Characterization of Soft Handoff in CDMA Systems

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Abstract—Many analytical approaches have been proposed for handoff analysis based on hard handoff in mobile communication systems. In code-division multiple-access (CDMA) systems with soft handoff, mobile stations (MS’s) within a soft-handoff region (SR) use multiple radio channels and receive their signals from multiple base stations (BS’s) simultaneously. Therefore, SR’s should be considered for handoff analysis in CDMA systems. In this paper, an analytical model for soft handoff in CDMA systems is developed by introducing an overlap region between adjacent cells and the handoff call attempt rate and the channel holding times are derived. Applying these results to a nonprioritized CDMA system, the effects of soft handoff and the mean cell residual time are investigated and compared with hard handoff.

Index Terms—Handoff traffic analysis, soft handoff.

I. INTRODUCTION

HANDOFF is an important issue in mobile communication systems and many analytical approaches have been proposed for handoff analysis in these systems [1]–[5]. Prior studies, however, were based primarily on hard handoff in time-division multiple-access (TDMA) systems, where handoffs occur at the boundary between two cells and only one radio channel is used throughout a call.

Unlike TDMA systems, code-division multiple-access (CDMA) systems can use soft handoff by employing universal frequency reuse, rake receivers, and combining techniques on reverse links [6]–[12]. Mobile stations (MS’s) within an SR use multiple radio channels and receive their signals from multiple base stations (BS’s) simultaneously. A soft-handoff decision generally depends on relative signal strength, and the signal strength depends on the signal traveling distance, shadowing loss, and fading effects.

Some previous studies [13], [14] on CDMA systems assumed that new call arrivals and handoff attempts follow an independent Poisson process. However, as noted in [1] and [4], the handoff call attempt rate and the channel holding time are functions of the new call arrival rate, terminal mobility, priority scheme, and other factors. Park et al. [15] and Kwon and Sung [16] proposed analytical soft-handoff models and calculated the probability distribution function of total sojourn time in an SR, and Cho et al. [18] calculated the calling rates and the channel holding time in a soft-handoff environment. In these previous studies an MS did not request another soft handoff while being in an SR. However, in soft-handoff systems if the pilot signal from a third BS became stronger than one of the original pilot signals, another handoff could occur.

In this paper, we extend the mathematical models for hard-handoff systems [1], [4] and develop a new analytical model to analyze the performance of CDMA soft-handoff systems. One cell area is divided into three regions in the analysis of soft handoff. These areas are an inner cell, an SR, and an outer cell. We introduce a region called the overlap region, which is a region of overlap between two adjacent outer cells. According to the cell structure, an SR consists of several overlap regions. Under this environment, the handoff call attempt rate and the channel holding time can be derived as a function of the new call arrival rate, new call blocking probability, handoff failure probability, cell residual time, call holding time, and parameters of the overlap region. Applying these results to a nonprioritized CDMA system, we investigate the effects of SR size, mean cell residual time, and parameters of the overlap region, and compare these results with those of hard handoff.

The rest of this paper is organized as follows. After the description of hard handoff and soft handoff in Section II, Section III derives the handoff call attempt rate and the channel holding time of CDMA systems based on soft handoff. Section IV investigates the effects of SR size, mean cell residual time, and parameters of the overlap region in a nonprioritized CDMA system and compares these results with those of hard handoff. Section V gives conclusions.

II. HANDOFFS IN CDMA SYSTEMS

Since communicating MS’s move from cell to cell, handoff is essential for seamless communication. There are two types of handoffs: hard handoff and soft handoff. Hard handoff is a break-before-make method, where a new channel is set up after the release of the old channel. A certain amount of margin may be introduced to eliminate the ping-pong effect. Hard handoff is supported by TDMA, frequency-division multiple-access (FDMA), and CDMA systems.

CDMA systems can also support soft handoff, which is a make-before-break method. When the pilot signal from a new BS is stronger than the threshold value T_ADD, a new link to the BS is established while maintaining the existing link. In this case the call is said to be in soft handoff. We here assume that a MS can be in soft handoff with two strong BS’s. If the pilot signal from a third BS becomes strong than either of the two strong pilot signals, another handoff occurs and the network drops the weakest link. When the pilot signal from either the old BS or the new BS weakens to below T_DROP, the bad connection is released and only a single good connection is maintained after that time. SR’s may vary according to handoff-related parameters, such as T_ADD and...
T.DROP, and handoff is also affected by radio propagation characteristics and the required $E_b/I_o$ value. Since an MS in soft handoff is power controlled by the BS which requires less power, soft handoff increases system capacity by reducing interference. On the other hand, soft handoff increases handoff traffic by using multiple channels and also increases signaling traffic, network processing, and the amount of radio equipment required at the BS’s [8], [9], [11].

### III. Traffic Model

Even in TDMA systems modeling accurate handoff is a difficult problem because of various factors, such as irregular cell boundaries, traffic conditions, and the movement of MS’s [5]. To analyze soft handoff we make the following assumptions.

1) The cell is square shaped [16], [17].
2) MS’s initiating calls are uniformly distributed throughout all cells.
3) The residual times are generally distributed [4].
4) New call arrival per cell follows a Poisson process with rate $\lambda_n$.
5) The call holding time $T_c$ is exponentially distributed with mean $1/\mu_c$.

Fig. 1 illustrates an example of regions and boundaries based on a square cell structure. For geometrical simplicity it is assumed that one cell area is divided into three regions in the analysis of soft handoff. These regions are: 1) the inner cell region; 2) the SR; and 3) the outer cell region. These regions are bounded by an inner boundary and an outer boundary. The region bounded by a cell boundary is called an ordinary cell. Even when an MS is in soft handoff, another handoff occurs if the pilot signal from a third BS becomes stronger than one of the original pilot signals. Thus, we here introduce an overlap region, which is the region between two overlapping adjacent outer cells. In this cell structure the SR is subdivided into four overlap regions. For a hexagonal cell structure, the SR consists of six overlap regions. The region excluding the SR in the ordinary cell is called a non-SR.

Two cases of mobile calls can be considered to investigate soft handoff. In the first case, an MS that makes a new call in an NSR (A0) requests a handoff at an inner boundary (A1), and then the old BS (cell 2) releases the old connection to the MS at an outer boundary (A2). Finally, the mobile call is terminated at A3. In the second case, an MS requests a handoff just after its new call connection. Then the BS (cell 4) executes a handoff and the old BS (cell 1) releases the connection simultaneously at an overlap boundary (B1). The BS in cell 2 releases the existing connection at an outer boundary (B2), and the mobile call is finally terminated at B3.

#### A. Handoff Call Attempt Rate

To calculate the handoff call attempt rate $\lambda_h$, we first consider when a new call arrives in an NSR with probability $P_{NS}$. No handoff request (HOR) occurs if the new call is blocked or if the remaining call holding time is shorter than the residual time in an inner cell. Otherwise, an HOR occurs. No more HOR’s occur if the following conditions are satisfied.

1) A handoff call attempt fails.

2) A handoff call attempt succeeds and if either conditions a) or b) is satisfied.

a) The call is terminated within an overlap region.

b) The mobile call is terminated within the inner cell after an MS crosses the inner cell boundary from the SR.

A handoff call requests another HOR if either of the following conditions is satisfied:

1) a communicating MS moves from its overlap region to another overlap region;

2) a communicating MS leaves its inner cell after it crosses the inner cell boundary from the SR.

When a new call arrives in the SR with probability $P_S$, it requests an HOR immediately if it is not blocked. By assuming a uniform distribution of new calls, we can describe the probabilities $P_{NS}$ and $P_S$ as

\[
P_{NS} = \frac{\text{NSR area}}{\text{Cell area}}
\]

\[
P_S = 1 - P_{NS}.
\]
density function (pdf), and cumulative distribution function (cdf) of a random variable \( X \), respectively, we can express 
\( P_{hi} \) and \( P_{vi} \) as
\[
P_{hi} = \Pr\{T_e > T_{hi}\} = \int_{0}^{\infty} e^{-\lambda t} f_{T_{hi}}(t) dt \tag{3}
\]
\[
P_{vi} = \Pr\{T_e > T_{vi}\} = \int_{0}^{\infty} e^{-\lambda t} f_{T_{vi}}(t) dt. \tag{4}
\]
Similarly, \( P_{h} \) and \( P_{v} \) are given by
\[
P_{h} = \Pr\{T_e > T_{h}\} = \int_{0}^{\infty} e^{-\lambda t} f_{T_{h}}(t) dt \tag{5}
\]
\[
P_{v} = \Pr\{T_e > T_{v}\} = \int_{0}^{\infty} e^{-\lambda t} f_{T_{v}}(t) dt. \tag{6}
\]
Let \( P_{B} \) denote the new call blocking probability and \( P_{fh} \) the handoff failure probability. If \( K \) is the number of handoff call attempts during a call holding time \( T_e \), the probability \( \Pr\{K = k\} \) can be written as
\[
\Pr\{K = 0\} = P_{NS}(1 - P_{B})(1 - P_{h}) + P_{NS}P_{B} + P_{S}P_{B} \tag{7}
\]
\[
\Pr\{K = 1\} = P_{NS}(1 - P_{B})P_{f}x_p + P_{S}(1 - P_{B})x_i \tag{8}
\]
\[
\Pr\{K = 2\} = P_{NS}(1 - P_{B})P_{f}x_p(1 - P_{fh})y_{x} + P_{S}(1 - P_{B})(1 - P_{fh})y_{x}x_i \tag{9}
\]
\[
\Pr\{K = 3\} = P_{NS}(1 - P_{B})P_{f}x_p(1 - P_{fh})y_{x}x_p + P_{S}(1 - P_{B})(1 - P_{fh})y_{x}y_{x}x_i \tag{10}
\]
\[
\vdots = \vdots
\]
\[
\Pr\{K = n\} = P_{NS}(1 - P_{B})P_{f}x_p(1 - P_{fh})y_{x}^{n-1}x_i + P_{S}(1 - P_{B})(1 - P_{fh})y_{x}^{n-2}x_i \tag{11}
\]
where \( x_i (y_{x}) \) is the probability that a new (handoff) call which requested an HOR does not request anymore HOR’s, and \( y_{x} (y_{h}) \) is the probability that a new (handoff) call makes another HOR. These values are given by
\[
x_i = P_{fh} + (1 - P_{fh})(1 - P_{f})x_i \tag{12}
\]
\[
x_h = P_{f}P_{h} + (1 - P_{f})(1 - P_{h})x_h \tag{13}
\]
\[
y_i = P_{f}P_{h} + P_{a}P_{h} \tag{14}
\]
\[
y_h = P_{f}P_{h} + P_{a}P_{h} \tag{15}
\]
where \( P_{a} \) and \( P_{h} \) are the conditional probabilities that an MS moves from an overlap region to an inner cell and to another overlap region, respectively, under the condition that it leaves the overlap region. Since \( P_{a} + P_{h} = 1 \), the following relations are true:
\[
1 - x_i = (1 - P_{fh})y_{x} \tag{16}
\]
\[
1 - x_h = (1 - P_{fh})y_{h}. \tag{17}
\]
Using the above relations we can show \( \sum_{k=0}^{\infty} \Pr\{K = k\} = 1 \).

The expected value of \( K \) is given by
\[
\overline{K} = \sum_{k=0}^{\infty} k \Pr\{K = k\} = \overline{K}_{NS} + \overline{K}_{S} \tag{18}
\]

where
\[
\overline{K}_{NS} = P_{S}(1 - P_{B})\left[ x_i + (1 - P_{fh})y_{x}x_i \frac{2 - (1 - P_{fh})y_{h}}{1 - (1 - P_{fh})y_{h}} \right] \tag{19}
\]
and
\[
\overline{K}_{S} = P_{S}(1 - P_{B}) \left\{ x_i + (1 - P_{fh})y_{h} \right. + (1 - P_{fh})y_{x}x_i \frac{2 - (1 - P_{fh})y_{h}}{1 - (1 - P_{fh})y_{h}}. \right. \tag{20}
\]

\( \overline{K}_{NS} \) and \( \overline{K}_{S} \) are the terms originated by a call occurring in an NSR and in an SR, respectively. Then, the handoff call attempt rate per cell is expressed as
\[
\lambda_h = \lambda_n \overline{K}. \tag{20}
\]

\section*{B. Channel Holding Time}

When a call is terminated or a communicating user leaves the outer cell, its occupied channel is released. Thus, the channel holding time \( T_{ch} \) can be expressed as
\[
T_{ch} = \min(T_c, T_{O}) \tag{21}
\]
where \( T_{O} \) is the residual time in an outer cell. Since \( T_c \) and \( T_{O} \) are mutually independent, the pdf of \( T_{ch} \) is expressed as
\[
f_{T_{ch}}(t) = f_{T_c}(t)(1 - F_{T_{O}}(t)) + f_{T_{O}}(t)(1 - F_{T_c}(t)) \tag{22}
\]
where \( F_{T_c}(t) \) and \( F_{T_{O}}(t) \) are the cdf’s of \( T_c \) and \( T_{O} \), respectively. Assuming different distributions of the residual time in an outer cell for new calls and handoff calls, we can obtain the pdf of \( T_{O} \)
\[
f_{T_{O}}(t) = \frac{\lambda_c}{\lambda_c + \lambda_{hc}} f_{T_{Oc}}(t) + \frac{\lambda_{hc}}{\lambda_c + \lambda_{hc}} f_{T_{Oh}}(t) \tag{23}
\]
where \( \lambda_c \) and \( \lambda_{hc} \) are the carried new call arrival rate and the carried handoff call attempt rate, respectively. These values are written as
\[
\lambda_c = \lambda_o (1 - P_{B}) \tag{24}
\]
\[
\lambda_{hc} = \lambda_h (1 - P_{fh}). \tag{25}
\]

\section*{IV. NUMERICAL EXAMPLES}

The distributions of the residual times and probabilities \( P_{S} \) and \( P_{a} \) depend greatly on user movement and region size. These parameters can be measured in real/test environments and can also be obtained analytically or by simulation with one of the special mobility models in [1], [2], [15], and [16]. The distributions and the probabilities allow calculation of the handoff call attempt rate and the channel holding time using the equations in Section III. For performance analysis, the following situation is considered under the assumptions in the following section to investigate the effectiveness of the SR size \( (P_{a}) \), the overlap ratio, and the mean cell residual time.
A. Assumptions

A square cell structure is shown in Fig. 1, where \(2a\) and \(2b\) are the length of a square cell and the width of an overlap region, respectively. Let \(k\) denote \(b/a\), then \(P_0\) can be simply expressed as

\[
P_0 = 1 - P_{NS} = k(2 - k).
\]  

(26)

The following assumptions are made to determine the values of parameters and variables.

1) Residual times in an inner cell, an overlap region, and an outer cell are exponentially distributed with mean \(1/\mu_I\), \(1/\mu_V\), and \(1/\mu_O\), respectively. A new call and a handoff call have the same distribution of residual times by virtue of the memoryless property of an exponential distribution. Thus, \(f_{T_I} = f_{T_{Ih}} = f_{T_I}\), \(f_{T_V} = f_{T_{Vh}} = f_{T_V}\), and \(f_{T_O} = f_{T_{Oh}} = f_{T_O}\). The relations of \(x_i = x_h = x\) and \(y_i = y_h = y\) are also obtained.

2) In general, MS's tend to reside for a longer time in a larger cell. The average residual time in a cell is known to be proportional to the cell radius and inversely proportional to the speed of an MS [2]. It is assumed that the average residual times in an inner cell, in an ordinary cell, and in an outer cell are proportional to the shortest distances (\(d_{min}\)) from the center to the boundary. Since the ratio of \(d_{min}\) of the inner cell, the ordinary cell, and the outer cell is \((1-k):(1+k):(1+k)\), the following relations among \(1/\mu_I\), \(1/\mu_{cell}\), and \(1/\mu_O\) are also assumed, where \(1/\mu_{cell}\) is the average residual time in an ordinary cell:

\[
\frac{1}{\mu_I} = \frac{1}{\mu_{cell}} (1 - k) \tag{27}
\]

\[
\frac{1}{\mu_O} = \frac{1}{\mu_{cell}} (1 + k). \tag{28}
\]

3) \(P_a (=1-P_0)\) and the average residual time in an overlap region depend on the region’s shape, its size, and the mobility model. If we assume that a mobile call passes through an overlap region boundary with equal probability, \(P_a\) is given by

\[
P_a = \frac{a - b}{a + (\sqrt{2} - 1)b}. \tag{29}
\]

Without loss of generality the average residual time in an overlap region \(1/\mu_V\) can be expressed as

\[
\frac{1}{\mu_V} = \text{overlap\_ratio} \left( \frac{1}{\mu_O} - \frac{1}{\mu_I} \right) \tag{30}
\]

where the parameter overlap\_ratio is not constant, but depends largely on the shape and size of the overlap region and the mobility model.

B. Handoff Call Attempt Rate and Channel Holding Time

Applying the above assumptions the handoff call attempt rate and the channel holding time can be obtained. The handoff call attempt rate \(\lambda_h\) is given by (20) and \(K\) can be obtained as

\[
K = \frac{(1 - P_B)x(P_{NS}P_I + P_0)}{1 - (1 - P_{fh})y} \tag{31}
\]

where

\[
P_I = \frac{\mu_I}{\mu_I + \mu_I}
\]

\[
P_V = \frac{\mu_V}{\mu_V + \mu_V}
\]

\[
x = P_{fh} + (1 - P_{fh})[1 - P_V + P_VP_A(1 - P_I)]
\]

\[
y = P_V(P_B + P_AP_I).
\]

From (21), the channel holding time is exponentially distributed and its mean of \(1/\mu_{ch}\) is given by

\[
1/\mu_{ch} = 1/(\mu_c + \mu_{cell}). \tag{32}
\]

With no margin in hard handoff, a handoff occurs at the cell boundary with simultaneous connection of a new BS and release of an old BS. The case where \(b = 0\) corresponds to hard handoff. Referring to [1] and [4], \(\mu_{ch}\) and \(\lambda_h\) for hard handoff can be obtained as

\[
\mu_{ch} = \mu_c + \mu_{cell} \tag{33}
\]

and

\[
\lambda_h = \lambda_c \frac{\mu_{cell}(1 - P_B)}{\mu_c + \mu_{cell}P_{fh}}. \tag{34}
\]

C. Performance Analysis

The performance of a nonprioritized CDMA system can now be analyzed. We assume that a cell can support \(C\) channels in a homogeneous cell structure at a steady state. Since the CDMA system capacity is limited by interference, blocking occurs when the interference level, due primarily to other user’s activities, exceeds an acceptable level [10], [12]. Since this system can be viewed as an M/M/C/C queueing system, the blocking probability can be expressed as

\[
P_B = \frac{\left(\lambda_n + \lambda_h\right)C}{C\mu_{ch}} P_0 \tag{35}
\]

where

\[
P_0 = \frac{1}{\sum_{i=1}^{C} \lambda_n \lambda_h^{i-1}}. \tag{36}
\]

The handoff failure probability is given by

\[
P_{fh} = P_{B}. \tag{37}
\]

\(P_B\) and \(P_{fh}\) are closely related to \(\lambda_n\) as described in (20), (31), (35), and (37). We calculate \(P_B\), \(P_{fh}\), and \(\lambda_h\) recursively.

Fig. 2 shows the mean channel holding time \(1/\mu_{ch}\) for various values of \(b\) as a function of mean cell residual time \(1/\mu_{cell}\). We assume \(a = 1\) and \(1/\mu_c = 100\) s. The mean channel holding time \(1/\mu_{ch}\) has a larger value for larger \(b\) and increases slowly as \(1/\mu_{cell}\) becomes larger. Compared with hard handoff, \(1/\mu_{ch}\) increases by approximately 9% when \(b = 0.2\) and \(1/\mu_{cell} = 100\) s (see Table I). The overlap\_ratio and \(P_a\) do not affect \(1/\mu_{ch}\).

Fig. 3 illustrates the effect of \(b\) on the blocking probability \(P_B\) for varying the new call arrival rate \(\lambda_n\). Soft handoff increases the system capacity. Referring to [11], the capacity increase factor for various values of \(b\) in [0, 0.3] can be...
Fig. 2. Mean channel holding time versus mean cell residual time for various values of $b$ ($a = 1, 1/\mu_c = 100$ s).

Fig. 3. Blocking probabilities versus new call arrival rate for various values of $b$ ($a = 1, P_a = 1$, overlap ratio $= 1, 1/\mu_c = 1/\mu_{cell} = 100$ s).

TABLE I

<table>
<thead>
<tr>
<th>$1/\mu_{ch}$ (sec)</th>
<th>Hard handoff</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
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<tr>
<td>50.0</td>
<td>52.38</td>
<td>54.55</td>
<td>56.52</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Blocking probabilities for various values of $b$ ($a = 1, P_a = 1$, overlap ratio $= 1, 1/\mu_c = 1/\mu_{cell} = 100$ s).

Fig. 5 illustrates $P_B$ for various values of the overlap ratio as a function of $a$, where $b = 0.2$. Since a smaller overlap ratio causes a smaller residual time in an overlap region, the blocking probability increases as the overlap ratio decreases. As the overlap ratio decreases from 1.0 to 0.6, $P_B$ decreases by approximately 5% when $P_a = 1$, as shown in Table V.

Fig. 6 shows the effect of the mean cell residual time $1/\mu_{cell}$ on $P_B$ for varying $\lambda_n$, where $b = 0.2$ and $1/\mu_c = 100$ s. More blockings occur for a larger $1/\mu_{cell}$. As $1/\mu_{cell}$ decreases from 100 to 20 s, $\lambda_n$ increases by approximately 15% and $1/\mu_{ch}$ decreases by approximately 64% (see Table VI).
The handoff call attempt rate and the channel holding time for CDMA systems were derived based on soft handoff. A newly introduced overlap region was used in soft-handoff analysis in addition to an inner cell, an outer cell, and an SR. An SR was divided into a number of overlap regions according to cell structure, and the new parameters $P_a, P_B$, and the overlap_ratio were developed. By obtaining the handoff call attempt rate and the channel holding time in a nonprioritized CDMA system with assumptions, the effects of the SR size, $P_a$, the overlap_ratio, and the mean cell residual time were investigated. These results were compared with hard handoff.

### V. Conclusions

Since the reverse link has worse characteristics than the forward link, system capacity is generally assumed to be limited on the reverse link. Assuming the propagation model and the analysis in [11] in a square cell structure where the BS is located at the center of the cell, the capacity increase factor can be estimated on the reverse link. The system capacity is inversely proportional to $1 + f$, where $f$ is defined as the average total interference from other cell users normalized by the average number of users per cell [11]. The capacity increase factor is defined as

$$\frac{1 + f_{\text{hard}}}{1 + f_{\text{soft}}}$$

(39)

### APPENDIX

Under the assumptions given in Section IV, more handoffs occur for a larger $b$, for a smaller $P_a$, and for a smaller overlap_ratio. When $P_a = 1$ and $b = 0.2$ where the SR corresponds to 36% of an ordinary cell, $\lambda_h$ for $\lambda_n = 0.3$ calls/s is approximately 40% larger than for hard handoff. Soft-handoff systems can accommodate approximately 64% more $\lambda_n$ for $P_B = 0.01$ with a capacity increase factor of 1.74. The performance of soft-handoff systems is different from hard-handoff systems, depending on SR size ($P_a$), the overlap_ratio, and the mean cell residual time.

#### TABLE IV

**NEW CALL ARRIVAL RATE $\lambda_n$ AND HANDOFF CALL ATTEMPT RATE $\lambda_h$ FOR VARIOUS VALUES OF $P_a$ ($a = 1, b = 0.2$, OVERLAP_RATIO $= 1$, NUMBER OF CHANNELS $= 52$, $1/\mu_c = 1/\mu_{\text{cell}} = 100$ s).** (a) $\lambda_n$ Satisfying $P_B = 0.01$ and (b) $\lambda_h$ AND $P_B$ FOR $\lambda_n = 0.3$ CALLS/s

<table>
<thead>
<tr>
<th>$P_a$</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_n$ (calls/sec)</td>
<td>0.270</td>
<td>0.294</td>
<td>0.317</td>
<td>0.337</td>
</tr>
</tbody>
</table>

(b)

| $P_B$ (%) | 2.52 | 1.22 | 0.52 | 0.21 | 0.68 |

#### TABLE V

**NEW CALL ARRIVAL RATE $\lambda_n$ AND HANDOFF CALL ATTEMPT RATE $\lambda_h$ FOR VARIOUS VALUES OF OVERLAP_RATIO ($a = 1, b = 0.2$, $P_a = 1$, NUMBER OF CHANNELS $= 52$, $1/\mu_c = 100$ s).** (a) $\lambda_n$ Satisfying $P_B = 0.01$ and (b) $\lambda_h$ AND $P_B$ FOR $\lambda_n = 0.3$ CALLS/s

<table>
<thead>
<tr>
<th>overlap_ratio</th>
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<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_n$ (calls/sec)</td>
<td>0.310</td>
<td>0.320</td>
<td>0.330</td>
<td>0.337</td>
<td>0.343</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>overlap_ratio</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_h$ (calls/sec)</td>
<td>0.41</td>
<td>0.39</td>
<td>0.37</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>$P_B$ (%)</td>
<td>0.68</td>
<td>0.44</td>
<td>0.30</td>
<td>0.21</td>
<td>0.16</td>
</tr>
</tbody>
</table>

#### TABLE VI

**NEW CALL ARRIVAL RATE $\lambda_n$, MEAN CHANNEL HOLDING TIME $1/\mu_{\text{ch}}$, AND HANDOFF CALL ATTEMPT RATE $\lambda_h$ FOR VARIOUS MEAN CELL RESIDUAL TIMES $1/\mu_{\text{cell}}$ ($a = 1, b = 0.2$, $P_a = 1$, OVERLAP_RATIO $= 1$, NUMBER OF CHANNELS $= 52$, $1/\mu_c = 100$ s).** (a) $\lambda_n$ AND (b) $\lambda_h$ Satisfying $P_B = 0.01$ and $\lambda_h$ AND $P_B$ FOR $\lambda_n = 0.3$ CALLS/s

<table>
<thead>
<tr>
<th>$1/\mu_{\text{cell}}$ (sec)</th>
<th>180</th>
<th>140</th>
<th>100</th>
<th>60</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_n$ (calls/sec)</td>
<td>0.321</td>
<td>0.322</td>
<td>0.337</td>
<td>0.352</td>
<td>0.388</td>
</tr>
<tr>
<td>$1/\mu_{\text{ch}}$ (sec)</td>
<td>68.4</td>
<td>62.7</td>
<td>54.5</td>
<td>41.9</td>
<td>19.4</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>$1/\mu_{\text{cell}}$ (sec)</th>
<th>180</th>
<th>140</th>
<th>100</th>
<th>60</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_h$ (calls/sec)</td>
<td>0.24</td>
<td>0.28</td>
<td>0.35</td>
<td>0.52</td>
<td>1.35</td>
</tr>
<tr>
<td>$P_B$ (%)</td>
<td>0.40</td>
<td>0.31</td>
<td>0.21</td>
<td>0.11</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fig. 5. Blocking probabilities versus new call arrival rate for various values of overlap_ratio (number of channels = 52, $a = 1, b = 0.2$, $P_a = 1, 1/\mu_c = 100$ s).

Fig. 6. Blocking probabilities versus new call arrival rate for various mean cell residual times (number of channels = 52, $a = 1, b = 0.2$, $P_a = 1$, overlap_ratio = 1, $1/\mu_c = 100$ s).
where \( f_{\text{hard}} \) and \( f_{\text{soft}} \) are the values of \( f \) in hard handoff and in soft handoff, respectively. The values of \( f \) for various values of \( b \) can now be obtained. In the case of hard handoff, in [11, eq. (18)] is modified as

\[
 f_{R1} = e^{(3\beta^2/2 \frac{1}{4} \int_{S_{0}} \left( \frac{r_2}{r_0} \right)^{\beta} dA)}
\]

where \( \beta = 1/(2\pi) \int_{0}^{\infty} e^{-y^2/2} dy \).

The three regions \( R1, R2 \) and \( R3 \) and the distances \( r_0, r_1 \) and \( r_2 \) are described in Fig. 7(b). By calculating \( f_{\text{soft}} \) for various values of \( b \), the capacity increase factor can be obtained. The capacity increase factor is shown for \( b = 0, 0.1, 0.2, \) and \( 0.3 \) in Table II by considering two tiers from the zeroth cell, where \( a = 1, \mu = 4, \) and \( \sigma = 8 \) dB. When all MS’s are in soft handoff (the case of \( b = 1 \)), the capacity increase factor differs from [11] by approximately 3%.

**REFERENCES**


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Dan Keun Sung (S’80–M’86), for a biography, see this issue, p. 1109.