Comparing Soft and Hard Handoffs

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***Abstract*—This paper studies the soft-handoff mechanism and compares its performance with hard handoff. Our study indicates that although a handset may potentially consume extra radio links in soft handoff, the mechanism provides better opportunity to transfer the link successfully in the handoff procedure. Thus, by carefully planning the overlay areas of cells, soft handoff can outperform hard handoff.**

***Index Terms*—Hard handoff, personal communications services, radio channel allocation, soft handoff.**

I. Introduction

In a mobile communication network, a handset communicates with the outside world through the radio contact to a base station (BS). When a call arrives at a *cell* (i.e., the *coverage area* of a BS), the destination (or the originating) handset is connected if a channel is available. Otherwise, the call is blocked (this is referred to as a *new call blocking*). When a communicating handset moves from one cell to another, the channel in the old BS is released and a channel is required in the new BS. This process is called *handoff*. In mobile systems such as AMPS [1], global system for mobile communication (GSM) without macrodiversity [2], DECT [3], D-AMPS [4], and PHS [5], *hard handoff* is employed [6], [7]. In hard handoff, the old radio link is broken before the new radio link is established, and a handset always communicates with one BS at any given time. In the handoff procedure, the network needs to set up the new voice path for the handoff call. This setup time is referred to as the *network response time* t_{nrt}. If the old radio link is disconnected before the network completes the setup, the call is forced terminated. Thus, even if idle channels are available in the new cell, a handoff call may fail if the network response time t_{nrt} for link transfer is too long. Note that a handoff failure may not necessarily cause a call drop. It is normally some time-out mechanism for the voice or signaling path which leads to a dropped call.

Some code-division multiple-access (CDMA) systems [8] and GSM with macrodiversity [2] utilize *soft handoff* where a handset may communicate with the outside world using multiple radio links through different BS's at the same time. During handoff, the signaling and voice information from multiple BS's are typically combined (or bridged) at the mobile switching center [9]. Similarly, voice and signaling information must be sent to multiple BS's, and the mobile station must combine the results. In some soft-handoff systems, a handset may connect up to three or four radio links at the same time.

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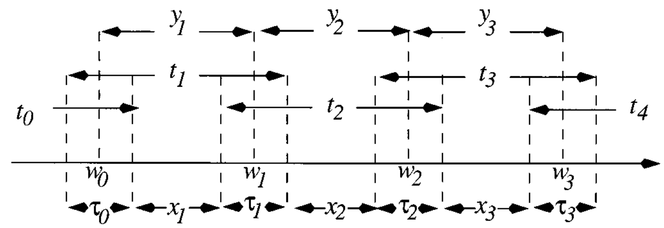

Fig. 1. The timing diagram for the hard-handoff model.

Thus, within the overlay area of cells, a handset can connect to multiple BS's. During the process of dropping a failing link, the handset may communicate using other radio links. Thus, link transfer is not sensitive to the elapsed link-transfer time. Note that the soft-handoff link-transfer procedure may not be faster than that for hard handoff. However, soft handoff is not time critical as compared with hard handoff [10].

On the other hand, soft handoff degrades channel availability because a handset may consume multiple radio channels. Thus, it is desirable to investigate the performance of soft handoff and the tradeoff between hard and soft handoffs. In this paper, we propose analytic and simulation models to study soft handoff and compare its performance with hard handoff. To strengthen the theme of our study, we do not consider the handoff prioritized schemes [11] that are seldom implemented in the commercial systems.

II. Analytic Model

With minor modifications to the two analytic models we developed in [12] and [11], we compare the performance for hard and soft handoffs. For the reader's benefit, we reiterate the models in [12] (for hard handoff) and [11] (for soft handoff) with new notation and new interpretation.

A. The Hard-Handoff Model

Fig. 1 illustrates the timing diagram for the hard-handoff model. In this figure, t_i represents the time that a handset can receive the signal from cell i (i.e., the time that the handset resides in cell i). Since the cells may overlay, the handset will enter the overlay area i before it moves from cell i to cell $i+1$. Let τ_i be the overlay time. Then t_i can be expressed as $\tau_{i-1} + x_i + \tau_i$, where x_i is the time that the handset stays in the nonoverlay area of cell i. In hard handoff, a communicating handset is switched from cell i to cell $i+1$ at some point within τ_i. In Fig. 1, the handoffs occur at time w_i, $i = 0, 1, 2, \cdots$. From the viewpoint of the hard-handoff scheme, the residence time of the handset at cell i is $y_i = w_i - w_{i-1}$. Let x_i be the nonoverlay period. If $E[x_i] = (1/\eta)$ and $E[\tau_i] = (1/\gamma)$, then

$$E[y_i] = E[x_i] + E[\tau_i] = \frac{1}{\theta} = \frac{\eta + \gamma}{\eta\gamma}. \tag{1}$$

Since the radio link between the BS and the handset is broken before it is connected in hard handoff, the link transfer may fail due to long network response time even if radio channels are available in the new BS. The following assumptions are used in the model.

- The call arrivals to/from a handset are a Poisson process. The net new call arrival rate to a cell is λ_o.
- The mobile residence time y_i in a cell i has an exponential distribution with the density function

$$f_m(y_i) = \theta e^{-\theta y_i}.$$

  This assumption will be relaxed to accommodate general residence time distribution in Appendix A.
- The call holding time t_c is exponentially distributed with the mean $1/\mu$.

The output measures are:

λ_h handoff call arrival rate to a cell;
p_o new call blocking probability;
p_r probability that a handoff call is blocked because no radio channel is available;
α_h probability that a hard-handoff call is blocked because the network response time t_{nrt} is too long;
p_f forced termination probability or the probability that a handoff call is blocked because no radio channel is available or because the network response time is too long;
p_{nc} call incompletion probability.

As mentioned before, a handoff call is forced terminated if the network response time is too long (with probability α_h) or no channel is available (with probability p_r). Since a nonprioritized scheme is considered, $p_r = p_o$ and

$$p_f = 1 - (1-\alpha_h)(1-p_o) = 1 - (1-\alpha_h)(1-p_r). \quad (2)$$

From [12], we have

$$\lambda_h = \frac{\theta(1-p_o)\lambda_o}{\mu + \theta[1-(1-\alpha)(1-p_o)]}. \quad (3)$$

The channel occupancy time of a call in a cell is the minimum of the remaining call holding time (note that the call holding time for a handoff call has the same distribution as a new call because of the memoryless property of the exponential distribution) and the remaining cell residence time. Thus, the channel occupancy time is also exponentially distributed with rate $\mu + \theta$. The net traffic to the system is $\lambda_o + \lambda_h$. Let c be the number of channels in a cell. The hard-handoff scheme can be modeled by an $M/M/c/c$ system and from the Erlang-B formula

$$p_r = p_o = \left[\frac{(\lambda_o+\lambda_h)^c}{(\mu+\theta)^c c!}\right]\left[\sum_{i=1}^{c}\frac{(\lambda_o+\lambda_h)^i}{(\mu+\theta)^i i!}\right]^{-1}. \quad (4)$$

The probability p_o can be obtained by assigning an initial value for λ_h and by iterating (4) and (3) until the λ_h value converges. From [12], the call incompletion probability is derived as

$$p_{nc} = p_o + \frac{\theta(1-p_o)[1-(1-\alpha)(1-p_o)]}{\mu+\theta[1-(1-\alpha)(1-p_o)]}. \quad (5)$$

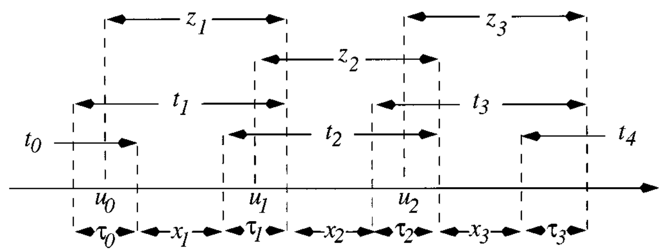

Fig. 2. The timing diagram for the soft-handoff model.

B. The Soft-Handoff Model

For the demonstration purpose, we assume that a handset can connect up to two radio links in a CDMA system. Fig. 2 illustrates the timing diagram for the soft-handoff model. The notations t_i, τ_i, and x_i are the same as that in Fig. 1. In soft handoff, a communicating handset at cell i utilizes one channel during the nonoverlay period x_i and is looking for a second radio link from cell $i+1$ during τ_i. Suppose that the second link is found at time u_i, then the channel occupancy time of the handset at cell $i+1$ is the minimum of z_{i+1} (in Fig. 2) and the remaining call holding time. Assume that t_i is exponentially distributed, then from the memoryless property, z_i also has the same distribution as t_i, i.e., it is exponentially distributed with mean

$$\frac{1}{\omega} = \frac{1}{\eta} + \frac{1}{\gamma} + \frac{1}{\gamma} = \frac{\gamma+2\eta}{\gamma\eta}$$

(nonexponential t_i are considered in Appendix A). For a fixed period, the number of cells visited by a handset is independent of the handoff schemes and the moving rate of a handset in soft handoff is θ as expressed in (1). Let α_s be the probability that a soft-handoff call is blocked because the network response time is too long. Unlike the hard handoff, it is apparent that $p_r < p_o$ in this scheme. Following the same reasoning in the previous section, p_f, λ_h, and p_{nc} for soft handoff are similar to (2), (3), and (5) and can be expressed as

$$\begin{aligned} p_f &= 1-(1-\alpha_s)(1-p_r) \\ \lambda_h &= \frac{\theta(1-p_o)\lambda_o}{\mu+\theta[1-(1-\alpha_s)(1-p_r)]} \end{aligned} \quad (6)$$

$$p_{nc} = p_o + \frac{\theta(1-p_o)[1-(1-\alpha_s)(1-p_r)]}{\mu+\theta[1-(1-\alpha_s)(1-p_r)]}. \quad (7)$$

To compute p_o and p_r, the soft-handoff scheme can be modeled by a Markov process with states $\mathbf{s}(n)$, where $n \geq 0$ represents the number of busy channels as in [11]. Fig. 3 illustrates the Markov process. When the process is in state $\mathbf{s}(n)$ (for $0 \leq n < c$), n channels are busy. The effective call traffic to a cell at $\mathbf{s}(n)$ is $\lambda_o + \lambda_h$ [and the process moves from $\mathbf{s}(n)$ to $\mathbf{s}(n+1)$ with this rate]. Since a busy channel is released with the rate $\mu+\omega$, the process moves from $\mathbf{s}(n)$ to $\mathbf{s}(n-1)$ (for $0 < n \leq c$) with the rate $n(\mu+\omega)$.

When the process is in $\mathbf{s}(c+j)$, where $j \geq 0$, all channels are busy, and j handoff calls are looking for the second links. When a call arrives at state $\mathbf{s}(c+j)$, the call is dropped immediately if it is a new call. On the other hand, if the call is a handoff call, then it is trying to connect to the second link before it leaves the overlay area. Thus, the process moves from $\mathbf{s}(c+j)$ to $\mathbf{s}(c+$

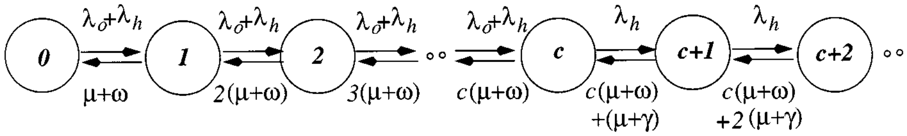

Fig. 3. The Markov chain.

$j+1)$ with rate λ_h for $j \geq 0$. Since all channels are busy, the first completion (among the c connected calls) releases its channel with rate $c(\mu+\omega)$. For those j handoff calls who look for the second links, before the second links are available, the calls may leave the system in two cases: either the handset leaves the overlay area (with rate γ) and is forced terminated or the call is completed (with rate μ). Thus, the first such call leaves the system with the rate $j(\mu+\gamma)$, and the process moves from $\mathbf{s}(c+j)$ to $\mathbf{s}(c+j-1)$ with rate $c(\mu+\omega)+j(\mu+\gamma)$ for $j > 0$.

Let π_i be the steady-state probability for $\mathbf{s}(i)$. Then

$$\pi_i = \begin{cases} \dfrac{(\lambda_o+\lambda_h)^i}{i!(\mu+\omega)^i}\,\pi_0, \quad i \leq c \\ \dfrac{(\lambda_o+\lambda_h)^c \lambda_h^{n-c}}{c!(\mu+\omega)^c \prod\limits_{1\leq j\leq n-c} [c(\mu+\omega)+j(\mu+\gamma)]}\,\pi_0, \\ \quad i > c. \end{cases}$$

Since $\pi_0+\pi_1+\cdots+\pi_n+\cdots=1$, we have

$$\pi_0 = \left\{ \sum_{n>c}^{\infty} \frac{(\lambda_o+\lambda_h)^c \lambda_h^{n-c}}{c!(\mu+\omega)^c \prod\limits_{1\leq j\leq n-c} [c(\mu+\omega)+j(\mu+\gamma)]} + \sum_{i=1}^{c} \frac{(\lambda_o+\lambda_h)^i}{i!(\mu+\omega)^i} + 1 \right\}^{-1}.$$

Since a new call is blocked when the system is in state $\mathbf{s}(n)$ (where $n \geq c$) at its arrival, the originating call blocking probability is

$$p_o = \sum_{n\geq c}^{\infty} \pi_n. \tag{8}$$

Following the technique we developed in [11], the probability p_r is derived as follows. Suppose that a handoff call C_t arrives at time t when the cell is in state $\mathbf{s}(n)$ (where $n = c+j$) and the call leaves the overlay area at time $t+\tau$. Let τ_c be the remaining call holding time of C_t at time t (i.e., the call will be completed at time $t+\tau_c$). From the memoryless property, τ_c has the same exponential distribution as t_c. Consider the $c+j$ outstanding calls that arrive at the cell earlier than C_t. Suppose that among these $c+j$ calls, the first call leaves the system (either completes, expires, or leaves the cell) at time $t+t_j$. Then the density function for t_j is

$$f_j(t_j) = [c(\mu+\omega)+j(\mu+\gamma)]e^{-[c(\mu+\omega)+j(\mu+\gamma)]t_j}. \tag{9}$$

If $t_j < \tau$, then at time $t+t_j$, C_t sees c handsets in conversations and $j-1$ handoff calls looking for the second links. Now consider the first call that leaves the system among these $c+j-1$ calls (excluding C_t). Suppose that the call leaves the system at time $t+t_j+t_{j-1}$. Because of the memoryless property of the call occupancy distribution and the overlay time distribution, t_{j-1} has the density distribution f_{j-1} as expressed in (9). Let $T_j = t_0+\cdots+t_j$. For a call C_t arriving at state $\mathbf{s}(n)$ $(n=c+j, j\geq 0)$, the probability that C_t is blocked is

$$\begin{aligned} &\Pr[\tau < T_j \text{ and } \tau > \tau_c|\mathbf{s}(c+j)] \\ &\quad = \int_{t_j=0}^{\infty}\cdots\int_{t_0=0}^{\infty}\int_{\tau=0}^{t_0+\cdots+t_j}\int_{\tau_c=0}^{\tau} \gamma e^{-\gamma\tau}\mu e^{-\mu\tau_c} \\ &\qquad \times \left[\prod_{0\leq k\leq j} f_k(t_k)\right] d\tau_c\, d\tau\, dt_0\cdots dt_j \\ &\quad = \frac{(j+1)\gamma}{c(\mu+\omega)+(j+1)(\mu+\gamma)}. \end{aligned}$$

Thus, the probability p_r (that no radio resource is available for a handoff call) is

$$\begin{aligned} p_r &= \sum_{0\leq j<\infty} \Pr[\tau < T_j \text{ and } \tau > \tau_c|\mathbf{s}(c+j)]\pi_{c+j} \\ &= \sum_{0\leq j<\infty} \frac{(j+1)\gamma\pi_{c+j}}{c(\mu+\omega)+(j+1)(\mu+\gamma)}. \end{aligned} \tag{10}$$

By using the same iterative procedure described in the previous sections, λ_h, p_o, p_f, and p_{nc} can be obtained.

TABLE I
THE PROBABILITY α_s FOR VARIOUS τ_i
$(\eta = 0.5\ \mu, \beta = 100\ \mu)$

τ_{ov}	$0.05/\mu$	$0.075/\mu$	$0.10/\mu$	$0.125/\mu$	$0.15/\mu$
$\lambda_o = 3\mu$(Simulation)	16.62%	11.69%	9.08%	7.36%	6.33%
$\lambda_o = 4\mu$(Simulation)	16.59%	11.63%	9.04%	7.26%	6.22%
$\lambda_o = 5\mu$(Simulation)	16.49%	11.67%	9.05%	7.26%	6.19%
$\lambda_o = 6\mu$(Simulation)	16.60%	11.62%	8.90%	7.33%	6.19%
Analysis	16.67%	11.76%	9.09%	7.41%	6.25%

C. Derivation for α_h and α_s

Suppose that τ_i and t_{nrt} are exponentially distributed with rates γ and β, respectively (nonexponential distributions will be considered in Appendix A). In soft handoff, let τ_i^* be the period between the handset connects to the new cell and when the handset leaves the overlay area. Then from the Markov model in Fig. 3, τ_i and τ_i^* have the same exponential distribution. Thus, we have

$$\begin{aligned} \alpha_s &= \Pr[t_{nrt} > \tau_i^*] \\ &= \int_{\tau_i^*=0}^{\infty}\int_{t_{nrt}=\tau_i^*}^{\infty} \beta e^{-\beta t_{nrt}}\gamma e^{-\gamma\tau_i^*}\, dt_{nrt}\, d\tau_i^* \\ &= \frac{\gamma}{\gamma+\beta}. \end{aligned} \tag{11}$$

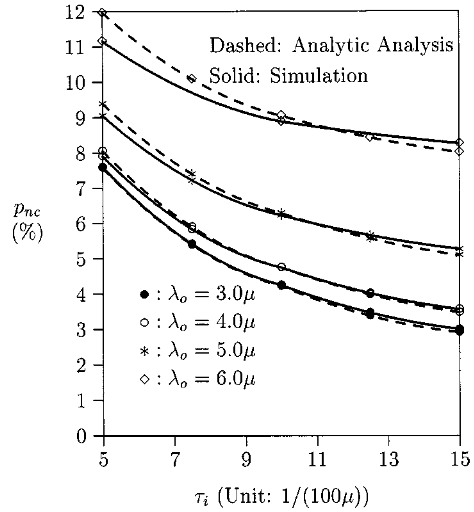

Fig. 4. Comparing the analytic and the simulation results.

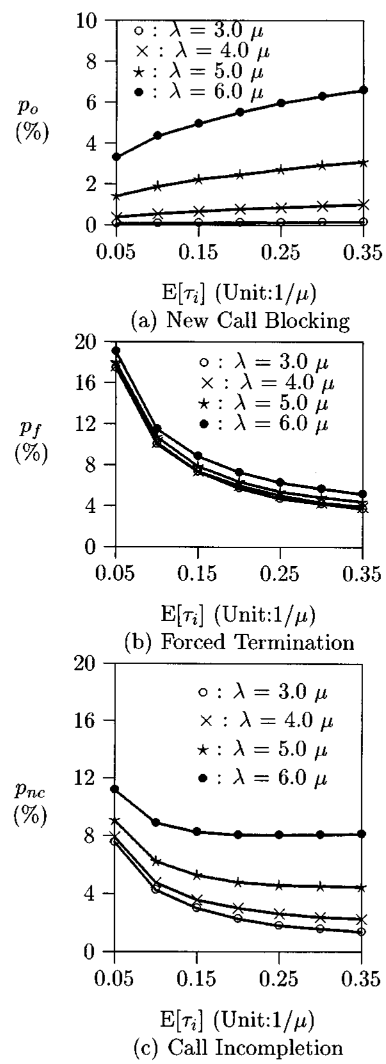

Fig. 5. The effect of the overlay time on soft handoff ($\eta = 0.5\ \mu$, $\beta = 100\ \mu$).

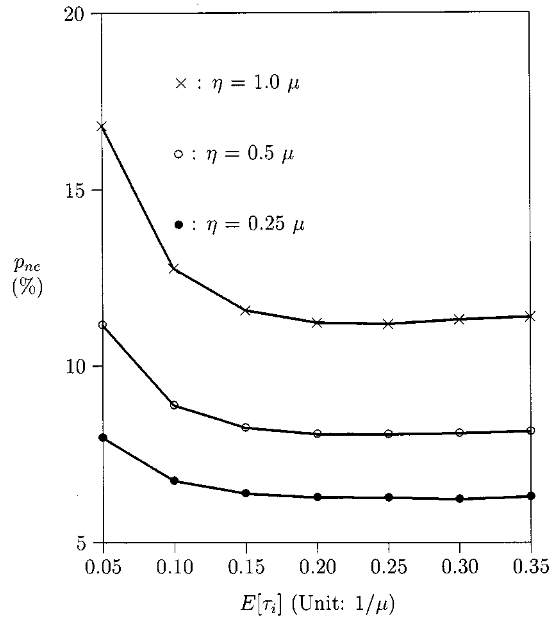

Fig. 6. The effect of the nonoverlay period [$\lambda_o = 6\ \mu$, $E[t_{nrt}] = 0.01\ \mu$ (exponential)].

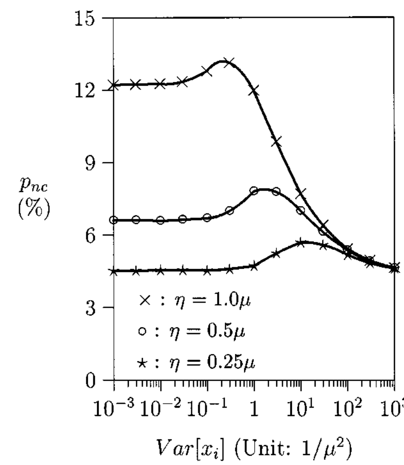

Fig. 7. The effect of the variance of the nonoverlay period ($E[t_{nrt}] = 0.01\ \mu$, $E[\tau_i] = 0.05\ \mu$, and $\lambda_o = 6\ \mu$).

Note that α_s is independent of λ_o, c, and η. Table I lists the α_s values obtained from simulation experiments (described in Appendix A) and the values computed from (11). The table indicates that (11) is consistent with the simulation experiments.

For hard handoff, the handoff procedure is initiated when the signal of the new link is better than the old link. Thus, we assume that $E[\tau_i^*] = 0.5E[\tau_i]$ and

$$\alpha_h = \frac{2\gamma}{2\gamma + \beta}. \qquad (12)$$

The analytic model is validated against a simulation model described in Appendix A.

Fig. 4 plots the p_{nc} curves obtained from the analytic model (the dashed curves) and the simulation model (the solid curves). The figure indicates that the analytic and the simulation results are consistent.

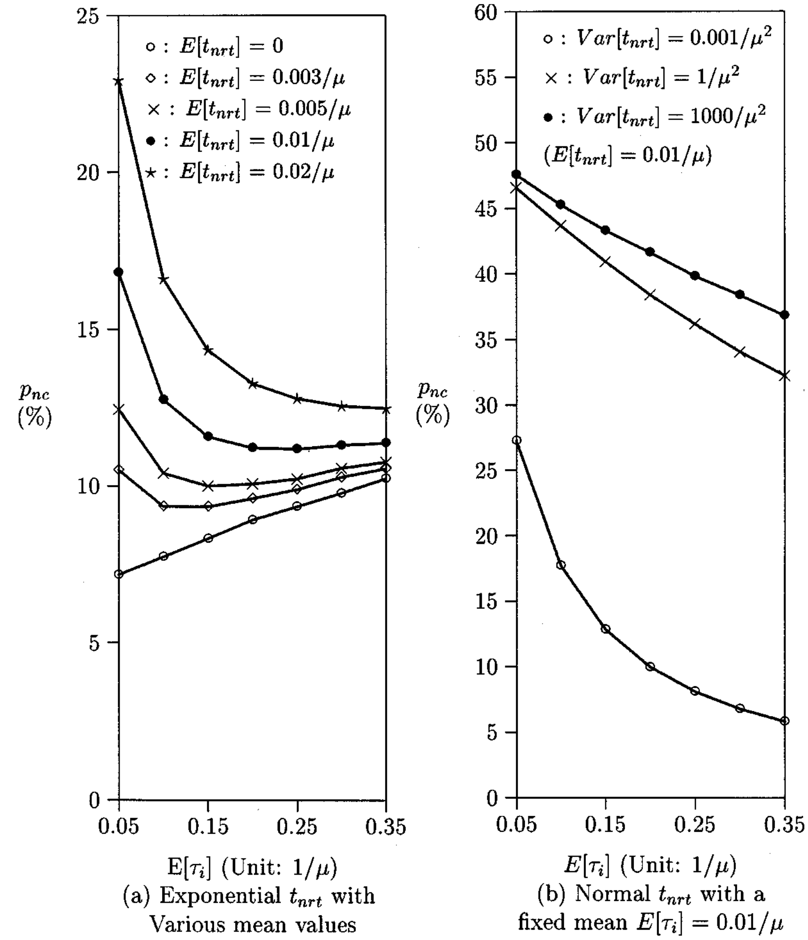

Fig. 8. The effect of network response time ($\lambda_o = 6\ \mu$, $\eta = \mu$).

III. Numerical Examples

This section uses some numerical examples to illustrate the effects of the overlay time τ_i, the mobility η, and the network response time t_{nrt} on output measures such as p_o, p_f, and p_{nc}.

1) The Effect of the Overlay Time: Fig. 5 illustrates the soft-handoff output measures p_o, p_f, and p_{nc} as functions of the exponential overlay time τ_i, where $\eta = 0.5\mu$ and the network response time is exponentially distributed with mean $0.01/\mu$. Fig. 5(b) shows that p_f decreases as τ_i increases (the longer the overlay time, the higher the probability that the second radio link is successfully connected to the handset). Fig. 5(a) shows that p_o increases as τ_i increases (since handoff calls have better opportunity to obtain radio channels as the overlay time increases, the new call attempts are more likely to be blocked). Fig. 5(c) plots the p_{nc} curves. We first note that p_o [in Fig. 5(a)] and p_f [in Fig. 5(b)] are two major factors [see (7)] that determine p_{nc}. For $\lambda_o \leq 5\ \mu$, p_o slightly increases as τ_i increases. On the other hand, p_f significantly decreases as τ_i increases. Thus, p_{nc} decreases as the overlay time increases. On the other hand, when the offered load is large (e.g., $\lambda_o = 6\mu$), p_o significantly increases as τ_i increases. Since p_f significantly decreases as τ_i increases, the net effect is that p_{nc} decreases then increases as τ_i increases.

2) The Effect of the Nonoverlay Period: Fig. 6 plots p_{nc} against the nonoverlay period $E[x_i] = 1/\eta$, where $\lambda_o = 6\mu$ and $E[t_{nrt}] = 0.01/\mu$. This figure indicates that p_{nc} is more sensitive to τ_i for large η than small η. In other words, when the user mobility is large, the cell overlay area layout significantly affects the performance of soft handoff. Fig. 7 plots p_{nc} against the variance $Var[x_i]$ of x_i with the normal distribution. We observe that when $[x_i] < 1/\mu^2$, p_{nc} is insensitive to the change of the variance of the nonoverlay period. On the other hand, when $Var[x_i] > 1/\mu^2$, p_{nc} is very sensitive to $Var[x_i]$.

3) The Effect of Network Response Time: Fig. 8 plots p_{nc} as a function of the network response time t_{nrt}. In this figure, $\eta = \mu$ and $\lambda_o = 6\ \mu$. Fig. 8(a) shows the effect of the exponential t_{nrt} with various mean values. If the network response time is zero, then $\alpha_s = 1$, and handoff always fails. In this case, p_{nc} increases as the overlay time increases. However, when t_{nrt} is nonzero, p_{nc} decreases then increases as τ_i increases [this phenomenon was explained in Fig. 5(a)]. The effect of t_{nrt} on p_{nc} is similar to the effect of τ_i. That is, p_{nc} is more sensitive to τ_i for large t_{nrt} than small t_{nrt}. Fig. 8(b) demonstrates how the variance $Var[t_{nrt}]$ of t_{nrt} with the normal distribution affects the system performance, where $\lambda_o = 6\mu$, $\eta = \mu$, and $E[t_{nrt}] = 0.01/\mu$. The curves indicate that p_{nc} decreases as $Var[t_{nrt}]$ decreases. When $Var[t_{nrt}] \geq 1$, the variance of the

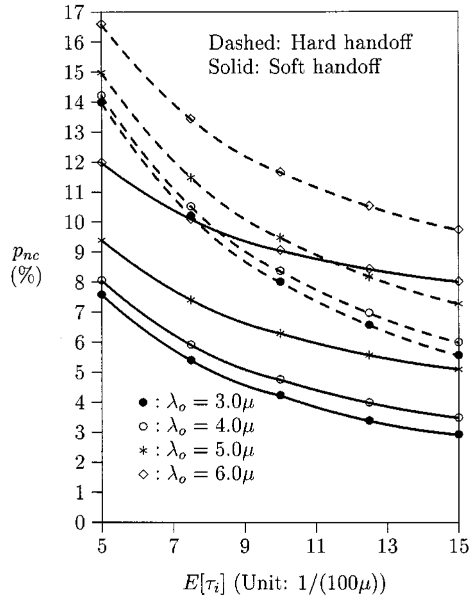

Fig. 9. Soft versus hard handoff.

t_{nrt} distribution only has an insignificant effect on p_{nc}. On the other hand, when $Var[t_{nrt}] < 1$, p_{nc} significantly decreases as $Var[t_{nrt}]$ decreases.

4) Soft Versus Hard Handoffs: Fig. 9 compares the call incompletion probabilities for soft handoff (the solid curves) and for hard handoff (the dashed curves). In this figure, (11) and (12) are used to compute α_s and α_h, respectively. The figure indicates that in the ranges of the input parameters we considered, soft handoff outperforms hard handoff.

IV. Conclusion

This paper proposed an analytic model and a simulation model to study the performance of soft handoff. Our study indicated that the handoff network response time, the mobility of the user and the overlay time significantly affect the performance of soft handoff. Furthermore, we observed that the call incompletion probability can be significantly affected by the variances of the network response time and the nonoverlay time. Under the ranges of the input parameters we considered, soft handoff may significantly outperform hard handoff. Our study provides guidelines to determine the degree of the overlay among cells.

Appendix I
The Simulation Model

This Appendix describes a simulation model to investigate the performance of CDMA soft handoff. In the simulation experiments, the PCS system consists of 64 BS's connected as an 8×8 wrapped mesh [13]. In the simulation model, a handset resides in the nonoverlay area of a cell for a period x_i, then moves to the overlay area of one of the four neighboring cells (selected with equal routing probabilities) for a period τ_i, and finally moves to the nonoverlay area of the new cell. In the simulation, a cell i is modeled as a `cell` object with data structure `C(i)` to represent the number of idle channels at the cell.

The simulation model consists of four types of events. Let *clock* be the system clock. The event types are described below.

- **ARRIVAL** event represents a new call arrival at a cell i. There are two cases.
  - `C(i)` > 0. In this case, `C(i)` is decremented by one, and the call holding time t_c and the nonoverlay time x_i for this call are generated. If $t_c > x_i$, then generate a **COMPLETION** event with timestamp $clock + t_c$. Otherwise, generate an **OVERLAY** event with timestamp $clock + x_i$ (with the destination cell where the handset is moving, and the overlay period τ_i).
  - `C(i)` $= 0$. The call is blocked. Update the call blocking statistics (p_o and p_{nc}).

  The simulation generates the next **ARRIVAL** event according to the call arrival rate λ_o.
- **OVERLAY** event represents that a handset in conversation moves into the overlay area between the old cell i and the new cell j.
  - `C(j)` > 0 (the soft-handoff procedure is exercised). Let t_c^* be the remaining call holding time and τ_i be the overlay period. Decrement `C(j)` by one. If $t_c^* < \tau_i$, then generate a **COMPLETION** event with timestamp $clock + t_c^*$. Otherwise, generate the handoff network response time t_{nrt}. Generate a **RELEASE** event with timestamp $clock + \tau_i$.
  - `C(j)` $= 0$. The handset should continue to try until a radio channel in the new cell is available. This part can be implemented by generating another **OVERLAY** event if the handset is still in the overlay area at the next try time, or a **RELEASE** event if the next try occurs after the handset leaves the overlay area (t_{nrt} is set ∞ to indicate soft failure due to shortage of radio channel).
- **RELEASE** event represents various situations described below.
  - $t_{nrt} = \infty$: The call is forced terminated because no radio channel is available. `C(i)` is incremented by one, and the output statistics (p_r and p_{nc}) are updated.
  - $\tau_i < t_{nrt}$: The call is forced terminated because long network response time. `C(i)` and `C(j)` are incremented by one, and the output statistics (α_s and p_{nc}) are updated.
  - $\tau_i \geq t_{nrt}$: The second link is successfully connected. Let t_c^* be the remaining call holding time. Generate the nonoverlay period x_j at cell j. If $t_c^* < x_j$ then generate a **COMPLETION** event with timestamp $clock + t_c^*$. Otherwise, generate an **OVERLAY** event as described before.
- **COMPLETION** event represents the completion of a call at cell i. If the completion occurs at the nonoverlay area of cell i, then `C(i)` is incremented by one. If the completion occurs at the overlay area between cell i and cell j, then both `C(i)` and `C(j)` are incremented by one.

In the simulation experiments, the PCS system consists of 64 BS's connected as an 8×8 wrapped mesh [13]. The call arrivals to a cell form a Poisson process with arrival rate λ_o. The call holding times t_c are exponentially distributed with mean $1/\mu$. The periods x_i, τ_i, and t_{nrt} are generated from exponential or normal random number generators. In the experiments, every BS has ten channels. In each simulation experiment, 500 000 incoming calls are simulated to ensure that the simulation results are stable.

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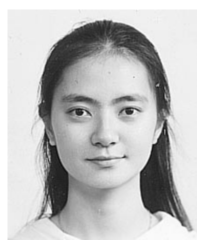

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