

# Design and Performance Analysis of a New Soft Handoff Scheme for CDMA Cellular Systems

Xiaomin Ma, *Member, IEEE*, Yun Liu, *Student Member, IEEE*, and Kishor S. Trivedi, *Fellow, IEEE*

**Abstract**—In this paper, a new soft handoff scheme for CDMA cellular systems is proposed and investigated. It is pointed out that some handoff calls unnecessarily occupy multiple channels with little contribution to the performance of handoffs in IS95/CDMA2000-based handoff schemes or systems. To alleviate performance degradation due to channel resource shortage during soft handoff, a new concept of channel convertible set (CCS), which contains several types of handoff calls that unnecessarily occupy extra channels by considering the relative mobility of the calls in the handoff area is introduced. A new scheme that reallocates those extra channels in the CCS to new handoff calls when there is no available free channel in the system is proposed. Furthermore, according to the variation of the CCS, the proposed scheme dynamically adjusts the number of guard channels reserved exclusively for handoff. Then, the feasibility and implementation issues of the proposed scheme are discussed. To evaluate and compare performance indexes of different soft handoff schemes, continuous-time Markov chain models are constructed. Automated generation and solution of the underlying Markov chains are facilitated by stochastic reward net models, which are specified and solved by stochastic Petri net package. Numerical results show that this scheme can significantly decrease both the number of dropped handoff calls and the number of blocked calls without degrading the quality of communication service and the soft handoff process.

**Index Terms**—Code-division multiple access (CDMA), performance, soft handoff, stochastic reward net (SRN).

## I. INTRODUCTION

AN important feature of cellular code-division multiple-access (CDMA) systems is soft handoff, which provides seamless connections of mobile calls between cells [9]. The soft handoff process is initiated and ended based on the received signal strength of a mobile station (MS). Comparing with hard handoff, which is used in frequency-division multiple-access (FDMA) and time-division multiple-access (TDMA) systems, there are many advantages of using soft handoff in CDMA systems along with power control, selection diversity, and rake receiver [1], [10], [11], [13], [14]. Although the capacity of CDMA systems is interference-limited in nature [6], channel shortages may occur, and the utilization efficiency of traffic channels may decrease because soft handoff

occupies multiple channels simultaneously. In urban CDMA cellular systems, the handoff area takes about 30%–50% [21] of the entire cell area. Therefore, the handoff process, in which each MS in the handoff area occupies two or more channels, would cause degradation in radio frequency (RF) capacity and an increase in call dropping probability in the downlink. Some techniques have been introduced to cope with these problems by adjusting soft handoff parameters to optimize performance [3]–[5], setting prioritized queues for handoff [16], using adaptive channel reservation [15], and eliminating pseudohandoff calls [2]. Lee and Cho [12] proposed channel borrowing from a stationary handoff call to reduce the chances of handoff dropping. However, those schemes only concentrate on improving a particular aspect of the performance in the CDMA system.

In this paper, we first analyze the conventional soft handoff scheme in CDMA cellular systems, such as IS95/CDMA2000 [17], [18]. We observe that there exist soft handoff calls that move away from the target cell to the neighboring cell or are in stationary status, which unnecessarily occupy multiple channels. The proposed scheme discriminates such pseudohandoff calls from real handoff calls by measuring and estimating their relative mobility, thus setting up a channel convertible set (CCS) [28]. When there are free channels, the handoff process operates in the same way as that in conventional IS95/CDMA2000 cellular systems. However, when all channels are occupied and a handoff request occurs, a weaker (or noncontrolling) channel used by a call in the CCS is converted to a new handoff request. Meanwhile, the number of guard channels reserved exclusively for soft handoff calls can be dynamically adjusted in terms of the size of the CCS so that more channel resources are saved for new calls. With our soft handoff scheme, the system channel shortage due to multiple-channel occupation by soft handoff calls is remarkably alleviated. Consequently, the performance of the CDMA system is improved without sacrificing the quality of service.

This paper is organized as follows: In Section II, some fundamental concepts and features of soft handoff in CDMA are described, and a relative mobility estimation method is illustrated and discussed. The proposed handoff scheme and its implementation issues are presented in Section III. To evaluate the new handoff scheme, stochastic reward nets (SRNs) are developed in Section IV. In Section V, the performance of the proposed scheme is analyzed and compared with that of the IS95/CDMA2000 conventional soft handoff scheme and channel-borrowing handoff scheme [12]. Finally, conclusions are made in Section VI.

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X. Ma is with the Department of Engineering and Physics, Oral Roberts University, Tulsa, OK 74171 USA (e-mail: mx@ee.duke.edu).

Y. Liu and K. S. Trivedi are with CACC, Department of ECE, Duke University, Durham, NC 27708 USA (e-mail: liu@ee.duke.edu; kst@ee.duke.edu).

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## II. SOFT HANDOFF DESCRIPTION AND RELATIVE MOBILITY ESTIMATION

### A. Brief Description of Soft Handoff in CDMA Systems

In CDMA cellular systems, each MS periodically measures and computes the received signal strength of the pilots from its surrounding base stations (BSs). The pilots identified by the MS are mainly categorized into three sets, namely 1) neighborhood set, 2) candidate set, and 3) active set. As an MS traverses a region of CDMA coverage, it searches for other usable channels from neighboring cells. All potential pilots from neighboring BSs are put into the neighborhood set of the MS. If the strength of a pilot in the neighborhood set exceeds a predefined threshold  $T_{ADD}$ , the detected pilot is transferred from the neighborhood set to the candidate set, indicating that the associated forward traffic channels could be successfully demodulated. The MS then generates a pilot strength measurement message (PSMM) and sends it to the BS controller, requesting a soft handoff channel from the neighboring BS. If the BS receives the PSMM, it sends a handoff direction message to indicate that the BS can assign a new channel for the handoff. Then, the MS sends a handoff completion message to the BS. If the BS receives the handoff completion message from the MS, the detected pilot is transferred from the candidate set to the active set. Thus, the speech frames will be sent between the mobile switch center (MSC) and the MS via the BS, whose pilots are in the active set. If the strength of a certain pilot that is currently in the active set is decreased to below the threshold  $T_{DROP}$ , the corresponding MS sends a PSMM to the BS associated with the pilot in order to request the release of the channel. Once the channel is released, the pilot is removed from the active set and transferred to the neighborhood set. In the mean time, the MS sends a handoff completion message to the BS. Path diversity reception, which is a key benefit of soft handoff, allows more than one BS in the active set during the handoff period, by which multiple signals from different BSs are combined to improve the signal-to-noise ratio (SNR) and the capacity of the system.

With regard to signal strength [26], [27], a cell can be divided into two areas, namely 1) the normal area and 2) 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  $T_{DROP}$ , broadcasted by the serving BS. Essentially, those areas are not always equivalent to the geometric areas identified by the physical distance at most time. The ratio  $a$  of the handoff area to the entire cell area is defined as

$$a = \frac{\text{area of the handoff region}}{\text{area of the cell}}. \quad (1)$$

Fig. 1 shows a visualization of the soft handoff area. The intersection area of two cells is considered the soft handoff area, in which all calls have two channels in their active sets. In the process of soft handoff, as defined in the U.S. IS95A, there can be more than two BSs in the active set. When the strength of one of the pilots in the active set is less than  $T_{DROP}$ , the

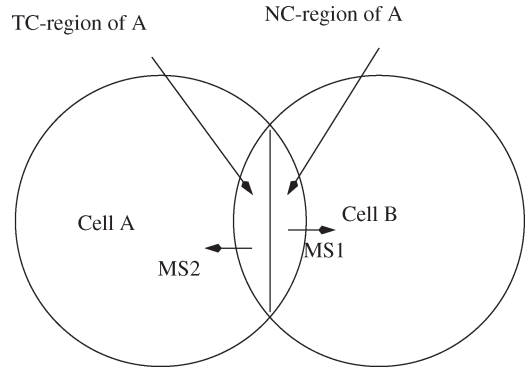


Fig. 1. Cellular geometry of soft handoff.

corresponding call will be considered to leave the handoff area for the normal area after waiting for a short period of duration. For IS95B/CDMA2000, three additional parameters are used in the soft handoff algorithm when the number of pilots in the active set is larger than three [29], [30], namely 1)  $SOFT_{SLOPE}$ , 2)  $ADD_{INTERCEPT}$ , and 3)  $DROP_{INTERCEPT}$ .

### B. Relative Mobility Estimation of MSs in the Handoff Area

We assume that the received pilot strength from a BS decreases as long as the MS moves away from the BS and increases as long as the MS moves toward the BS. An MS in the handoff area can detect pilot strength from the serving BS and the current time  $t$  broadcasted by the *sync* channel [7]. Let  $ps(t, i)$  be the received pilot strength from the serving BS, which is measured at time  $t$  by MS  $i$ , and let  $cr\_ps(t, i)$  be the rate of changing of  $ps(t, i)$ , which is given as

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

where  $\Delta t$  is the time period of the information update in the cellular system.

With the pilot strength and the rate of changing, the relative mobility of calls in the handoff area, such as relative position, moving direction, and velocity, can be estimated. It is reasonable that the BS with stronger pilot strength  $ps(t, i)$  in the active set of MS  $i$  in the process of handoff should be nearer to the MS than the BS with weaker pilot strength. In addition, a handoff call must be moving toward the BS if the rate of changing  $cr\_ps(t, i)$  detected by the BS is greater than zero. The bigger the  $cr\_ps(t, i)$ , the higher the velocity of the MS. If  $|cr\_ps(t, i)| < \epsilon$ , where  $\epsilon$  is small enough, the MS is considered stationary. The stationary calls in the handoff area request multiple channels, even though the call is not actually approaching the neighboring BS from the target BS.

Therefore, soft handoff can be performed in terms of both the received signal strength and the measured relative mobility of calls. In other words, the defined cellular areas 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 call in the area is greater than  $T_{ADD}$ ; the soft handoff area

of two cells is determined by checking if more than two pilot strengths from both the target BS (i.e., BS in cell A of Fig. 1) and the neighboring BS (i.e., BS in cell B) at time  $t$  are greater than  $T_{\text{ADD}}$ , which means that there are more than two channels in the active set of the call. Therefore, the normal area of a target cell is determined by checking if the  $ps(t, i)$  from the target BS is greater than  $T_{\text{ADD}}$  and the pilot strengths from all neighboring BSs are less than  $T_{\text{DROP}}$ . As demonstrated in Fig. 1, the handoff area can be further divided into the target controlling region (TC-region) and neighboring controlling region (NC-region) according to the relative received pilot strength. Let  $ps_T(t, i)$  be the strength of the pilot received from the target BS, and let  $ps_N(t, i)$  be the strength of the pilot received from the neighboring BS. If  $ps_T(t, i) > ps_N(t, i)$ , the MS must be in the TC-region, in which calls are mainly controlled by the target BS. On the other hand, if  $ps_T(t, i) < ps_N(t, i)$ , the MS must be in the NC-region, in which calls are controlled by the neighboring BS.

As a result of the adverse effects of signal propagation in the wireless environment, such as the effects of shadowing and fast fading, the aforementioned measurements may not reflect the real mobility situation of a call in the wireless cellular area, thus resulting in accurate decisions about the position or relative mobility of the call. Various schemes have already been suggested for overcoming the effects of signal propagation on the link quality [25]–[27] and deciding when a handoff should be performed. Of these schemes, temporal and spatial averaging signal-strength-based handoff algorithms have received the most attention because of their simplicity and good performance. It has been concluded [27] that time averaging, along with the required average signal strength difference or hysteresis, can significantly reduce the effect of fading and shadowing variations that would otherwise cause a large number of unnecessary handoffs. For the same reason, the time and spatial averaging method can also be employed in our relative mobility algorithm to reduce false measurements of pilot strength under the situation of disturbance and fading. On the other hand, pilot messages from multiple BSs are combined in MSC for the relative mobility estimation. These multiple measurements are able to not only enhance the accuracy and reliability of the estimation but also avoid the so-called corner effect [31], which occurs when turning corners or when big buildings are present, which make some mobiles suddenly lose links with the serving BSs. The detailed algorithm for relative mobility measurement and estimation can be found in [2]. In fact, there are several other effective methods used to estimate the speed of an MS in a wireless environment, including global positioning systems (GPSs) [22], microsensors [23], and cell sojourn time [24].

It should be noted that relative mobility estimation is essentially different from mobility management, which is utilized in current wireless cellular systems. The main purpose of mobility management is to support the registration and deregistration of an MS by using a direct-transfer application part (DTAP) message, whereas relative mobility estimation is concerned with the relative position, speed, and moving direction of an MS in a soft handoff area needed for constructing the CCS in terms of the measured signal strength.

### III. HANDOFF SCHEME OF CHANNEL-CONVERSION WITH DYNAMIC GUARD CHANNEL RESERVATION (CCDG)

Based on the estimation of relative mobility of MSs in the handoff area, the proposed scheme is divided into two steps, namely 1) construction of CCS and 2) channel allocation for soft handoff requests.

#### A. Construction of CCS

The set that contains all handoff calls in the NC-region of the target cell, such that they have channels from both the target BS and neighboring BS and they are staying stationary or moving away from the target cell, is defined as the CCS of the target cell.

According to the preceding definition, a CCS includes three types of soft handoff calls: The first are new calls that originated in the NC-region of the soft handoff area and are moving away from the target cell. These calls request soft handoff to the neighboring BS immediately after their new calls are accepted by the serving BS. The number of such calls is about 25% [26] of the total number of new calls in the handoff area. The second are handoff calls that stay stationary while talking. In real urban CDMA systems, the number of stationary MS calls are about 40%–50% [29] of the total number of the MS calls. The calls in the preceding two cases are defined as pseudohandoff calls in this paper because those calls do not really carry out handoff. The third are calls that are moving from the TC-region to the NC-region of the target cell while talking and are continuing to move toward a neighboring cell. In this case, the BS of the neighboring cell has been changed as the controlling BS of the call during the handoff process.

In each BS, a CCS is set up to identify pseudohandoff calls and serve for incoming handoff calls. The CCS is constructed and managed as shown in Fig. 2. Fig. 2(a) illustrates how the CCS is constructed. For each handoff call in the target cell, the relative mobility in the soft handoff area is periodically measured and estimated, as described in Section II-B. Once the relative mobility is updated, the call will be checked if it stays in the NC-region of the target cell such that  $ps_T(t, i) < ps_N(t, i)$ . Then, all handoff calls in the NC-region should be tested in the MSC to make sure that each of them holds at least two channels in its active set. If so, (2) and  $cr\_ps(t, i)$  will be evaluated to see if the call is stationary or moving away from the target cell such that  $cr\_ps(t, i) < 0$  or  $|cr\_ps(t, i)| < \epsilon$ . The call will be added to the CCS of the target cell if all the constraint conditions in the CCS definition are met. On the other hand, Fig. 2(b) illustrates how handoff calls are removed from the CCS. Each handoff call in the CCS is also periodically checked. The call will be taken out of the CCS of the target cell if one of following three situations takes place: it is out of coverage of the target cell, it completes its call, or it no longer satisfies the conditions for a pseudohandoff call.

#### B. Channel Allocation for Soft Handoff Requests

In order to improve the efficiency of channel utilization and reduce both dropping and blocking probabilities, a new handoff

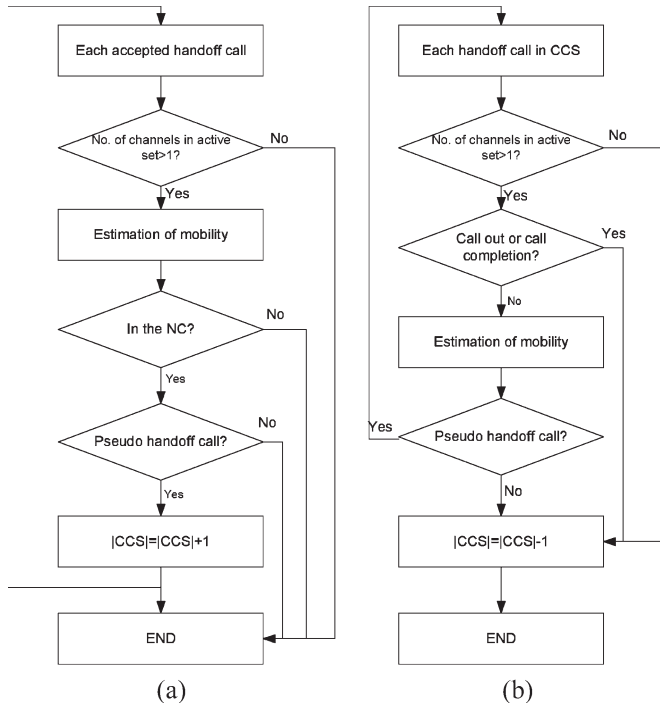


Fig. 2. Flow diagram of CCS construction and update.

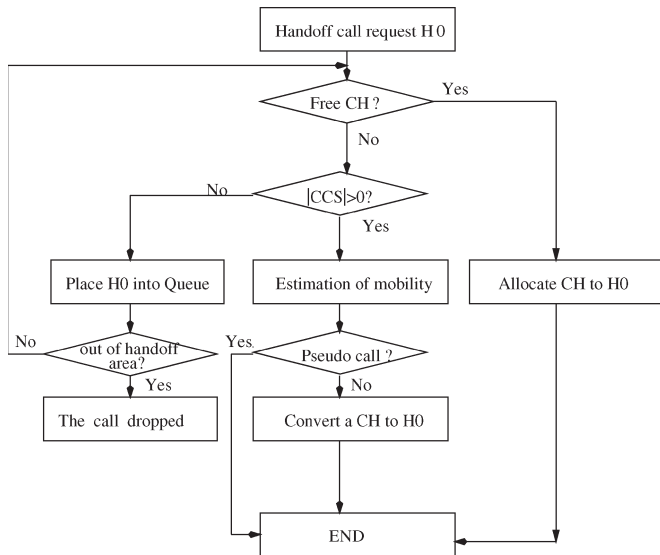


Fig. 3. Flow diagram of the channel allocation in the CCDG scheme.

scheme based on the relative mobility of users is proposed. Calls in the NC-region of the target cell periodically report their pilot strength to the BS and the MSC, where the CCS is constructed and updated, as discussed in Section III-A. Fig. 3 shows the proposed handoff scheme for new handoff calls. When a new handoff call arrives, the BS at the target cell first checks if there exists any free channel. If so, the channel is allocated to the handoff call. If no free channel is available and the new handoff call is a real handoff call, the noncontrolling channel (or the channel with weaker pilot strength) of a call in the CCS is converted to the new handoff request as long as the CCS is not empty. Otherwise, the new handoff call is placed in

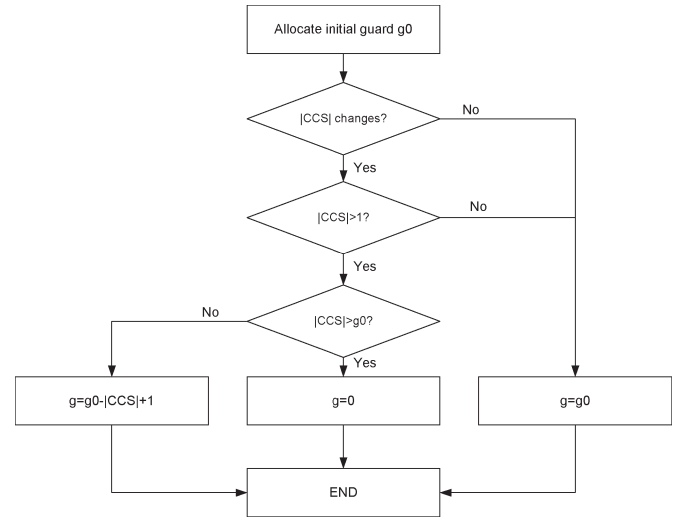


Fig. 4. Flow diagram of dynamic guard channel reservation in the CCDG scheme.

a queue to wait for a free channel or a channel from a call in the CCS. The call will be refused if the queue is full. However, refusing a handoff call request does not mean that it is dropped. A handoff call in the handoff queue would be dropped only after the call moves out of the handoff area without getting any channel from the target cell.

Since the dropping of a handoff call is considered more severe than the blocking of a new call, a fixed number of channels is often reserved exclusively for handoff calls. These exclusively reserved channels are referred to as guard channels. It is not efficient for such guard channels to be reserved even when handoff traffic is not heavy. Thus, in our scheme, the number of soft guard channels for handoff is dynamically adjusted according to the variation of the CCS. The number of guard channels is updated every time that the CCS is changed. The bigger the CCS, the less the number of guard channels. Fig. 4 shows a flow diagram of dynamic channel reservation. At first, the number of guard channels is initialized as  $g_0$ . Then, the number of guard channels is dynamically adjusted. If the number of calls in the CCS is less than or equal to 1,  $g$  remains the assigned value  $g_0$ . If  $|CCS| > g_0$ , which means there are enough channels in the CCS that are available for new handoff calls,  $g$  is set to 0. Otherwise, if  $0 < |CCS| < g_0$ ,  $g$  is set to  $g_0 - |CCS| + 1$ . This scheme avoids unnecessary guard channel assignment when adequate channel resources are available for handoff requirement.

When channel conversion is performed, it is important not to influence the quality of voice and increase the total interference. Since selection diversity is used for uplink interference in a CDMA system where one BS (called controlling BS) that has a higher receiving power than another BS demodulates the received signal, the transmitting power of the MS will remain almost the same. In the proposed scheme, the noncontrolling channel of a call in the CCS is converted to an incoming handoff call without remarkably degrading voice quality, handoff process, and interference requirement as the channel conversion goes on.

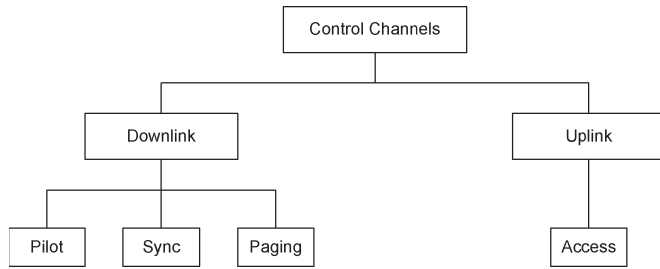


Fig. 5. Logic control channels in IS95 CDMA systems.

### C. Implementation Issues in Current IS95 CDMA Systems

Our proposed CCDG scheme can be implemented in current IS95 CDMA systems. No hardware change is required in the relevant system components such as MSC, BS, and MS to perform the new scheme. However, some software updates are needed at the MS and MSC. With respect to the functionality, the software change has mainly two parts:

First, the pilot strength measurement protocol needs to be introduced in the current systems. As shown in Fig. 5, paging channels, pilot channels (PCs), and access channels are control channels in the IS95 CDMA. MS measures the pilot strength through the PC of surrounding cells. Then, the pilot signal strength is periodically reported to the BS through the PSMM. The new protocol must make the mobile frequently send the PSMM of all the pilots in the active set to the BS so that the MSC is able to estimate the relative mobility in a desirable resolution. Note that the CDMA system has been designed with a very flexible signaling and control structure that allows for new features and capabilities to be readily added. Variable rate speech coding allows both voice and control messages to be sent during 20-ms frames. In the IS95 system, control messages are sent via dim and burst, or blank and burst schemes [7]. For dim and burst, control information is sent in the unused portion of a vocoded frame during periods of low-speech activity, whereas for blank and burst, control information replaces one or more frames of primary traffic data. This can be realized by letting the BS periodically send the mobile a pilot strength measurement request message through the downlink paging channel (PgC). Upon receiving the measurement request, the mobile mixes the PSMM with the voice data on the reverse traffic channel (RTC) and sends them to the BS or the MSC. When operating on the CDMA channel, the PSMM messages can be sent by using the blank and burst scheme or the dim and burst scheme, depending on the traffic load. Dim and burst inserts PSMM messages when speech activity is low. Hence, the messages have no effect on speech quality. Of course, the PSMM message transmissions by blank and burst degrade speech quality because they replace speech frames with control information. However, the quality degradation for only one isolated replacement is always imperceptible. For example, if the time period of the PSMM update is set as 100 ms and a frame takes 20 ms, a slot with a duration of 1.25 ms is needed for the PSMM transmission per five speech frames.

Second, after the BS forwards the PSMM to the MSC, a new software component in the MSC should perform further processing of the collected data to implement the CCDG algo-

rithm. The three major computation tasks have been discussed in the previous parts of this section. The first task is for the MSC to estimate the relative mobility from the PSMM of multiple BSs. As the wireless channel may experience severe fading, the smoothing statistical technique is used to obtain accurate pilot strength estimation. To make the proposed scheme robust, when the pilot measurements of multiple BSs give contradictory mobility information, the relative mobility should not be used in neither the CCS construction nor channel conversion. This situation is inevitable in a wireless communication environment since the channel quality is affected by many factors. As a result, the handoff call without reliable mobility measurement should be treated as that in the system that CCDG is not implemented. This means that this handoff is regarded as a real handoff and will not be included in the CCS. This can avoid potential performance degradation due to the false relative mobility estimation. Two other tasks, the CCS construction and channel conversion, are also realized by the new software component residing in the MSC.

## IV. SRN MODELS FOR THE CCDG SCHEME

We construct analytic models by using SRN to evaluate the benefits of employing the CCDG handoff scheme in CDMA cellular systems. SRN [19] is an extension of Petri net (PN), which is a high-level description language for formally specifying complex systems. In this paper, we use the tool stochastic Petri net package (SPNP) [20] to specify and solve the SRN models.

### A. Model Description

The main parameters used in our analytical models are given as follows:

- $T_d$  number of channels in a cell;
- $l_e$  maximum handoff queue length;
- $a$  ratio of the handoff area to the entire cell area;
- $\lambda_n$  new call arrival rate in a cell;
- $\lambda_h$  handoff arrival rate in a cell;
- $\lambda_n^c$  new call arrival rate in normal area;
- $\lambda_n^s$  new call arrival rate in handoff area;
- $\lambda_c^d$  transferring rate of a call from the normal area to the handoff area;
- $\lambda_c^a$  transferring rate of a call from the handoff area to the normal area;
- $\lambda_s^d$  call departure rate from handoff area;
- $\lambda_t$  call departure rate from normal area;
- $\lambda_h^d$  moving rate to an adjacent cell;
- $\lambda_s^c$  moving rate from TC-region to NC-region of the target cell;
- $\lambda_0^1$  call departure rate from CCS;
- $\lambda_0^2$  call departure rate from handoff queue;
- $T_c$  channel holding time;
- $\mu_c$  mean of channel holding time;
- $c$  probability that a handoff call is a pseudohandoff call;
- $g$  current number of guard channels;
- $g_0$  predefined initial number of guard channels.

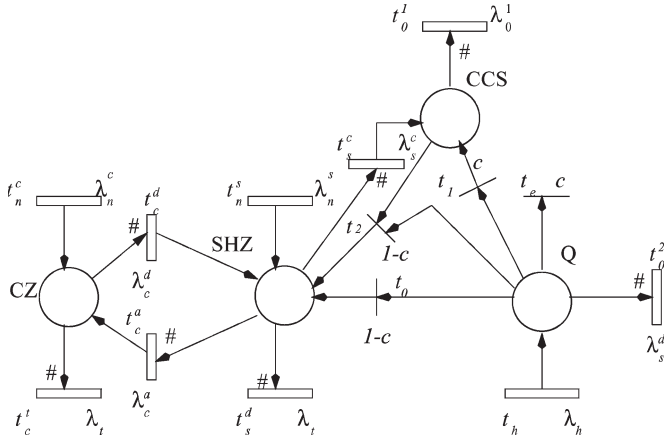


Fig. 6. SRN model for the CCDG handoff scheme.

Under the condition that all the neighboring cells are statistically identical and behave independently, the characteristics of the overall system can be captured by focusing on a single cell. In our analytic model, we only consider that there are, at most, two different sources in diversity reception. Each cell will reserve  $g$  channels out of a total of  $T_d$  available channels exclusively for handoff calls. Every handoff request is assumed to be perfectly detected in our model, and the assignment of the channel is instantaneous if the channel is available. It is also assumed that the allowable maximum handoff queue length is equal to  $l_e$ . In addition, we assume that calls initiated within the cell arrive at a Poisson rate of  $\lambda_n$ , handoff request arrivals also form the Poisson process with rate  $\lambda_h$ , and channel holding time  $T_c$  follows an exponential distribution with mean  $\mu_c^{-1}$ . Assuming that the location of a newly generated call is uniformly distributed over a cell, the new call arrival rates in the normal and handoff regions are  $\lambda_n^c = (1 - a)\lambda_n$  and  $\lambda_n^s = a\lambda_n/2$ , respectively. Notice that we just consider new calls in the TC-region of the target cell as new calls in the handoff region, from the viewpoint of the target cell, whereas the new calls in the NC-region of the target cell are taken as handoff calls to the target cell. The dwelling times of a call in the two distinct regions are assumed to be exponentially distributed. The transferring rate of a call from the normal area to the handoff area is  $\lambda_c^d$ , and the transferring rate of a call from the handoff area to the normal area is  $\lambda_c^a$ . The rate that a call is terminated is denoted as  $\lambda_t$ , the rate that a call moves to an adjacent cell is  $\lambda_h^d$ , and the rate that a call moves from the TC-region to the NC-region of the target cell is  $\lambda_s^c$ . These quantities can be evaluated by using similar methods described in [8].

According to the preceding description, we construct an SRN model that can be automatically converted to a Markov chain to calculate performance indexes. Fig. 6 shows the SRN model for the CCDG handoff scheme. Place CZ represents the normal area of a generic cell; place CCS represents the CCS in the handoff area; place SHZ represents a set of handoff calls apart from the CCS; and place Q represents the queue for handoff calls. New call arrivals for the CZ and SHZ are represented

TABLE I  
ENABLING FUNCTIONS FOR THE CCDG HANDOFF SCHEME

Transition	Enabling Function
$t_n^c, t_n^s$	$(\#CZ) + (\#SHZ) + (\#CCS) < T_d - g$
$t_h$	$(\#Q) < l_e$
$t_0, t_1$	$(\#CZ) + (\#SHZ) + (\#CCS) < T_d$
$t_2, t_e$	$(\#CZ) + (\#SHZ) + (\#CCS) \geq T_d$ & $\&\&(\#CZ) + (\#SHZ) < T_d$

by the transitions  $t_n^c$  and  $t_n^s$ , respectively. If the current traffic load of the target cell is under the predefined threshold, the new calls are accepted. That a call moves from the CZ to (from) the SHZ while talking is represented by transition  $t_c^d$  ( $t_c^a$ ). With regard to the other cell that covers the SHZ, its handoff arrival is also represented by transition  $t_c^d$ . Call departure from CZ is depicted through transition  $t_c^t$  with rate  $\lambda_t$ . Considering that call departure in the handoff area is caused by either call termination or call leaving for the adjacent cell, thus, call departures from SHZ, CCS, and Q are represented by transitions  $t_s^d$  with rate  $\lambda_s^d = \lambda_h^d + \lambda_t$ ,  $t_0^1$  with rate  $\lambda_0^1$ , and  $t_0^2$  with rate  $\lambda_0^2 = \lambda_h^d + \lambda_t$ , respectively. That a call leaves SHZ for CCS is represented by the transition  $t_c^c$  with rate  $\lambda_c^c$ .

For a handoff arrival, which is represented by transition  $t_h$ , the call can be accepted immediately through transition  $t_0$  by SHZ with probability  $1 - c$ , or through transition  $t_1$  by CCS with probability  $c$  if the cell is not overloaded. Here,  $c$  is the probability that a handoff call is a pseudohandoff call. If the effective load is over the threshold and CCS is not empty, a channel of a call in CCS is converted to the real new handoff call, which is accepted by SHZ through transition  $t_2$  with probability  $1 - c$ , and the pseudohandoff calls are ignored in the queue through transition  $t_e$  with probability  $c$ . If the effective load is over the threshold and CCS is empty, and the queue is not full, the handoff call can wait in the queue. Then, once the queue is full and CCS is empty, the new handoff call is forcibly terminated. Transitions  $t_c^c$ ,  $t_c^d$ ,  $t_c^a$ ,  $t_s^d$ ,  $t_0^1$ , and  $t_0^2$  have marking-dependent firing rates, i.e., the actual firing rates for these transitions are proportional to the number of tokens in the respective input places. In SRN, the marking-dependent firing rate is represented by the sharp sign (#).

Table I summarizes the enabling functions (also called guards) for the SRN model, where # represents the number of tokens in a place. The enabling function of a transition determines whether a transition is enabled or not. This is an added condition on top of the explicit input and inhibitor arcs.

With different new call arrival rates, the fixed-point iteration [19] method is employed to determine handoff arrival rate  $\lambda_h$  and probability  $c$  that a handoff call is a pseudohandoff call. We have noted that a call that enters the handoff area from the normal area of the target cell will ask for a channel from the neighboring cell; thus, it will be a handoff arrival from the point of view of the neighboring cell. Besides, a new generated call in the TC-region of the target cell will become a handoff arrival to the neighboring cell immediately after it gets a channel from

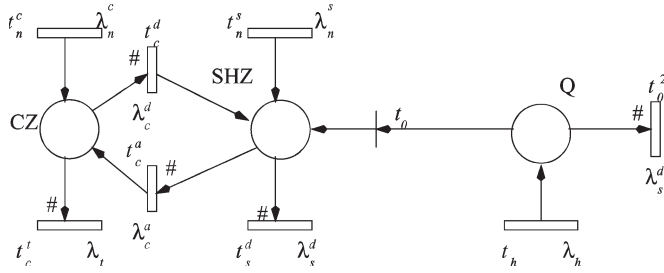


Fig. 7. SRN model for the conventional handoff scheme.

TABLE II  
ENABLING FUNCTIONS FOR THE IS95 HANDOFF SCHEME

Transition	Enabling Function
$t_n^c, t_n^s$	$(\#CZ) + (\#SHZ) < T_d - g$
$t_h$	$(\#Q) < l_e$
$t_0, t_1$	$(\#CZ) + (\#SHZ) < T_d$

the target cell. Therefore, such parameters are calculated as follows:

$$\lambda_h = \Lambda_c^d + \lambda_n^s(1 - P_B) \quad (3)$$

$$c = \frac{2}{3} \frac{\Lambda_n^s}{\Lambda_n^s + \Lambda_c^d} \quad (4)$$

$$g = \begin{cases} g_0, & (\#CCS) = 0, 1 \\ g_0 - (\#CCS) + 1, & 1 < (\#CCS) < g_0 \\ 0, & (\#CCS) \geq g_0 \end{cases} \quad (5)$$

where  $\Lambda_c^d$ ,  $\Lambda_n^s$ , and  $\Lambda_n^c$  denote the throughputs of transitions  $t_c^d$ ,  $t_n^s$ , and  $t_n^c$ , respectively. We assume here that the moving directions of new call in the handoff area are uniformly distributed over three event spaces, namely 1) being stationary, 2) moving toward the target cell, and 3) moving away from the target cell. Thus, according to the previous definition of pseudohandoff call, the ratio of pseudohandoff calls to new calls in the handoff area is 2/3.  $P_B$  is the blocking probability defined in (6).  $g_0$  denotes the predefined initial number of guard channels.

For comparison purposes, an SRN model of the IS95 conventional soft handoff scheme is described in Fig. 7. Since channel conversion and dynamic guard reservation are not deployed in the conventional soft handoff scheme, place CCS and the corresponding transitions in Fig. 6 are removed. As a result of the differences, enabling functions of the transitions for the IS95 soft handoff schemes are changed (Table II). Accordingly, the rates of transitions  $t_s^d$  and  $t_0^2$  are also changed.

## B. Performance Measures

1) *New Call Blocking Probability*: We denote the blocking probability from the cell's point of view as  $P_B$  and the blocking probabilities from the system's point of view as  $P_{BS}$ . They are computed as

$$P_B = \sum_{j \in \Omega} r_h^j \pi_j \quad (6)$$

$$P_{BS} = a \cdot P_B \cdot P_B + (1 - a) \cdot P_B \quad (7)$$

where  $\Omega$  is the set of tangible markings in the SRN model and  $\pi_j$  is the steady-state probability of marking  $j$ . In the handoff area, if the new call is blocked at one cell, it still has a chance to obtain a channel from a neighboring cell. That is the reason  $P_B$  appears twice in the preceding equation for system blocking probability evaluation. The reward rate assignment  $r_h^j$  takes the following form:

$$r_h^j = \begin{cases} 1, & (\#CZ) + (\#SHZ) + (\#CCS) > T_d - g \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

2) *Handoff Refused Probability*: An incoming handoff request to a cell may be refused under either of the following circumstances: 1) the handoff queue is already full or 2) it does not obtain a handoff channel until either call completion or departure of the caller from the cell takes place. Let  $P_{DS}$  denote the handoff refused probability for the CCDG and the IS95 soft handoff schemes from the system's point of view, which is given by

$$P_{DS} = P_q^f + \frac{\Lambda_0^2}{\Lambda_h} \quad (9)$$

where  $P_q^f$  is the probability that the queue is full, which is calculated as the steady-state expected reward rate

$$P_q^f = \sum_{j \in \Omega} r_q^j \pi_j, \quad r_q^j = \begin{cases} 1, & (\#Q) = l_e \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

and  $\Lambda_h$  and  $\Lambda_0^2$  are the throughputs of transitions  $t_h$  and  $t_0^2$ , respectively.

3) *Average Number of Guard Channels*: The average number of guard channels  $E[g]$ , which reflects the variation of guard channel reservation for handoff call, is equal to  $g_0$  for IS95 handoff schemes. For the proposed CCDG handoff scheme, it is given by

$$E[g] = \sum_{j \in \Omega} (g_0 - \min(g_0, \max((\#CCS), 1) - 1)) \pi_j. \quad (11)$$

4) *Carried Handoff Traffic*: The carried handoff traffic per cell is defined as the average number of occupied channels in the handoff area of the target cell, i.e.,

$$C_H = \sum_{j \in \Omega} ((\#SHZ) + (\#CCS)) \pi_j. \quad (12)$$

5) *Carried Traffic*: The carried traffic per cell is defined as the average number of occupied channels in the target cell. Therefore, carried traffic  $C_T$  is calculated by

$$C_T = \sum_{j \in \Omega} ((\#CZ) + (\#SHZ) + (\#CCS)) \pi_j. \quad (13)$$

6) *Conversion Probability*: The conversion probability is defined as probability that conversion transition  $t_2$  is enabled during the handoff process, i.e.,

$$P_c = \sum_{j \in \Omega} r_c^j \pi_j, \quad r_c^j = \begin{cases} 1, & \text{if } t_2 \text{ is enabled} \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

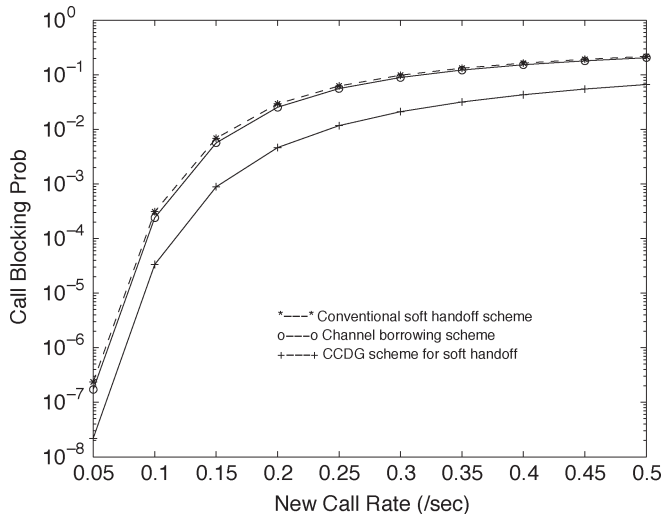


Fig. 8. New call blocking probability versus new call arrival rate (calls/s).

V. NUMERICAL RESULTS

Numerical results are reported in this section. We consider a system with parameters  $T_d = 15$ ,  $a = 0.5$ ,  $g_0 = 2$  (channels),  $\lambda_t = 0.01$  (calls/s),  $\mu_{dc} = (T_{dc})^{-1} = 0.03$  (calls/s), and  $le = 4$ . According to [8], other parameters can be derived as  $\lambda_c^d = 0.0365854$  (calls/s),  $\lambda_c^a = 0.024$  (calls/s),  $\lambda_h^d = 0.051$  (calls/s), and  $\lambda_s^c = 0.066889$  (calls/s).

The SRN models for the proposed CCDG handoff scheme, conventional IS95 handoff schemes, and channel-borrowing handoff scheme [12] are constructed and compared. All such SRN models are converted into Markov chains in SPNP. The number of states and the number of transitions in the CTMC are 200 and 999, respectively, for the conventional IS95 soft handoff scheme; 880 and 5943, respectively, for the channel-borrowing handoff scheme; and 880 and 6779, respectively, for the CCDG handoff scheme.

Fig. 8 shows the new call blocking probabilities of the three handoff schemes. The new call blocking probability of channel borrowing is almost same as that of the conventional IS95 soft handoff scheme because the channel-borrowing handoff scheme does not help improve the performance of new calls. However, the blocking probability of the CCDG scheme is about ten times lower than that of the two other handoff schemes because the CCDG scheme accommodates more handoff calls by channel conversion and gets more channel resources for a new call due to dynamic guard channel adjustment.

Fig. 9 shows the handoff refused probability of three handoff schemes. The improvement on handoff refused probability by CCDG handoff scheme is steady and significant (about two orders of magnitude relative reduction), and much greater than the improvement made by only channel borrowing because the CCDG scheme distinguishes handoff calls in the CCS from ordinary handoff calls and serves more handoff calls by channel conversion.

Fig. 10 shows the average number of guard channels for the three handoff schemes.  $E[g]$  is a constant for both the IS95 handoff scheme and the channel-borrowing handoff scheme because the number of guard channels in the systems is fixed

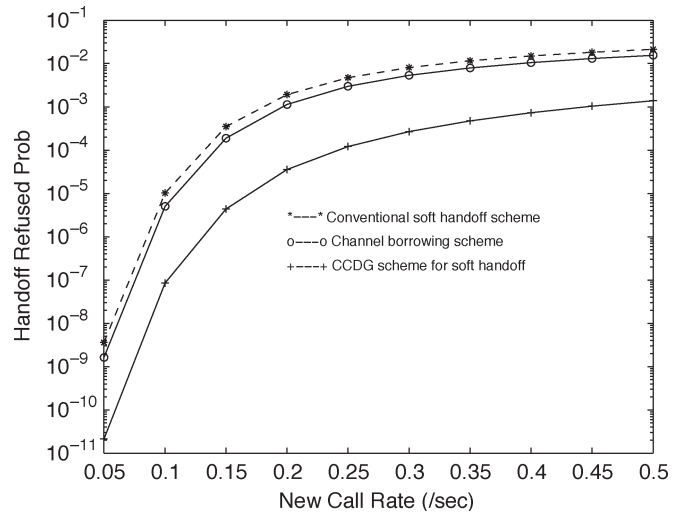


Fig. 9. Handoff refused probability versus new call arrival rate (calls/s).

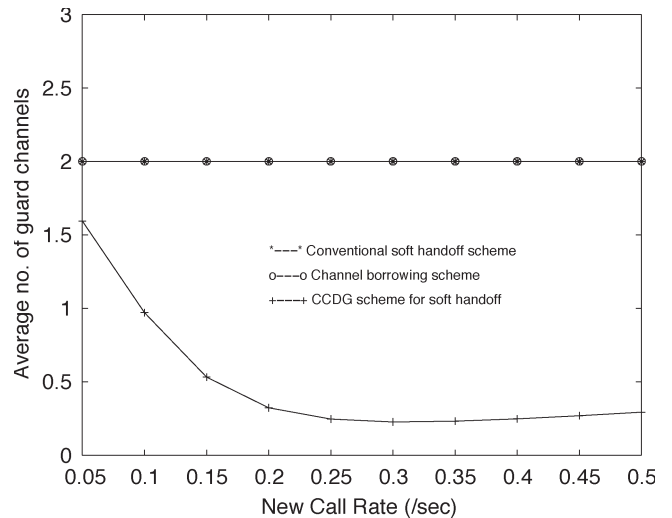


Fig. 10. Average number of guard channels versus new call arrival rate (calls/s).

throughout the channel allocation process. However, for the CCDG handoff scheme, it decreases when a cell is in higher load, which implies that the channel conversion policy and dynamic channel reservation increase capacity for new calls in the normal area.

Figs. 11 and 12 show the carried handoff traffic and total handoff traffic of the three schemes, respectively. The average number of handoff calls for the CCDG scheme is bigger than that for the two other schemes, which indicates that the CCDG handoff scheme makes more handoff calls being served by the systems.

Fig. 13 shows the enabling probability of channel conversion during the handoff process for the CCDG scheme, which increases with the call arrival rate. However, as traffic is getting heavy, the increase of conversion probability gradually turns slower till it finally becomes a constant. This is because more channels occupied by handoff calls in the CCS may contribute to alleviating possible handoff dropping as traffic is getting heavier and until the channel pool in the CCS is out of supply.

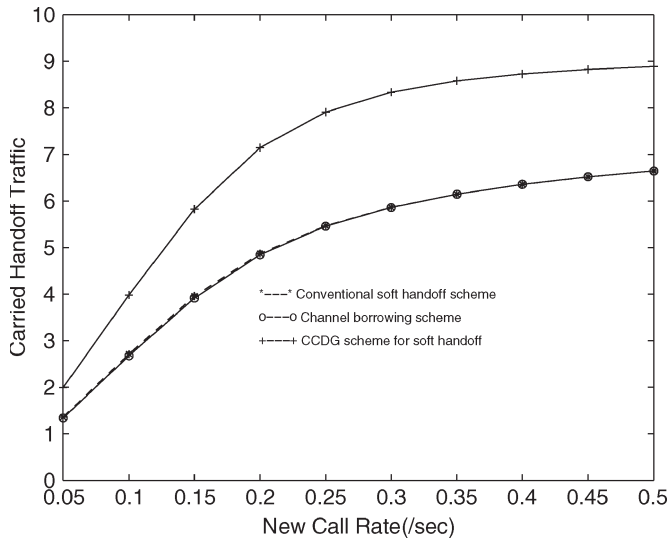


Fig. 11. Carried handoff traffic versus new call arrival rate (calls/s).

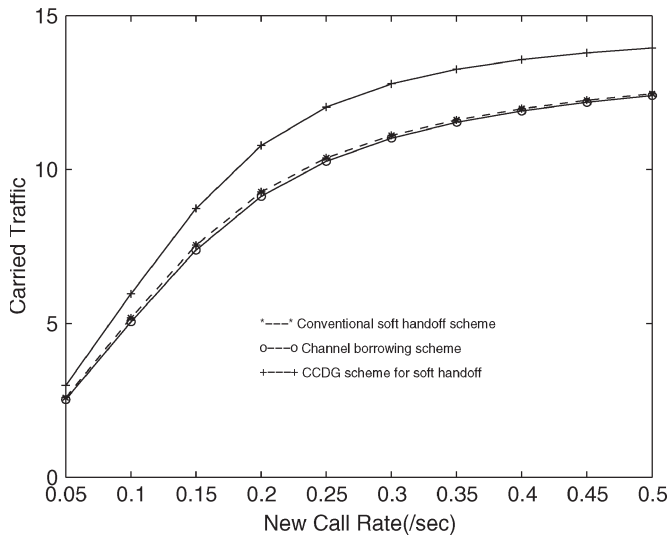


Fig. 12. Carried traffic versus new call arrival rate (calls/s).

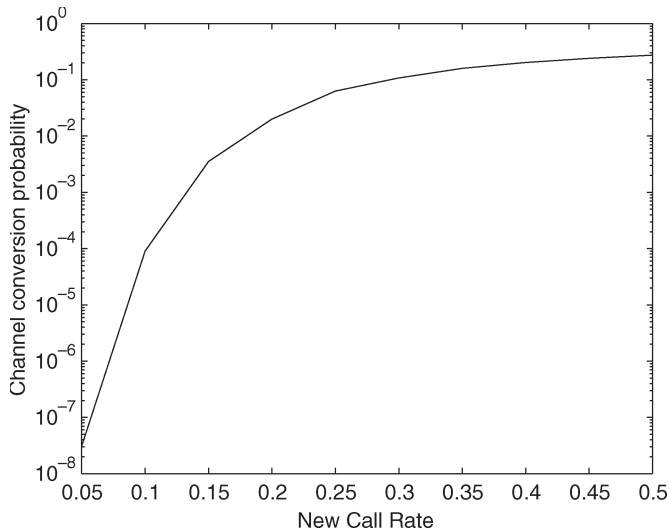


Fig. 13. Conversion probability versus new call arrival rate (calls/s).

## VI. CONCLUSION

Since an MS holds at least two traffic channels in the soft handoff area, a handoff scheme to increase the utilization efficiency of traffic channels is desirable in CDMA cellular systems. In this paper, CCDG is proposed, and SRN models are developed to analyze the performance of our scheme. The proposed scheme frequently measures and estimates the relative mobility of new handoff calls. When all channels in a cell are occupied, the noncontrolling channel of a handoff call in CCS is converted to a new real handoff call. Our scheme does not increase interference to other users and does not degrade the quality of the soft handoff process.

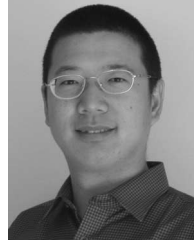
Numerical results show that the proposed scheme outperforms the conventional handoff scheme. Compared with the soft handoff schemes proposed in patents and related publications, the advantages of our scheme for soft handoff are that 1) the scheme can significantly reduce both new call blocking probability and the handoff refused probability, 2) it does not noticeably degrade the quality of service, and 3) it adds little extra hardware burden and computation complexity.

Future research will consider the performability of CDMA systems with soft handoff, prioritized queue, and non-Poisson traffic.

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**Yun Liu** (S'99) received the M.S. degree in 2002 from the Department of Electrical and Computer Engineering, Duke University, Durham, NC, for the study of performance analysis of cellular networks. He is currently working toward the Ph.D. degree at Duke University in the area of survivability analysis of networked systems.

His research interests include performance, reliability, availability, and survivability modeling of telecommunications and computer networks.



**Kishor S. Trivedi** (M'86–SM'087–F'92) received the B.Tech. degree from the Department of Electrical Engineering, Indian Institute of Technology, Bombay, India, in 1968 and the M.S. and Ph.D. degrees from the Computer Science Department, University of Illinois, Urbana, in 1972 and 1974, respectively.

He is the Hudson Chair with the Department of Electrical and Computer Engineering, Duke University, Durham, NC, where he has been a Member of the faculty since 1975. He is also the Duke-Site Director of a National Science Foundation Industry–University Cooperative Research Center between NC State University and Duke University for carrying out applied research in computing and communications. He is the author of a well-known text entitled *Probability and Statistics with Reliability, Queuing and Computer Science Applications* (New York: Wiley, 2001), with the revised second edition under publication, and two other books entitled, *Performance and Reliability Analysis of Computer Systems* (Boston, MA: Kluwer, 1996) and *Queuing Networks and Markov Chains* (New York: Wiley, 2006). He has also published over 300 articles, lectured extensively on performance and reliability analysis, and supervised 37 Ph.D. dissertations. He is a codesigner of the HARP, SAVE, SHARPE, and SPNP software packages, which have been well circulated. His research interests include reliability and performance assessments of computer and communication systems.

Dr. Trivedi is a Golden Core Member of the IEEE Computer Society.



**Xiaomin Ma** (M'03) received the B.E. and M.E. degrees in electrical engineering and the Ph.D. degree in information engineering from Beijing University of Posts and Telecommunications, Beijing, China, in 1984, 1989, and 1999, respectively.

From 2000 to 2002, he was a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, Duke University, Durham, NC. He is currently an Assistant Professor with the Department of Engineering and Physics, Oral Roberts University, Tulsa, OK. His research interests include stochastic

modeling and analysis of computer and communication systems, computational intelligence and its applications to coding, signal processing, and control, and quality of service and call admission control protocols in wireless networks.