Performance Analysis of Channel-Borrowing Handoff Scheme Based on User Mobility in CDMA Cellular Systems

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***Abstract*—Code-division multiple-access (CDMA) cellular systems use soft handoff. Although the capacity of CDMA systems is interference-limited in nature, channel shortages may occur because soft handoff uses several channels simultaneously. To cope with this problem, we propose an improved handoff method that borrows channels from stationary calls participating in soft handoff and allocates the borrowed channels to handoff requests by moving calls when a channel shortage occurs. Borrowing from stationary calls is possible because these calls do not undergo fast-fading and do not require receiver diversity. The proposed method is designed to avoid increased interference resulting from channel borrowing. The proposed channel-borrowing handoff scheme is analyzed in a situation involving both moving and stationary calls. A comparison is made between the performances of the typical IS-95-based handoff scheme and the proposed scheme. Numerical results show that the proposed scheme is better than the IS-95 scheme in view of the handoff refused probability, the handoff queuing delay, and total interference.**

***Index Terms*—Code-division multiple-access (CDMA) systems, channel borrowing, soft handoff, speed estimation.**

I. Introduction

CELLULAR communication systems require handoff to provide seamless service for users moving across cells. The two types of handoff are soft handoff, which is used in code-division multiple-access (CDMA) systems, and hard handoff, which is used in frequency-division and time-division multiple-access systems [1], [2].

IS-95 defines a soft handoff scheme [3] in which soft handoff is initiated and ended based on received signal strength of a mobile station (MS). It is generally accepted that the reverse link capacity is more crucial than the forward link capacity in CDMA systems. Selection diversity is used in the reverse link of IS-95 soft handoff. In actual urban CDMA cellular systems, the handoff area occupies about 30–40% of the entire cell area, and the number of stationary MS calls is about 40–50% of the number of the total MS calls. This large handoff area may be beneficial to fast moving calls, but it is useless to stationary calls, which constitute a large part of the total calls. Stationary or slow-moving calls experience weak fast-fading and do not require receiver diversity. Therefore, it can be beneficial to perform soft handoff, considering both the mobility of calls and the received signal strength.

We propose a speed-based handoff scheme in CDMA cellular systems, which uses the estimated speeds of MSs and the received signal strengths. We assume that there are moving and stationary calls in service. The proposed scheme operates like the normal IS-95 soft handoff scheme when free channels exist. However, when all channels are occupied and a handoff request occurs, a channel is borrowed from a stationary call participating in soft handoff and allocated to the handoff request. Therefore, the handoff refused probability is lowered. The IS-95-based soft handoff scheme and the proposed scheme are analyzed and compared.

The remaining part of this paper is organized as follows. The proposed channel-borrowing handoff scheme is described in detail in Section II. Section III presents an analysis of both the IS-95 and the proposed handoff schemes using a birth–death process. Numerical results of the two schemes are compared in Section IV. Remarks on interference aspects of the proposed scheme are contained in Section V. Section VI presents a conclusion.

II. Channel-Borrowing Handoff Scheme

To facilitate the proposed handoff scheme, we assume that the speed of a communicating MS can be estimated. There are several methods used to estimate the speed of an MS, including GPS [4], microsensor [5], cell sojourn time [6], [7], and fast fading [8], [9]. Based on the estimated speeds, calls are classified as either stationary or moving.

Channels are reserved for handoff calls in typical handoff schemes because handoff success is more important than new call acceptance. When all channels, except the reserved channels, are used, new calls are blocked and only handoff requests are accepted. This is called as a cutoff state. If all channels are used, handoff requests are placed into a queue waiting for a free channel.

We propose an improved handoff scheme based on the mobility of calls in CDMA cellular systems. This scheme assumes that a channel shortage is more crucial than the amount of interference. The amount of total interference of a cell in CDMA systems depends on not only the number and speed distribution of calls in the cell but also on other cell traffic. In this situation, the number of available channels could be insufficient, although the amount of interference is below the maximum allowable level. The proposed scheme is applied to this situation. Un-

Manuscript received September 17, 1999; revised April 5, 2000.

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Publisher Item Identifier S 0018-9545(00)10442-6.

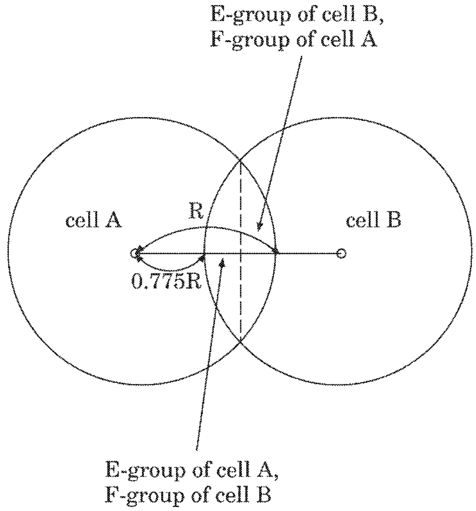

Fig. 1. Cellular system model and E-group and F-group area with no fading effect.

like the IS-95 handoff scheme, if all channels are occupied and a handoff request occurs, a channel is borrowed from a stationary call participating in a soft handoff process and is allocated to the handoff request. We call this process channel borrowing. If there are no stationary calls in the soft handoff process, the handoff request is placed into a queue and waits for free channels.

When channel borrowing is performed, it is important not to increase the total interference. Because uplink interference is more critical than downlink interference in CDMA systems, we consider the uplink interference here. Selection diversity is used for uplinks in IS-95 CDMA systems where one base station (BS), which has a higher receiving power than another BS, is selected to demodulate the received signal. In IS-95, the selected BS is called the controlling BS. When the call moves during the handoff process, the controlling BS will be changed depending on the degree of path loss and fading. However, if the call is stationary in soft handoff, the controlling BS will not be changed during the call duration. When channel borrowing cuts the connection between an MS and a controlling BS, the MS still has a connection with the previous noncontrolling BS and should increase its transmitting power. When a channel is borrowed from the noncontrolling BS, the transmitting power of the MS will remain the same. Therefore, in the proposed scheme, the channel is borrowed from the noncontrolling BS and total interference is not increased.

Stationary calls in soft handoff are divided into two groups: *E-group* and *F-group*. Let $P_{r,A}$ be the received power at BS A of a signal transmitted by a stationary MS call in soft handoff with cell A and B. Also, let $P_{r,B}$ be the received power at BS B of a signal transmitted by the MS call. Then, the *E-group* and the *F-group* can be defined as follows.

1) If $P_{r,A} > P_{r,B}$, that is, if BS A is the controlling BS of the call, the call is in the $E - group$ of cell A and the *F-group* of cell B.
2) If $P_{r,A} < P_{r,B}$, that is, if BS B is the controlling BS of the call, the call is in the *F-group* of cell A and the *E-group* of cell B.

Note that the *E-group* of one cell is the *F-group* of a neighbor cell. Fig. 1 shows the *E-group* and the *F-group* when there is no fading effect. Fig. 2 shows the case that a channel is borrowed from a stationary call in soft handoff when an incoming handoff request to a cell occurs with no free channels. In this case, a channel is borrowed from a call in the *F-group* of the cell to release a connection with the noncontrolling BS of the call. If there are no calls in the *F-group* of the cell, the incoming handoff request is placed into a queue. If there are calls in the *F-group* of the cell, a channel is borrowed from a call in the *F-group* and allocated to the handoff request. In this case, channel borrowing from a call in the *F-group* of one cell corresponds to channel borrowing from a call in the *E-group* of a neighbor cell.

Using the proposed channel-borrowing scheme, the handoff refused probability can be lowered compared with the IS-95 handoff scheme, while the new call blocking probability does not vary.

III. Modeling and Analysis

We analyze the IS-95 soft handoff scheme and the proposed channel-borrowing handoff scheme using a birth–death process considering coexisting moving and stationary calls. It is assumed that a call can be in soft handoff with two BSs simultaneously. The considered cellular system is the same as [10]. The entire cell area is divided into a normal area and a handoff area. Each cell is assumed to be surrounded by six cells. All cells are the same size and have identical stationary probability distributions. The parameters used in this analytical model are as follows:

a	ratio of the handoff area to the entire cell area;
b	ratio of the stationary new call arrival rate to the total new call arrival rate;
Λ_{m1}	moving new call arrival rate in the handoff area;
Λ_{m2}	moving new call arrival rate in the normal area;
Λ_{s1}	stationary new call arrival rate in the handoff area;
Λ_{s2}	stationary new call arrival rate in the normal area;
Λ_n	total new call arrival rate in the entire cell area;
Λ_h	handoff request arrival rate;
μ_{nh}	transfer rate of a moving call from the normal area to the handoff area of the same cell;
μ_{hn}	transfer rate of a moving call from the handoff area to the normal area of the same cell;
μ_{ho}	outgoing departure rate of a moving call from the handoff area;
T_c	mean call duration time;
T_{dc}	mean dwell time of a moving call in the whole cell;
C	number of channels in a cell;
C_h	number of reserved channels for handoff requests only;
Q	maximum queue length.

Here, $\Lambda_n = \Lambda_{m1} + \Lambda_{m2} + \Lambda_{s1} + \Lambda_{s2}$ and $\mu_h = \mu_{hn} + \mu_{ho}$. The call duration time is assumed to be exponentially distributed with a mean of $T_c = \mu_c^{-1}$. Values of μ_{nh}, μ_{hn}, and μ_{ho} are obtained from T_{dc} and a, as described in [10].

A. Analysis of IS-95 Handoff Scheme

The process state in the IS-95 handoff scheme is defined as

$$s = (i, j, k, l, q) \tag{1}$$

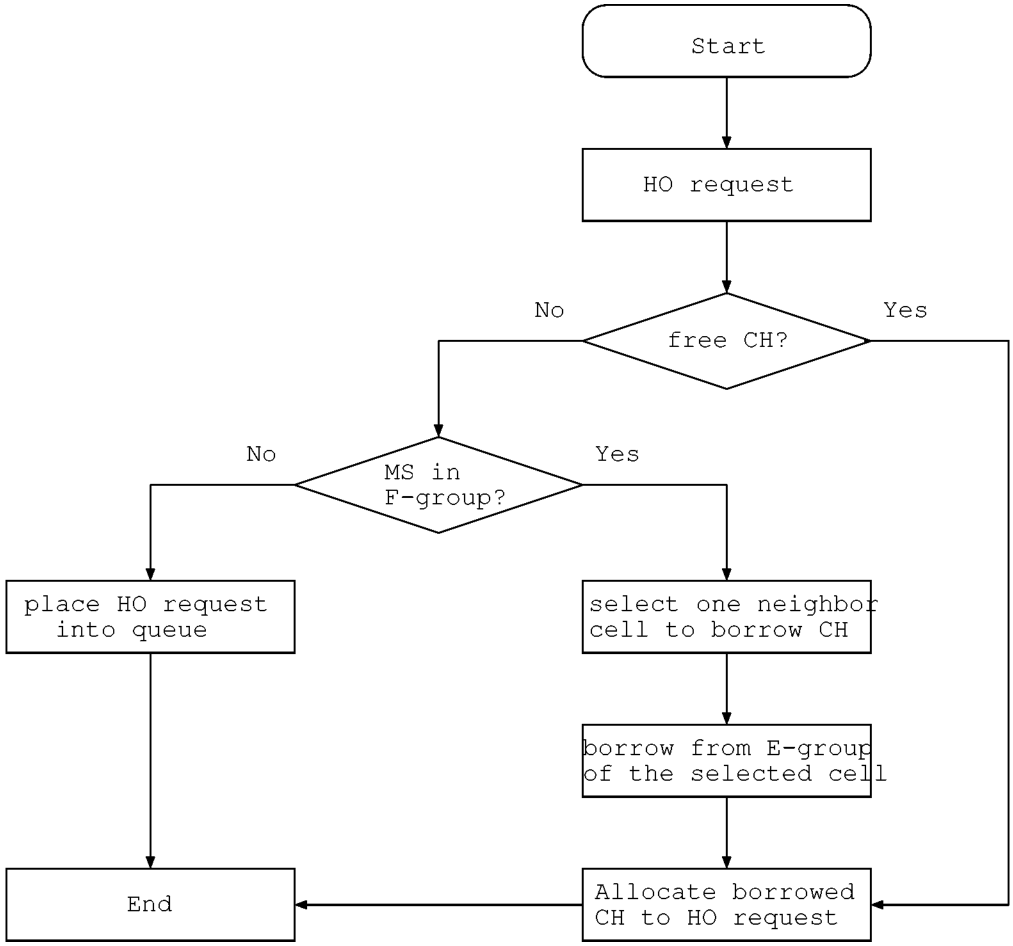

Fig. 2. Flow diagram of the channel-borrowing handoff scheme.

where

- i number of active moving calls in the handoff area;
- j number of active moving calls in the normal area;
- k number of active stationary calls participating in the soft handoff process;
- l number of active stationary calls not participating in the soft handoff process;
- q number of calls in queue.

$N(s)$ is the total number of active channels in state s of a cell, i.e., $N(s) = i + j + k + l$. New calls are blocked when the cell is in a cutoff state, i.e., $N(s) \geq C - C_h$, and handoff arrivals are put into a queue when all channels are used, i.e., $N(s) = C$. The ranges of the state variables are as follows:

$$\begin{aligned} &0 \leq i \leq C, \quad 0 \leq j \leq C \\ &0 \leq k \leq C - C_h, \quad 0 \leq l \leq C - C_h \\ &0 \leq k + l \leq C - C_h, \quad 0 \leq N(s) \leq C \\ &0 \leq q \leq Q. \end{aligned}$$

Let $p(i, j, k, l, q)$ be the steady-state probability of the state $s = (i, j, k, l, q)$. The important parts of the entire state transition diagram are shown in Figs. 3 and 4. Fig. 3 is the birth–death process of a cell before the cutoff state. When the cell is in the cutoff state, the new call arrival rates in Fig. 3 become zero. Fig. 4 shows the queuing part of the birth-death process when $N(s) = C$. Here, $\Lambda_k = \Lambda_{s1} \cdot (1 - P_B)^2$ and $\Lambda_l = \Lambda_{s2} \cdot (1 - P_B) + \Lambda_{s1} \cdot (1 - P_B) \cdot P_B/2$. P_B is the new call blocking probability of a cell. $\Lambda_{s1} \cdot (1 - P_B) \cdot P_B/2$ represents the situation where a stationary new call arrival in the handoff region acquires only one channel instead of two channels due to the cutoff state of the adjacent BS. For ease of analysis, it is assumed throughout this paper that new calls that occur in the handoff area and fail to receive a channel do not retry. Therefore, handoff arrival rate is expressed as

$$\Lambda_h = \sum_s (j \cdot \mu_{nh}) \cdot p(i, j, k, l, q). \tag{2}$$

Stationary state probabilities are obtained using the iterative method in [11].

B. Analysis of Channel-Borrowing Handoff Scheme

The process state of the proposed handoff scheme is defined as

$$v = (i, j, e, f, l, q) \tag{4}$$

where

- i number of active moving calls in the handoff area;
- j number of active moving calls in the normal area;
- e number of active stationary calls in the *E-group* participating in the soft handoff process;

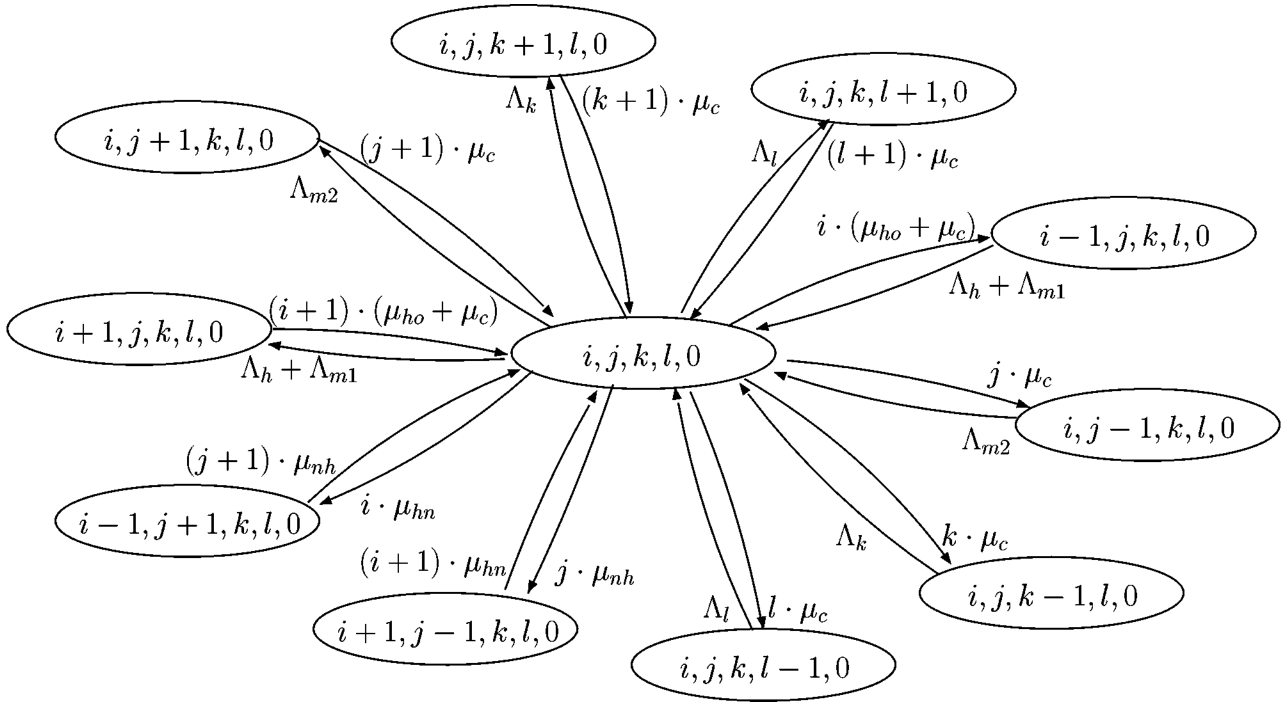

Fig. 3. Birth–death process of the IS-95 handoff scheme before the cutoff state.

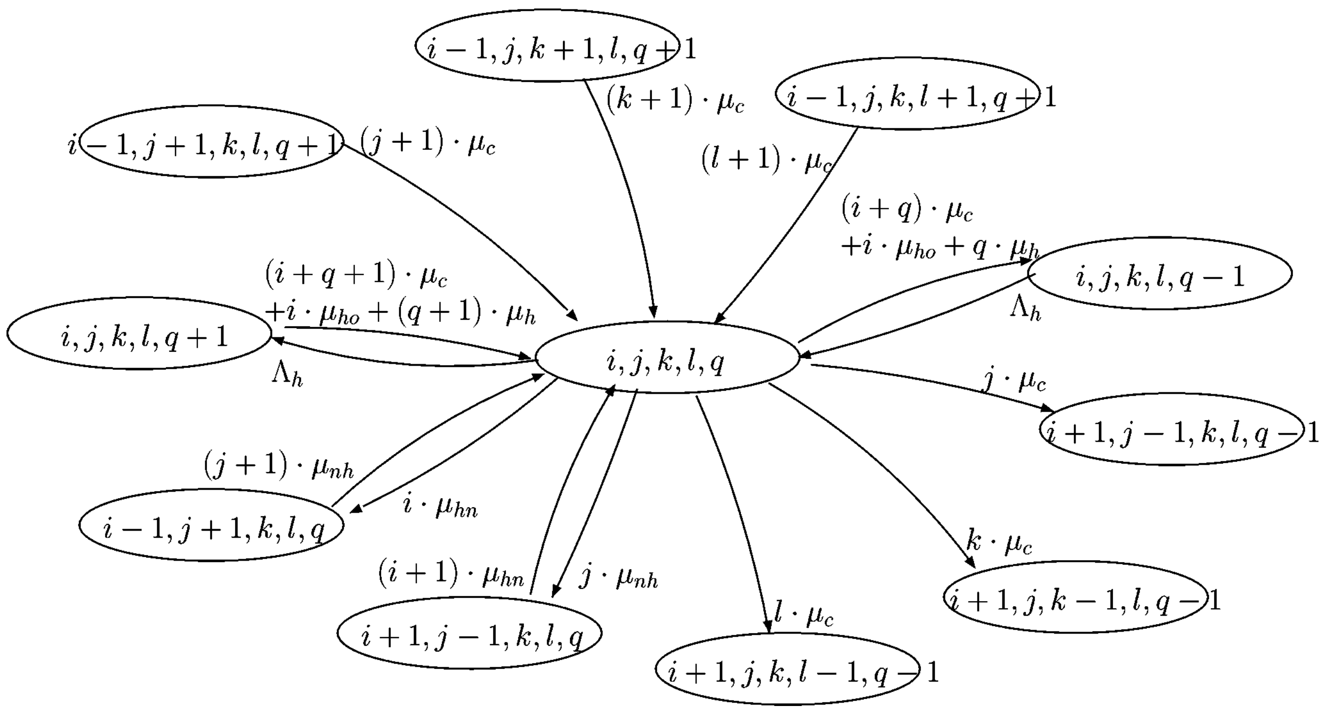

Fig. 4. Queuing part of the birth–death process of the IS-95 handoff scheme when $N(s) = C$ and $q > 0$.

- f number of active stationary calls in the *F-group* participating in the soft handoff process;
- l number of active stationary calls not participating in the soft handoff process;
- q number of calls in queue.

The total number of active channels for state v of a cell is $N(v) = i + j + e + f + l$. The ranges of the state variables of this scheme are as follows:

$$0 \le i \le C, \quad 0 \le j \le C$$
$$0 \le e \le C - C_h, \quad 0 \le f \le C - C_h$$
$$0 \le l \le C - C_h, \quad 0 \le e + f + l \le C - C_h$$
$$0 \le N(v) \le C, \quad 0 \le q \le Q.$$

Let $p(i, j, e, f, l, q)$ be the steady-state probability of the state $v = (i, j, e, f, l, q)$. The important parts of the entire

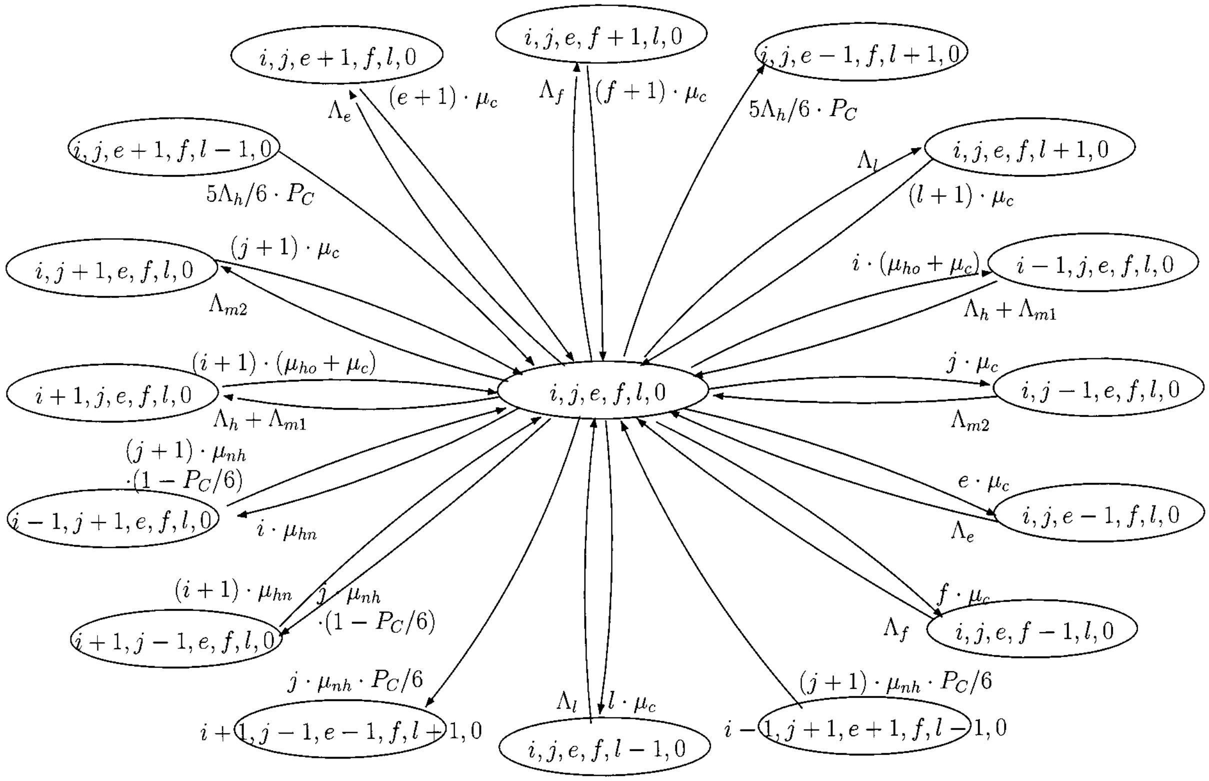

Fig. 5. Birth–death process of the channel-borrowing handoff scheme before the cutoff state, $e > 0$ and $f > 0$.

state transition diagram are shown in Figs. 5 and 6. It is assumed that the new call acceptance rates in the *E-group* and the *F-group* are the same, i.e., $\Lambda_e = \Lambda_f = \Lambda_{s1} \cdot (1 - P_B)^2/2$. In addition, $\Lambda_l = \Lambda_{s2} \cdot (1 - P_B) + \Lambda_{s1} \cdot (1 - P_B) \cdot P_B/2$. We define *borrowing state* as the state in which $N(v) = C$ and $f > 0$. In the *borrowing state*, there are no free channels in a cell. However, a channel can be borrowed from stationary calls in the *F-group* participating in soft handoff. P_C is defined as the probability that a cell is in the *borrowing state*. Then, P_C is given by

$$P_C = \sum_{C_1} p(i,\, j,\, e,\, f,\, l,\, q) \tag{4}$$

where $C_1 = \{v | N(v) = C,\, f > 0\}$. When $N(v) = C$ and $f = 0$, handoff arrivals are placed into a queue.

Fig. 5 is the birth–death process of the channel-borrowing handoff scheme before the cutoff state with $e > 0$ and $f > 0$. In Fig. 5, (5/6)$\Lambda_h \cdot P_C$ is the rate at which a channel is borrowed from an *E-group* call in the considered cell, because a neighboring cell is in the *borrowing state* and a handoff arrival from a cell other than the considered cell occurs in the neighboring cell.

The case where $j \cdot \mu_{nh} \cdot P_C/6$ is applied is as follows: A call in the normal region of the considered cell moves to the handoff region located between the considered cell and a neighbor cell with a rate $j \cdot \mu_{nh}$. The moving call requests a channel from the neighboring cell for handoff. However, when the neighboring cell is in the *borrowing state* with a probability of P_C, a channel should be borrowed from an *F-group* call of the neighboring cell, which is also an *E-group* call of the considered cell with a probability of 1/6. Meanwhile, $j \cdot \mu_{nh} \cdot (1 - P_C/6)$ is applied for the same situation where a call in the normal region of the considered cell moves to the handoff region located between the considered cell and a neighbor cell and the neighbor cell is in the *borrowing state*. However, in this case, the borrowed channel from the *F-group* call in the neighbor cell is not obtained from the *E-group* of the considered cell, but from another cell. Therefore, $1 - P_C/6$ is multiplied to $j \cdot \mu_{nh}$. If the number of the *E-group* calls of the considered cell is zero, i.e., $e = 0$, $j \cdot \mu_{nh}$ is used instead. In the cutoff state, the new call arrival rates are zero. Fig. 6 shows the queueing part of the birth–death process of the channel-borrowing handoff scheme when $N(s) = C$, $f = 0$, and $q > 0$. When the queue is not empty, f is always zero due to channel borrowing. Handoff arrival rate is represented as

$$\Lambda_h = \sum_{v} (j \cdot \mu_{nh}) \cdot p(i,\, j,\, e,\, f,\, l,\, q). \tag{5}$$

To determine stationary state probabilities, the iterative method in [11] is used.

C. Performance Measurements

A new call is blocked by a BS when the number of used channels $N(s)$ in the BS is not less than $C - C_h$. The new call-blocking probability from the viewpoint of a cell for the IS-95 handoff scheme is represented as

$$P_{B_0} = \sum_{B_0} p(i,\, j,\, k,\, l,\, q) \tag{6}$$

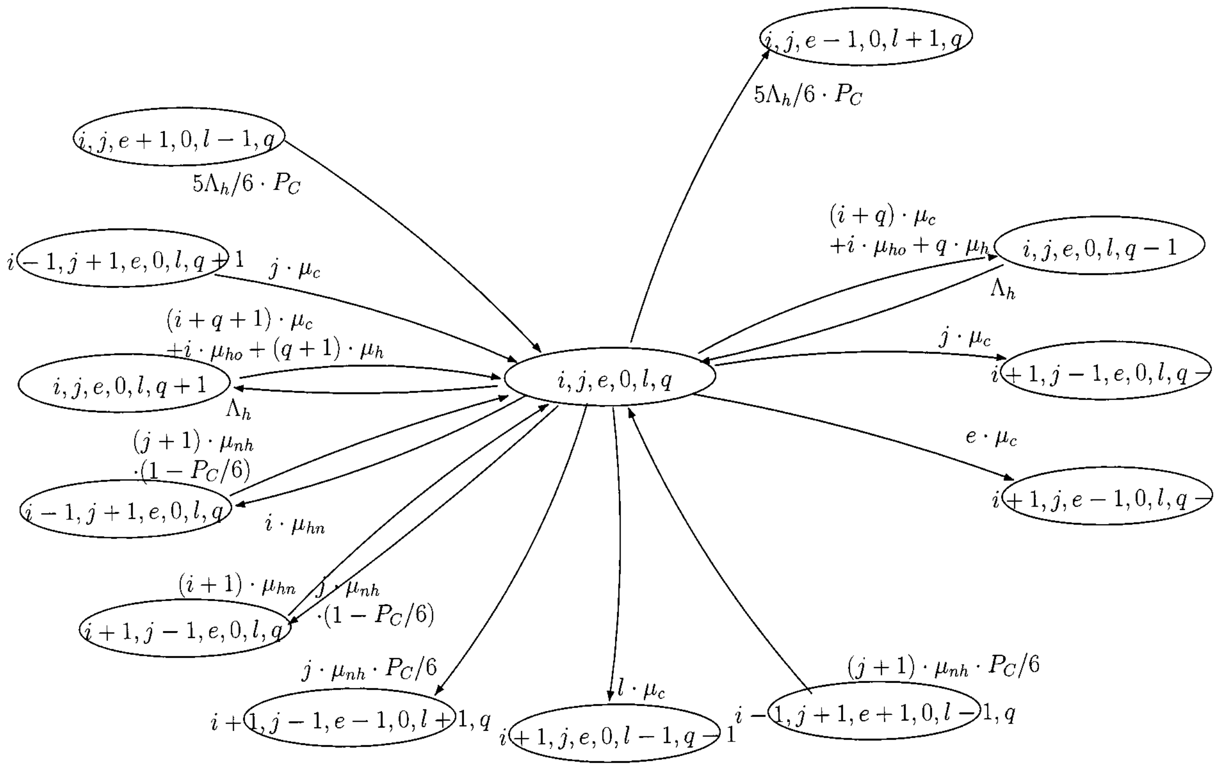

Fig. 6. Queuing part of the birth–death process of the channel-borrowing handoff scheme when $N(s) = C,\ f = 0$, and $q > 0$.

where $B_0 = \{s | C - C_h \le N(s),\ 0 \le q \le Q\}$, and for the channel-borrowing scheme

$$P_{B_1} = \sum_{B_1} p(i,\ j,\ e,\ f,\ l,\ q) \tag{7}$$

where $B_1 = \{v | C - C_h \le N(v),\ 0 \le q \le Q\}$.

A new call in the handoff area can request channels from two BSs. Therefore, the blocking probability of the new call in the handoff area is the square of the new call-blocking probability from the viewpoint of a cell. Therefore, the new call-blocking probability from the viewpoint of a system for the IS-95 scheme is given by

$$P_{BS_0} = \frac{(\Lambda_{m1} + \Lambda_{s1}) \cdot P_{B_0}^2 + (\Lambda_{m2} + \Lambda_{s2}) \cdot P_{B_0}}{\Lambda_n} \tag{8}$$

and for the channel-borrowing scheme

$$P_{\mathrm{BS}_1} = \frac{(\Lambda_{m1} + \Lambda_{s1}) \cdot P_{B_1}^2 + (\Lambda_{m2} + \Lambda_{s2}) \cdot P_{B_1}}{\Lambda_n} \tag{9}$$

where $\Lambda_{m1} + \Lambda_{s1}$ is the new call arrival rate in the handoff area and $\Lambda_{m2} + \Lambda_{s2}$ is the new call arrival rate in the normal area.

The handoff refused probability is defined as the probability that an incoming handoff request does not obtain a handoff channel until either call completion or cell departure of the caller. The handoff refused probability for the IS-95 scheme is described as

$$P_{HR_0} = \frac{P_{HB_0}}{\Lambda_h \cdot (1 - P_{HA_0})} + P_{HA_0} \tag{10}$$

where

$$P_{HA_0} = \sum_s = p(i,\ j,\ k,\ l,\ Q)|_{N(s)=C} \tag{11}$$

and

$$P_{HB_0} = \sum_s q \cdot (\mu_c + \mu_h) \cdot p(i,\ j,\ k,\ l,\ q)|_{N(s)=C}. \tag{12}$$

Here, P_{HA} represents the situation where there is no free channel for a handoff request and the request is queued in the target BS. P_{HB} represents the situation where the handoff request in the queue is terminated by call completion or caller's leaving of the handoff area while waiting in the queue. Similarly, for the proposed scheme, the handoff refused probability is as follows:

$$P_{HR_1} = \frac{P_{HB_1}}{\Lambda_h \cdot (1 - P_{HA_1})} + P_{HA_1} \tag{13}$$

where

$$P_{HA_1} = \sum_v p(i,\ j,\ e,\ f,\ l,\ Q)|_{N(v)=C,\, f=0} \tag{14}$$

and

$$P_{HB_1} = \sum_v q \cdot (\mu_c + \mu_h) \cdot p(i,\ j,\ e,\ f,\ l,\ q)|_{N(v)=C,\, f=0}. \tag{15}$$

The total carried traffic per cell is defined as

$$C_{T_0} = \sum_s (i + j + k + l) \cdot p(i,\ j,\ k,\ l,\ q) \tag{16}$$

for the IS-95 scheme and

$$C_{T_1} = \sum_v (i + j + e + f + l) \cdot p(i,\, j,\, e,\, f,\, l,\, q) \tag{17}$$

for the channel-borrowing scheme.

Carried handoff traffic is defined as the mean number of calls using two channels simultaneously. Therefore, the carried handoff traffic per cell is expressed as

$$C_{H_0} = \sum_s (i \cdot R_n + k) \cdot p(i,\, j,\, k,\, l,\, q) \tag{18}$$

for the IS-95 scheme and

$$C_{H_1} = \sum_v (i \cdot R_n + e + f) \cdot p(i,\, j,\, e,\, f,\, l,\, q) \tag{19}$$

for the channel-borrowing scheme, where R_n is the ratio of the number of moving calls in soft handoff to the total number of moving calls in the handoff region. R_n is obtained from [10] as

$$R_n = \frac{F_n + F_h + F_t}{F_n + F_h + F_t + F} \tag{20}$$

where $F_n = \Lambda_{m1} \cdot (1 - P_B)^2$, $F_h = F_t = \Lambda_h \cdot (1 - P_{HR})$, and $F = \Lambda_{m1} \cdot (1 - P_B) \cdot P_B + \Lambda_h \cdot P_{HR}$. F_n represents new call arrivals from moving users in the handoff region that succeed in obtaining two channels for handoff. F_h indicates incoming handoff requests that succeed in obtaining a channel for handoff. F_t represents moving calls transferring from the normal region to the handoff region of the same cell and succeeding in obtaining a channel for handoff from the neighbor cell. F represents the situation where a moving new call arrival in the handoff region acquires only one channel and a handoff request fails to obtain a channel.

Channel efficiency is defined as the ratio of the mean number of calls served in a cell to the total carried traffic. The mean number of calls served in a cell is the difference between the total carried traffic and the half of the carried handoff traffic. Therefore, channel efficiency E_C is calculated by

$$E_C = \frac{C_T - C_H/2}{C_T}. \tag{21}$$

When a handoff request arrives and there are no free channels, the handoff request is placed into a queue. For an unlimited queue size, the mean queuing delay of an incoming handoff request under the condition that the handoff request should wait in queue is represented using Little's law as

$$D = E_Q/\Lambda_h \tag{22}$$

where E_Q is the mean queue size under the condition that all channels are used in a cell. E_Q is obtained as follows:

$$E_{Q0} = \sum_s q \cdot p(i,\, j,\, k,\, l,\, q)|_{N(s)=C} \tag{23}$$

for the IS-95 scheme and

$$E_{Q1} = \sum_v q \cdot p(i,\, j,\, e,\, f,\, l,\, q)|_{N(v)=C,\, f=0} \tag{24}$$

for the channel-borrowing scheme.

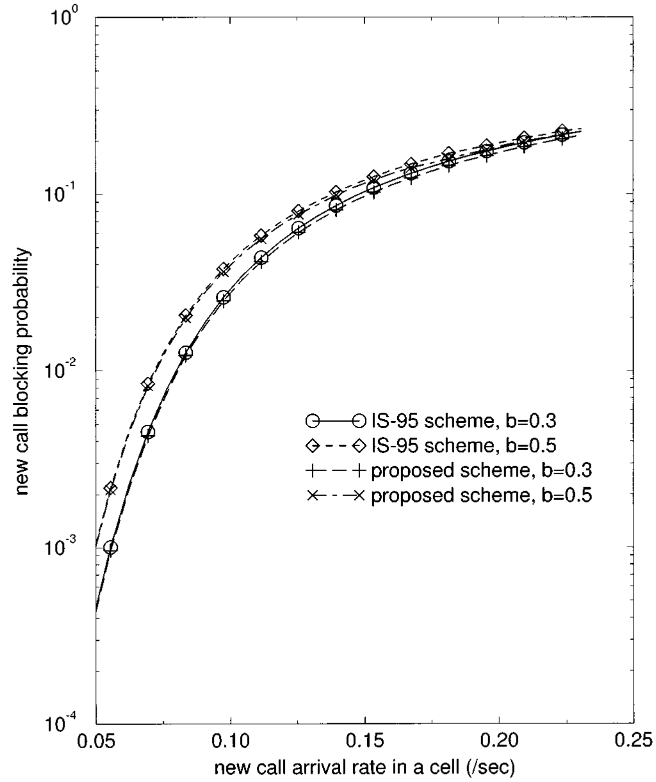

Fig. 7. New call-blocking probability versus total new call arrival rate.

IV. Numerical Results

The system parameters used in numerical analysis are $a = 0.4$, $C = 12$, $C_h = 1$, $\mu_c = 0.01$, and $T_{dc} = 100/3$. The values of μ_c and T_{dc} are taken from [10]. The maximum queue size Q is eight. Numerical results show that the probability that the system will achieve the maximum queue size of eight is zero for all considered cases. Thus, the system can be considered as having an unlimited queue size.

Figs. 7–12 show numerical results. Fig. 7 shows the new call-blocking probability $P_{\rm BS}$ of the IS-95 and the channel-borrowing handoff schemes for different values of b, a ratio of the stationary new call arrival rate to the total new call arrival rate in a cell. The new call-blocking probability of the channel-borrowing scheme is almost equal to, or slightly lower than, the probability of the IS-95 handoff scheme because the channel-borrowing scheme serves more moving handoff calls than the IS-95 scheme by borrowing channels from stationary handoff calls to serve moving handoff requests. Therefore, the number of moving calls and the mean cell departure rate both increase using the channel-borrowing handoff scheme compared with the IS-95 scheme. In this case, the actual cell load decreases and the new call-blocking probability decreases, although the difference between the new call-blocking probability of the two schemes is small.

Fig. 8 shows the handoff refused probability P_{HR} of the IS-95 and the channel-borrowing handoff schemes. The handoff-refused probability of the channel-borrowing scheme is lower than that of the IS-95 scheme.

Fig. 9 shows the total carried traffic in a cell C_T. The carried traffic increases as the new call arrival rate increases. The

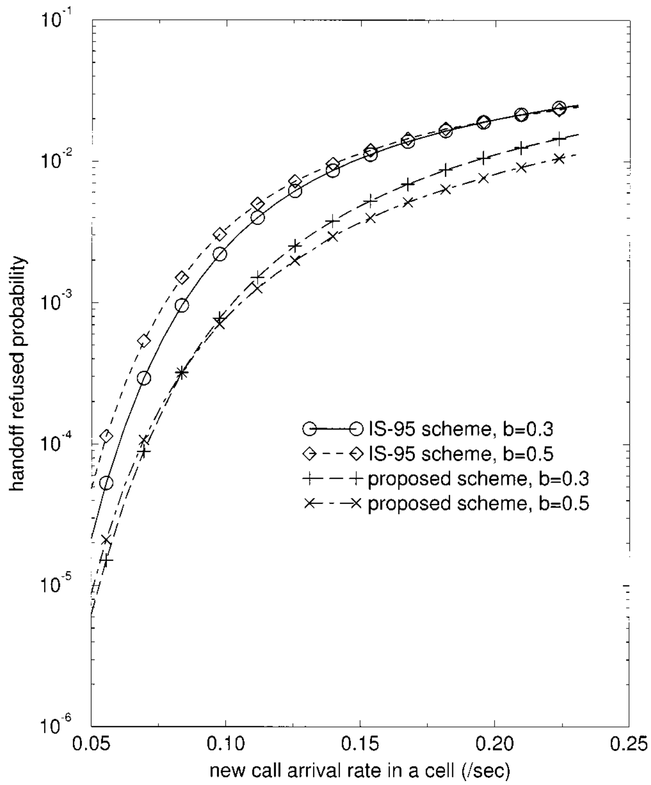

Fig. 8. Handoff refused probability versus total new call arrival rate.

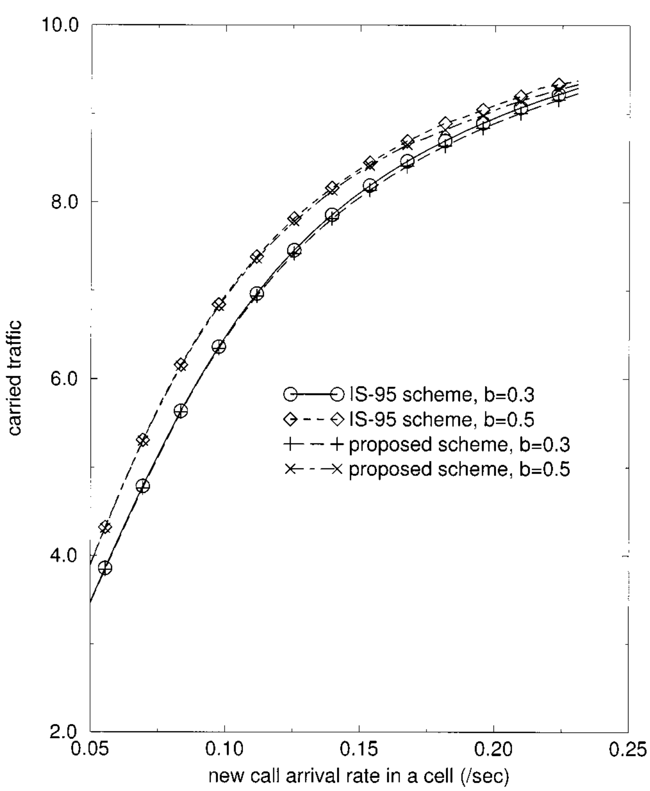

Fig. 9. Total carried traffic versus total new call arrival rate.

carried traffic of both schemes is nearly equal. When channel borrowing is performed, a channel used by a stationary handoff call is reallocated to an incoming handoff request. Therefore, the number of used channels in a cell does not vary before and after the channel-borrowing process, and the total carried traffic of the two handoff schemes is nearly equal. The amount of carried traffic is reduced as b decreases. With a smaller value of b, both the mean cell departure rate and the handoff request arrival rate increase. The influence of the increased handoff request arrival rate is dominant over the influence of the increased cell departure rate on the cell load. Therefore, with a smaller value of b, cell load decreases, resulting in less carried traffic.

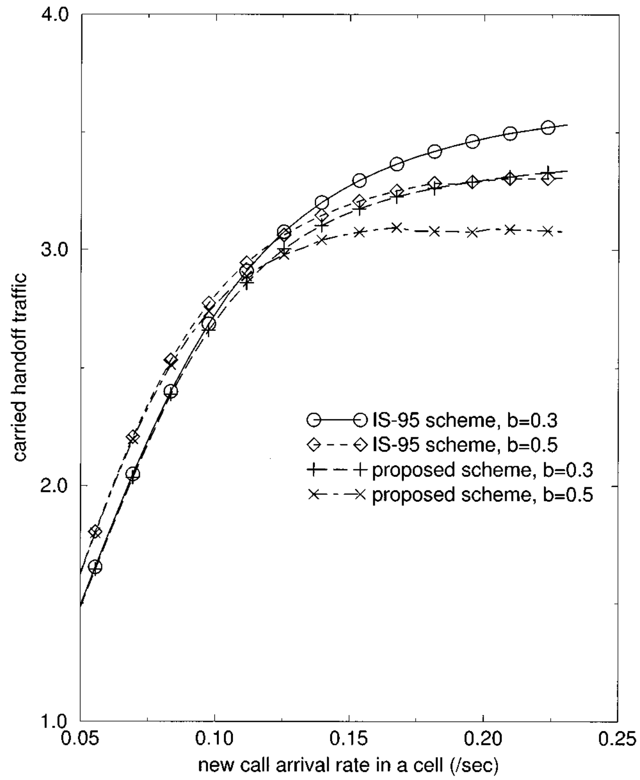

Fig. 10. Carried handoff traffic versus total new call arrival rate.

The carried handoff traffic C_H is shown in Fig. 10. The amount of carried handoff traffic of the IS-95 scheme is greater than that of the channel-borrowing scheme when the new call arrival rate is high because stationary handoff calls are deprived of channels in the channel-borrowing scheme when the cell is in the *borrowing state* and moving handoff requests arrive. Therefore, handoff calls in the IS-95 scheme is more likely to stay in the handoff area, resulting in more handoff traffic.

Fig. 11 shows the channel efficiency E_C, which is the ratio of the mean number of calls served in a cell to the total carried traffic. The channel efficiency increases as the value of b and the new call arrival rate increase. As shown in Fig. 10, the carried handoff traffic of the channel-borrowing scheme is less than that of the IS-95 scheme. Therefore, the channel efficiency of the channel-borrowing scheme is higher than that of the IS-95 scheme.

Fig. 12 shows the mean queuing delay D of an incoming handoff request under the condition that all channels are occupied when the handoff request arrives. The queuing delay of the channel-borrowing scheme is far less than that of the IS-95 scheme because the channel-borrowing scheme provides more channels for handoff requests than the IS-95 scheme. This lower

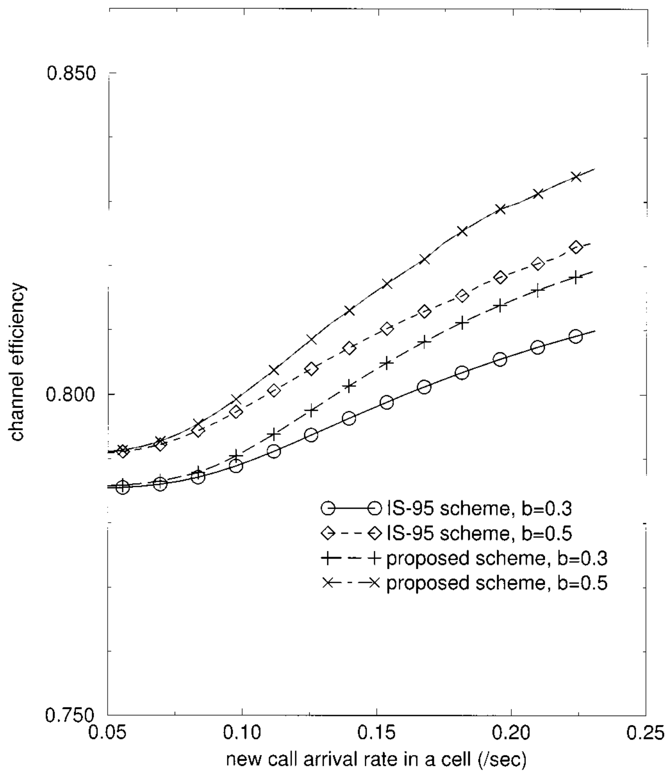

Fig. 11. Channel efficiency versus total new call arrival rate.

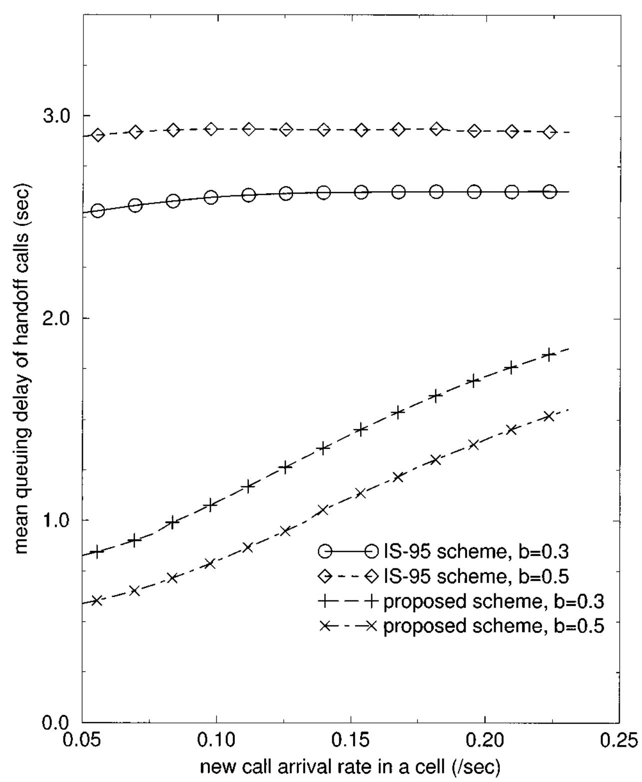

Fig. 12. Mean queuing delay under the condition that a handoff request is placed into a queue versus total new call arrival rate.

queuing delay under the condition that all channels are used results in less interference when a cell is in a high load condition.

TABLE I
RECEIVED SIGNAL POWER AT BSs WHEN AN MS REQUESTS HANDOFF AND RECEIVES A HANDOFF CHANNEL IN THE IS-95 AND CHANNEL-BORROWING SCHEMES

	d_A	P_t	$P_{r,A}$	$P_{r,B}$
when initiating HO	$0.775R$	$0.36R^4P$	P	$0.36P$
proposed scheme	$0.835R$	$0.49R^4P$	P	$0.62P$
IS-95 scheme	$0.935R$	$0.76R^4P$	P	$1.53P$

Therefore, the channel-borrowing scheme is preferable to the IS-95 scheme with respect to interference.

V. REMARKS ON INTERFERENCE ASPECTS

We consider interference from two viewpoints. First, let us consider the influence on interference when a channel is borrowed from a stationary handoff call in the channel-borrowing scheme. In this case, the channel is borrowed from a noncontrolling BS of a stationary call. Thus, the transmitting power of the MS remains the same before and after channel borrowing, and the interference increase is negligible.

Secondly, the channel-borrowing handoff scheme has an advantage over the IS-95 handoff scheme with respect to interference due to queuing delay. The queuing delay of the channel-borrowing scheme is shorter than that of the IS-95 scheme, as shown in Fig. 12. When there are many calls in a cell, interference is high and increased interference must be avoided. When there are no free channels, a handoff request is placed into a queue. Let us assume that the MS requesting a handoff channel moves from one cell to another cell. Until the queued handoff request receives a free channel for handoff or leaves the handoff area, the transmitting power of the MS requesting handoff will increase as the MS approaches the target cell. This increased transmitting power of the MS leads to greater interference. Since the total interference is already large in this case, the interference increase due to handoff queuing delay is highly undesirable. As the proposed channel-borrowing scheme has a shorter queuing delay than the IS-95 scheme, the amount of increased interference due to a queued handoff request of the channel-borrowing scheme is less than that of the IS-95 scheme.

Assume that an MS moves from cell A to cell B in linear motion, as shown in Fig. 1. There is no fading effect, and the path loss exponent is four. In Fig. 1, when $a = 0.4$ and the cell radius is R, the radius of the inner normal area of the cell is $0.775R$. The transmitting power of the MS when initiating a handoff request P_t is expressed as

$$P_t = P \cdot d_A^4. \tag{25}$$

BS A's receiving power of the signal transmitted by the MS is $P_{r,A}$. BS B's receiving power of the signal transmitted by the MS is $P_{r,B}$. In this case, BS A is the controlling BS of the MS and the controlled receiving power at BS A is $P_{r,A} = P$. Then, $P_{r,B}$ is obtained as

$$P_{r,B} = \frac{P_t}{(1.775R - d_A)^4}. \tag{26}$$

The queuing delay under the condition that a handoff request is placed into a queue is approximately 3 s for the IS-95 scheme and approximately 1 s for the channel-borrowing scheme when the new call arrival rate is about 0.1, as shown in Fig. 12. If the time for the MS to traverse the cell radius R is presumed to be $T_{\rm dc}/2 = 50/3$, the distance traversed by the MS until acquiring a handoff channel is approximately $0.165R$ for the IS-95 scheme and $0.065R$ for the channel-borrowing scheme. The resulting values of the received power at BS B are shown in Table I. We can see that when the handoff request acquires the handoff channel, the received power at BS B is $0.62P$ for the channel-borrowing scheme and $1.53P$ for the IS-95 scheme. This result illustrates that the IS-95 scheme causes more interference than the channel-borrowing scheme when a cell is in a full usage of the channels. Although the result shown in Table I is one of many possible values, it is apparent that the large queuing delay of the IS-95 scheme causes more interference than the channel-borrowing scheme.

VI. Conclusions

We propose a channel-borrowing handoff scheme based on user mobility in CDMA cellular systems in which a channel is borrowed from a stationary call in soft handoff and given to a handoff request of a moving call, when all channels in a cell are occupied. The proposed scheme does not increase interference to other users. We analyze the performances of the IS-95 soft handoff and the proposed handoff schemes considering both moving and stationary calls. Numerical results show that the proposed scheme outperforms the IS-95 scheme with respect to the handoff refused probability, queuing delay, and interference.

References

[1] A. J. Viterbi, *CDMA Principles of Spread Spectrum Communication*. Reading, MA: Addison-Wesley, 1995.

[2] D. Wong and T. J. Lim, "Soft handoffs in CDMA mobile systems," *IEEE Personal Commun. Mag.*, pp. 6–17, Dec. 1997.

[3] *Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System*, July 1993.

[4] I. A. Getting, "The global positioning system," *IEEE Spectrum*, pp. 36–47, Dec. 1993.

[5] , http://www.janet.ucla.edu/lpe.lwim.

[6] K. L. Yeung and S. Nanda, "Channel management in microcell/macrocell cellular radio systems," *IEEE Trans. Veh. Technol.*, vol. 45, pp. 601–612, Nov. 1996.

[7] Y. U. Chung, D. J. Lee, B. C. Shin, and D. H. Cho, "A new macrocell/microcell selection method in multitier cellular system," in *Proc. IEEE VTC'99*, 1999, pp. 1016–1020.

[8] W. C. Jakes, *Microwave Mobile Communications*: IEEE Press, 1993.

[9] M. D. Austin and G. L. Stüber, "Velocity adaptive handoff algorithms for microcellular systems," *IEEE Trans. Veh. Technol.*, vol. 43, pp. 549–561, Aug. 1994.

[10] S. L. Su, J. Y. Chen, and J. H. Huang, "Performance analysis of soft handoff in CDMA cellular networks," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 1762–1769, Dec. 1996.

[11] R. W. Wolff, *Stochastic Modeling and the Theory of Queues*. Englewood Cliffs, NJ: Prentice-Hall, 1989.

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