cases A and B can be observed because additional reservations are made as T_{Rsrv} becomes less than T_{DROP} (Case A becomes Case B at a d_{RSR} value just larger than 0.1). As d_{RSR} increases, the GoS reduction increases because more capacity is dynamically reserved according to user requests. Fig. 9 shows the average size of reserved channel capacity versus the offered load. The size of reserved capacity varies adaptively according to the offered load, and the variation is larger as d_{RSR} increases.

Table II shows the GoS values of the proposed and the fixed schemes that are found by simulation when the mean of the offered load is changed every 30 min by the sequence $1.173 \cdot \{L_{\text{off}}, L_{\text{off}}+1, L_{\text{off}}+2, L_{\text{off}}+3, L_{\text{off}}+4\}$. The percentage reduction in GoS is 9.5% when L_{off} is 0.5, i.e., the mean of the offered load varies between 0.587 and 5.279 Erlangs.

V. CONCLUSION

An adaptive channel reservation scheme for soft handoff has been proposed in DS-CDMA cellular systems. The proposed scheme reserves an amount of channel capacity according to users' requests in order to minimize excessive reservations of channel capacity. It also includes a procedure to keep a balance between new call blocking and soft handoff call failure probabilities.

The performance of the proposed scheme is investigated using a Markovian model and is verified by simulations. The proposed scheme is an improvement on the fixed reservation scheme because it has larger system capacity than the fixed scheme even if the reservation size of the fixed scheme is

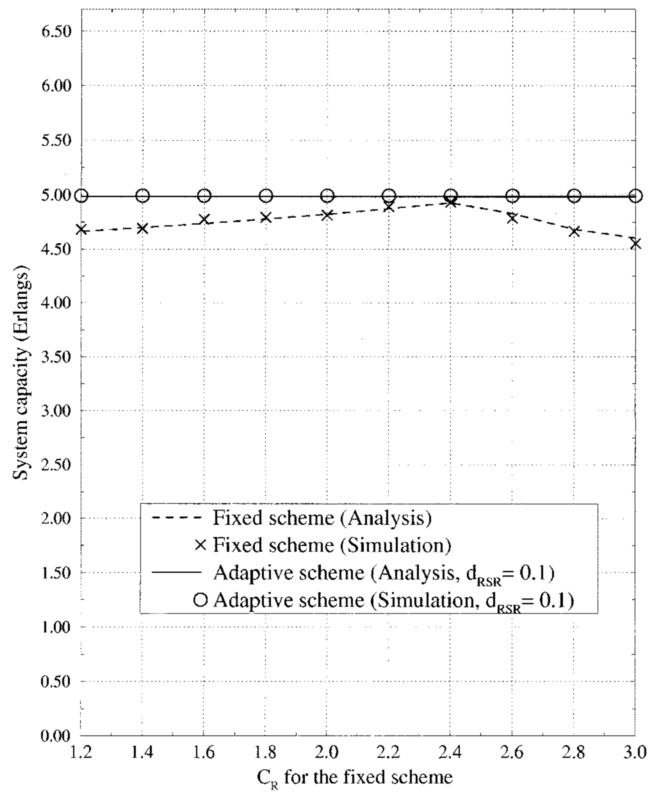

Fig. 7. System capacity satisfying P_b of 10^{-2} and P_{hf} of 10^{-3} for the proposed adaptive scheme and the fixed channel reservation scheme ($C_{R\ \max} = 10.0$ and $\beta_K = 1.0$ for $K > 0$).

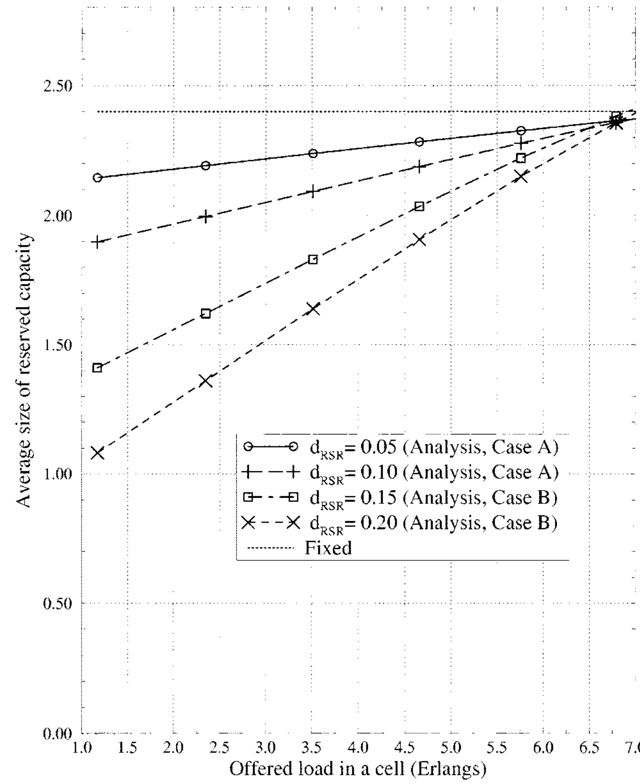

Fig. 9. Average size of reserved capacity versus new call arrival rate for several values of $d_{\rm RSR}$ ($\max = 10.0$ and $\beta_K = 1.0$ for $K > 0$).

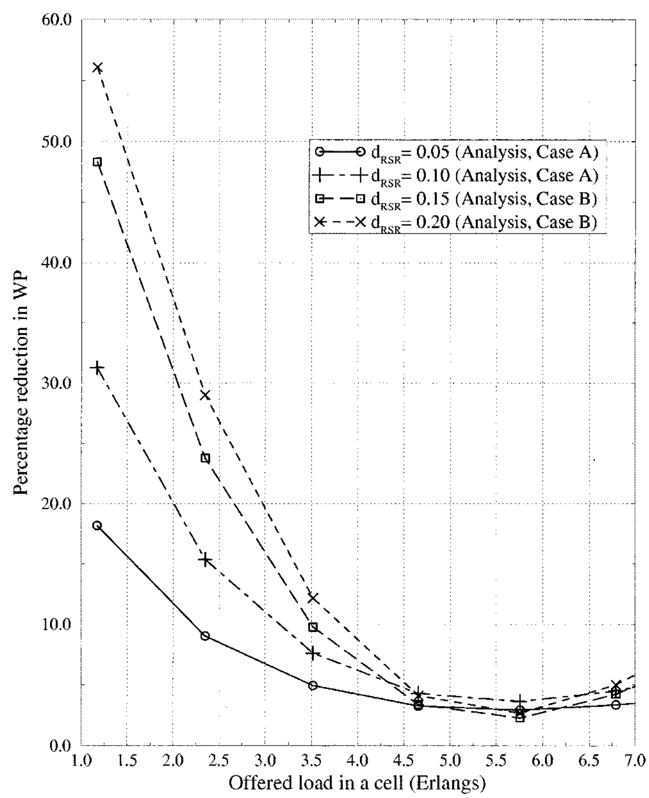

Fig. 8. Percentage reduction in the weighted probability versus the offered load in a cell for several values of $d_{\rm RSR}$ ($f_w = 10.0, C_{R\ \max} = 10.0, \beta_K = 1.0$ for $K > 0$ and $C_R = 2.4$ for the fixed scheme).

TABLE II
GoS VALUES OF PROPOSED AND FIXED SCHEMES WHEN THE OFFERED LOAD IS CHANGED EVERY 30 min BY THE SEQUENCE $1.173 \cdot \{L_{\rm off},\ L_{\rm off}+1,\ L_{\rm off}+2,\ L_{\rm off}+3,\ L_{\rm off}+4\}$ (SIMULATION, $d_{\rm RSR} = 0.1$)

L_{off}	GoS		% Reduction
	The proposed scheme	The fixed scheme	
0.5	0.009255	0.010227	9.5
1.0	0.015929	0.017138	7.1
2.0	0.039048	0.041229	5.3
3.0	0.077698	0.084080	7.6

adjusted so that the system capacity is maximal. A considerable reduction of the proposed scheme in GoS compared with the fixed scheme is obtained in the normal operating range of cellular systems. The proposed scheme can be used in various practical situations with robustness to varying soft handoff traffic.

APPENDIX I

To derive (11), soft handoff attempts without reservation requests are classified into two types. The first type is a soft handoff attempt originated in an $\rm SHR_{ADD}$ region with the number of attempts $K_{\rm DRC\_S}$. The second type is a soft handoff attempt originated in a non-$\rm SHR_{ADD}$ with the number of attempts $K_{\rm DRC\_NS}$. $K_{\rm DRC\_S}$ is considered first. There are two cases where a call in an $\rm SHR_{DROP}$ region makes another handoff request. The first case is a communicating MS moving to another overlap region. The second case is a communicating MS moving to an inner region and then moving to an $\mathrm{SHR}_{\mathrm{ADD}}$ region. In the first case, a soft handoff attempt is required without a reservation request. Thus, the conditional probability $\Pr\{K_{\mathrm{DRC\_S}} = l | K_{\mathrm{sh\_S}} = k\}$ can be written as

$$\begin{aligned}\Pr\{K_{\mathrm{DRC\_S}} =& l|K_{\mathrm{sh\_S}} = k\} \\ &= {}_kC_l \left(\frac{P_b}{P_b + P_a P_I}\right)^l \left(\frac{P_a P_I}{P_b + P_a P_I}\right)^{k-l} \\ &\quad \text{for } k = 1, 2, \ldots, \text{ and } l = 1, 2, \ldots, k.\end{aligned} \tag{41}$$

The average number of handoff attempts without reservation requests can be derived as

$$\begin{aligned}\overline{K}_{\mathrm{DRC\_S}} &= \sum_{l=1}^{\infty} l \Pr\{K_{\mathrm{DRC\_S}} = l\} \\ &= \sum_{l=1}^{\infty} l \sum_{k=l}^{\infty} \Pr\{K_{\mathrm{DRC\_S}} = l | K_{\mathrm{sh\_S}} = k\} \\ &\quad \cdot \Pr\{K_{\mathrm{sh\_S}} = k\} \\ &= \sum_{k=1}^{\infty} \sum_{l=1}^{k} l_k C_l \left(\frac{P_b}{P_b + P_a P_I}\right)^l \cdot \left(\frac{P_a P_I}{P_b + P_a P_I}\right)^{k-l} \\ &\quad \cdot \Pr\{K_{\mathrm{sh\_S}} = k\} \\ &= \sum_{k=1}^{\infty} k \left(\frac{P_b}{P_b + P_a P_I}\right) \sum_{l=1}^{k} {}_{k-1}C_{l-1} \\ &\quad \cdot \left(\frac{P_b}{P_b + P_a P_I}\right)^{l-1} \left(\frac{P_a P_I}{P_b + P_a P_I}\right)^{k-l} \\ &\quad \cdot \Pr\{K_{\mathrm{sh\_S}} = k\} \\ &= \sum_{k=1}^{\infty} k \left(\frac{P_b}{P_b + P_a P_I}\right) \Pr\{K_{\mathrm{sh\_S}} = k\} \\ &= \overline{K}_{\mathrm{sh\_S}} \left(\frac{P_b}{P_b + P_a P_I}\right).\end{aligned} \tag{42}$$

In a similar way, $\overline{K}_{\mathrm{DRC\_NS}}$ can be derived as

$$\begin{aligned}\overline{K}_{\mathrm{DRC\_NS}} =& \{\overline{K}_{\mathrm{sh\_NS}} - (1 - P_B)P_I\} \left(\frac{P_b}{P_b + P_a P_I}\right) \\ &+ (1 - P_B).\end{aligned} \tag{43}$$

Therefore, $\overline{K}_{\mathrm{DRC}}$ in (11) is verified as

$$\overline{K}_{\mathrm{DRC}} = P_S \overline{K}_{\mathrm{DRC\_S}} + P_{\mathrm{NS}} \overline{K}_{\mathrm{DRC\_NS}}. \tag{44}$$

REFERENCES

[1] I. Katzela and M. Naghshineh, "Channel assignment scheme for cellular mobile telecommunication systems: A comprehensive survey," *IEEE Personal Commun.*, vol. 3, pp. 10–31, June 1996.

[2] D. Hong and S. S. Rappaport, "Traffic model and performance analysis for cellular mobile radio telephone Systems with prioritized and non-prioritized handoff procedures," *IEEE Trans. Veh. Technol.*, vol. 35, pp. 77–92, Aug. 1986.

[3] S. Tekinay and B. Jabbari, "A measurement-based prioritization scheme for Handover in micro cellular networks," *IEEE J. Select. Areas Commun.*, vol. 10, Oct. 1992.

[4] Y. B. Lin, S. Mohan, and A. Moerpel, "PCS channel assignment strategies for handoff and initial Access," *IEEE Personal Commun.*, 3rd quarter 1994.

[5] C. H. Yoon and C. K. Un, "Performance of Personal portable radio telephone systems with and without guard channels," *IEEE J. Select. Areas Commun.*, vol. 11, Aug. 1993.

[6] K. S. Gilhousen *et al.*, "On the capacity of a cellular CDMA system," *IEEE Trans. Veh. Technol.*, vol. 40, pp. 303–312, May 1991.

[7] A. M. Viterbi and A. J. Viterbi, "Erlang capacity of a power controlled CDMA system," *IEEE J. Select. Areas Commun.*, vol. 11, pp. 892–900, Aug. 1993.

[8] Z. Liu and M. El Zarki, "SIR-based call admission control for DS-CDMA cellular systems," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 638–644, May 1994.

[9] S. M. Shin and D. K. Sung, "DS-CDMA reverse link channel assignment based on Interference measurements," *Electron. Lett.*, vol. 31, no. 22, pp. 1897–1899, 1995.

[10] Y. Ishikawa and N. Umeda, "Capacity design and performance of call admission control in cellular CDMA systems," *IEEE J. Select. Areas Commun.*, vol. 15, pp. 1627–1635, Oct. 1997.

[11] F. D. Priscoli and F. Sestini, "Fixed and adaptive blocking thresholds in CDMA cellular networks," *IEEE Personal Commun.*, vol. 5, Apr. 1998.

[12] S.-L. Su *et al.*, "Performance analysis of soft handoff in CDMA cellular networks," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 1762–1769, Dec. 1996.

[13] D. K. Kim and D. K. Sung, "Characterization of soft handoff in CDMA cellular systems," *IEEE Trans. Veh. Technol.*, vol. 48, pp. 1195–1202, July 1999.

[14] TIA/EIA Interim Standard (IS-95), "Mobile station—Base station compatibility standards for dual-mode wideband spread spectrum cellular systems,", July 1993.

[15] TR45.5, "The cdma2000 ITU-R RTT candidate submission,", June 1998.

[16] ETSI/RES3, "A guide to DECT features,", vol. RES3, Feb. 1992.

[17] S. M. Shin, C.-H. Cho, and D. K. Sung, "Interference-based channel assignment for DS-CDMA cellular systems," *IEEE Trans. Veh. Technol.*, vol. 48, pp. 233–239, Jan. 1999.

[18] J. K. Kwon and D. K. Sung, "Soft handoff modeling in CDMA cellular Systems," *Proc. IEEE VTC*, pp. 1548–1551, 1997.

[19] S. Ariyavisitakul, "Signal and interference statistics of a CDMA system with feedback power control—Part II," *IEEE Trans. Commun.*, vol. 42, pp. 579–605, Feb./Mar./Apr. 1994.

[20] R. A. Guerin, "Channel occupancy time distribution in a cellular radio system," *IEEE Trans. Veh. Technol.*, vol. VT-36, pp. 89–99, Aug. 1987.

Jin Weon Chang (S'94) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Taejon, in 1993, 1995, and 2000, respectively.

Currently, he is with Samsung Electronics Co., Ltd. His research interests include communication networks, mobility/traffic analyses, and resource control strategies in cellular networks.

Dan Keun Sung (S'80–M'86–SM'00) received the B.S. degree in electrical engineering from Seoul National University, Seoul, Korea, in 1975 and the M.S. and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin in 1982 and 1986, respectively.

From 1977 to 1980, he was a Research Engineer with the Electronics and Telecommunications Research Institute, where he had been engaged in research on the development of electronic switching systems. In 1986, he joined the Faculty of the Korea Institute of Technology. He is currently a Professor in the Department of Electrical Engineering at the Korea Advanced Institute of Science and Technology (KAIST), Taejon. His research interests include ATM switching systems, wireless networks, intelligent network performance and reliability of systems, mobile communication systems, wireless ATM, and CDMA system.

Prof. Sung is a member of IEICE, KITE, KICS, and KISS.