Soft Handoff Extends CDMA Cell Coverage and Increases Reverse Link Capacity

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Abstract—The effect of handoff techniques on cell coverage and reverse link capacity is investigated for a spread spectrum CDMA system. It is shown that soft handoff increases both parameters significantly relative to conventional hard handoff.

I. INTRODUCTION

SOFT HANDOFF1 (handover) is a technique whereby mobile units in transition between one cell and its neighboring cells can receive the same signal from both base stations simultaneously. With spread spectrum CDMA employing universal frequency reuse, and a Rake receiver in the mobile, the two signals can be isolated and aligned both in time and phase to reinforce one another on the forward link. On the reverse link, the mobile switching center (or base station interconnection) must resolve which base station is receiving the stronger and hence better replica and decide in its favor. Decisions as to when to enter soft handoff and when to release the weaker (older) base station generally depend on the relative signal strengths. Such algorithms and protocols are described, for example, in CDMA standards documents such as the Telecommunication Industry Association’s IS-95 Standard [1]. We shall not dwell upon these issues here, nor shall we present the intuitive arguments in favor of soft handoff in preference to hard handoff, where the second base station is connected and the first released simultaneously. Ample experimental data has been presented in support of this advantage [2], [3]. Rather, in this paper we shall derive quantitative performance improvement measures for both cell coverage and capacity of the reverse link, based on a generally accepted propagation model [4]. In the next section, we briefly describe the model, which includes log-normally distributed shadowing, and in the following two sections we analyze, respectively, the coverage and capacity gains of soft handoff.

II. PROPAGATION MODEL

The propagation attenuation is generally modeled [4] as the product of the $\mu$th power of distance and a log-normal component representing shadowing losses. These represent slowly varying variations even for users in motion and apply to both reverse and forward links. Thus for a user at a distance $r$ from a base station, attenuation is proportional to

$$\alpha(r, \zeta) = r^\mu 10\zeta^{1/10}$$  \hspace{1cm} (1)

where $\zeta$ is the dB attenuation due to shadowing, with zero mean and standard deviation $\sigma$. Alternatively, the losses in dB are

$$10 \log \alpha(r, \zeta) = 10 \mu \log r + \zeta.$$  \hspace{1cm} (2)

Experimental data suggests the choices of $\mu = 4$ for power law and $\sigma = 8$ dB for standard deviation of $\zeta$, the log-normal shadowing.

Since any analysis of inter-cell interference involves comparison of propagation losses among two or more base stations, the model must take into consideration the dependence of the propagation losses to two different base stations from a mobile user. Since the propagation losses in dB are Gaussian, we assume a joint Gaussian probability density for losses to two or more base stations. Equivalently, we may express the random component of the dB loss as the sum of a component in the near field of the user, which is common to all base stations, and a component which pertains solely to the receiving base station and is independent from one base station to another. Thus we may express the random component of the dB loss for the $i$th base station ($i = 0, 1, 2, \ldots$) as

$$\zeta_i = a \xi_i + b \xi_i, \text{ where } a^2 + b^2 = 1$$  \hspace{1cm} (3)

with

$$E(\zeta_i) = E(\xi_i) = E(\xi_i) = 0,$$
$$\Var(\zeta_i) = \Var(\xi_i) = \Var(\xi_i) = \sigma^2 \text{ for all } i,$$
$$E(\xi_i) = 0 \text{ for all } i,$$
and

$$E(\xi_i \xi_j) = 0 \text{ for all } i \text{ and } j, i \neq j.$$

Thus the normalized covariance (correlation coefficient) of the losses to two base stations, $i$ and $j$, is

$$\frac{E(\zeta_i \xi_j)}{\sigma^2} = a^2 = 1 - b^2.$$  \hspace{1cm} (4)

It is recognized that there has been little experimental verification of this model for random attenuation components.\footnotetext{1}{Handoff and handover are synonymous, the latter being in common use in the European literature. Similarly, alternate terms for reverse and forward links are uplink and downlink, respectively.}
to two or more spatially displaced users. It is, nevertheless, the logical extension of the well accepted log-normal attenuation model for a single user. It includes the limiting cases of independent attenuations \((a = 0)\) and of highly correlated attenuations (where \(a \) is nearly unity), which might apply when the mobile is completely shadowed in all directions.

A reasonable assumption is that the near field and base station specific propagation uncertainties have equal standard deviations in which case \(a^2 = b^2 = 1/2\) and the normalized covariance is 1/2 for all pairs of base stations. We shall use these values throughout in all numerical results, although all expressions will be derived for arbitrary covariance value, \((4)\).

III. CELL COVERAGE WITH HARD AND SOFT HANDOFF

All comparisons are made on the basis of received power including the log-normal shadowing effects, Rayleigh fading effects, which are partially mitigated by the use of a Rake receiver and partly also by coding with interleaving, are accounted for by the bit energy-to-interference requirement, which because of the additional diversity, will be somewhat lower for soft handoff, but we neglect this additional advantage as it has much less impact on performance. We establish first the margin required with hard handoff and then with soft.

A. Hard Handoff

Consider first a hard handoff which occurs exactly at the boundary between hexagonal cells, as shown in Fig. 1, (assuming an ideal condition established by an external ideal observer). Then the relative attenuation from the mobile user at the boundary to either base station at distance \(r_1\) is given by \((2)\).

\[
10 \log \alpha(r_1, \zeta_i) = 10 \mu \log r_i + \zeta_i \quad i = 0, 1
\]  

where \(r_i\) are the normalized distances to the base stations, and \(\zeta_i\) are the corresponding log-normal shadowing with zero mean and standard deviation \(\sigma\).

Without shadowing, the minimum power required from the mobile’s transmitter just to overcome background noise is, of course, proportional to \(10 \mu \log r\). Normalizing the cell radius (of the circle which circumscribes the hexagon) to \(r = 1\), we eliminate this (common) term at the boundary. On the other hand, the random component due to shadowing, \(\zeta\), requires that the minimum power be increased to guarantee the same performance most of the time. Suppose we impose the requirement that the link achieve at least the performance of unshadowed propagation for all but a fraction \(P_{\text{out}}\) of the time, which will be denoted the outage probability. This requires that a margin \(\gamma\) dB be added to the transmitted power. Further, the desired performance will be achieved whenever the shadowing attenuation \(\zeta < \gamma\) so that the outage probability, or fraction of the time, that the performance is not achieved is

\[
P_{\text{out}} = \Pr(\zeta > \gamma) = \frac{1}{\sqrt{2\pi} \sigma} \int_{\gamma}^{\infty} e^{-x^2/2\sigma^2} \, dx = Q\left(\frac{\gamma}{\sigma}\right).
\]  

If we require that 90% of the time adequate coverage is achieved for points on the boundary, then \(P_{\text{out}} = 0.1\), and for \(\sigma = 8\) dB, it follows that the margin \(\gamma = 10.3\) dB.

On the other hand, for hard handoff the ideal condition of handoff at cell boundary is both unrealistic and undesirable since this can lead to the “ping-pong” effect where the user is handed back and forth several times from one base station to the other while it hovers around the boundary. In practical hard handoff systems, the handoff occurs only after the first cell’s base station power is reduced by a sufficient amount below its value at the boundary. Let us assume that this happens when the user has moved a reasonable distance beyond the boundary. Let the ratio of this distance to the cell radius be \(r_0 > 1\). At this distance from the first cell’s base station, the outage probability, for a margin \(\gamma\), becomes

\[
P_{\text{out}} = \Pr(10 \mu \log r_0 + \zeta > \gamma) = Q\left(\frac{\gamma - 10 \mu \log r_0}{\sigma}\right)
\]  

where \(Q(y) = \int_{y}^{\infty} e^{-x^2/2} \, dx = \int_{-\infty}^{y} e^{-x^2/2} \, dx\).

Now, therefore, for an outage probability \(P_{\text{out}} = 0.1\) and \(\sigma = 8\) dB, we must have a required margin

\[
\gamma = 10 \mu \log r_0 + 10.3\ dB.
\]  

The second column of Table 1 shows the margin required for a propagation law \(\mu = 4\) as a function of \(r_0\), the relative distance beyond the cell boundary at which hard handoff occurs, as given in the first column. Thus for a relatively small range of additional distance beyond the cell boundary (10% to 25%) for the hard handoff, the margin must be increased by 2 to 4 dB.

B. Soft Handoff

For soft handoff, we shall now show that the required margin is much reduced. Soft handoff will occur throughout a range of distances from the two base stations. At any
TABLE 1

<table>
<thead>
<tr>
<th>Relative Distance Beyond Cell Boundary $r_0$</th>
<th>Hard Handoff Required Margin $\gamma_{\text{Hard}}$ (dB)</th>
<th>Relative Margin $\gamma_{\text{Soft}}$ (dB) - $\gamma_{\text{Hard}}$ (dB)</th>
<th>Relative Coverage Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>11.1</td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td>1.5</td>
<td>12.0</td>
<td>5.8</td>
<td>6.2</td>
</tr>
<tr>
<td>1.25</td>
<td>14.2</td>
<td>8.0</td>
<td>6.2</td>
</tr>
</tbody>
</table>

given time, or for any given frame or packet, the better of the two base stations' receptions will be utilized at the switching center. Taking this for simplicity to depend only on attenuation, the lesser of the attenuations of (5) will apply. Thus the margin $\gamma$ needs only be such that

$$ P_{\text{out}} = \Pr \{ \min \{10 \mu \log_2 r_0 + \xi_0, 10 \mu \log_2 r_1 + \xi_1 \} > \gamma \} \quad (9) $$

But since $\xi_0$ and $\xi_1$ are correlated according to their definition (3), we may express them in terms of the independent variables $\xi$, $\xi_0$, and $\xi_1$, thus obtaining

$$ P_{\text{out}} = \Pr \{ \min \{10 \mu \log_2 r_0 + b \xi_0, 10 \mu \log_2 r_1 + b \xi_1 \} > \gamma - \alpha \xi \} $$

$$ = \frac{1}{(2\pi \sigma)^{\frac{3}{2}}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-\xi^2/2\sigma^2} d\xi_0 d\xi_1 $$

$$ \times \int_{-\infty}^{\gamma - \alpha \xi_0 + 10 \mu \log_2 r_0} \int_{-\infty}^{\gamma - \alpha \xi_1 + 10 \mu \log_2 r_1} e^{-\xi_2^2/2\sigma^2} d\xi_2 d\xi_1 $$

$$ = \frac{1}{(2\pi \sigma)^{\frac{3}{2}}} \int_{-\infty}^{\infty} e^{-\xi^2/2\sigma^2} \left[ Q \left( \frac{\gamma - \alpha \xi + 10 \mu \log_2 r_0}{b \sigma} \right) \right] dx $$

$$\times Q \left( \frac{\gamma - \alpha \xi + 10 \mu \log_2 r_1 + a \sigma x}{b \sigma} \right) dx. \quad (10) $$

Now since the mobile is assumed to be either in cell 0 or 1, so that either $r_0 \leq 1$, $r_1 \geq 1$ or $r_0 \geq 1$, $r_1 \leq 1$. It is established numerically that $r_0 = r_1 = 1$, where the mobile is exactly on the boundary, represents the worst case, so that

$$ P_{\text{out}} = \frac{1}{(2\pi \sigma)^{\frac{3}{2}}} \int_{-\infty}^{\infty} e^{-\xi^2/2\sigma^2} \left[ Q \left( \frac{\gamma + a \sigma x}{b \sigma} \right) \right]^2 dx. \quad (11) $$

For $a = b = 1/\sqrt{2}$ and $\sigma = 8$ dB, we find by numerical means that for outage probability $P_{\text{out}} = 0.1$, the margin $\gamma_{\text{Soft}} = 6.2$ dB.

Actually, however, (11) is an upper bound because at $r_0 = r_1 = 1$, the mobile is in a corner of the hexagonal and hence is equally distant from a third cell. Including the effect of this third cell, (11) would be changed so that the $Q()$ term in the integral would be raised to the power of 3 rather than 2 thus reducing the outage probability. The 6.2 dB margin should therefore be taken as an upper bound.

Thus, as noted from the third column of Table I, the required margin for soft handoff is (conservatively) about 6 dB to 8 dB less than for hard handoff. Since cell area is proportional to the square of the radius while propagation loss is proportional to the 4th power, it follows that this margin reduction represents a cell area increase for soft handoff of 3 to 4 dB, or a reduction in the number of cells and consequently base stations by a factor of 2 to 2.5, as shown in the fourth column of Table I.

When the system is loaded, coverage will depend also on the number of users per sector, and ultimately cell size will depend on the number of users and their distribution in a particular geographical area. In the next section, we examine the ultimate cell capacity independent of size.

IV. REVERSE LINK CAPACITY

While coverage is essentially symmetrical, applying equally to forward and reverse link propagation, capacity is fundamentally asymmetric. We consider here only reverse link capacity, which involves many-to-one multiple access. The effect of soft handoff here is tightly coupled with the fast closed loop power control techniques described previously [1], [5], [6], [8]. These guarantee, that for the controlling base station, each user's received signal energy-to-interference is normalized to be equal to that of all other users. This limits each other-cell user's interference to a normalized value less than unity, for otherwise those users would be controlled by the given cell. Capacity is then reduced by the aggregate of all other-cell user's relative energy. Hence it is inversely proportional to $1 + f$ where

$$ f = \frac{\text{average total interference from other-cell users}}{k_u} \quad (12) $$

and $k_u =$ average number of users per cell (at capacity). We therefore proceed to determine $f$ and the resulting capacity reduction with hard and soft handoff. The latter is determined successively for handoff between two cells and among more than two cells.

A. Hard Handoff

Suppose that a single cell is being received at any one time, with hard handoff between cells being performed at the hexagonal cell boundary (Fig. 1). This is somewhat idealized because, as previously noted, even if the boundaries were known, such a process would lead to multiple rapid handoffs for users at or near the boundary, a condition alleviated only by requiring handoffs to occur only when the second cell's pilot strength is sufficiently above that of the first. Nevertheless, we shall use this for comparison with the soft handoff results, recognizing that this hard handoff model may accentuate the performance disparity between hard and soft handoff. A better hard handoff algorithm proposed by Vijayan and Holtzman [7] provides better performance, but only if the network can support fast handoff on a per frame basis whose practicality has not been demonstrated.

We normalize to unity each cell's radius defined as the maximum distance from any point in the cell to the base.

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2 The effect of soft handoff on forward link capacity is more complex and would require a separate and different analysis, similar to that for the forward link in [8]. Since it is generally accepted that the limiting link is in the reverse direction, for the sake of brevity and cohesion it is not presented here.
station at its center, and we assume a uniform density of users throughout all cells. Letting \( k_u \) be the average number of users per cell, then because of the hexagonal shape of the normalized cell, this density is

\[
\kappa = \frac{2k_u \text{ users}}{3\sqrt{3} \text{ unit area}}. \tag{13}
\]

Then we denote the cell under consideration as the zeroth cell and the distance from the user at coordinates \((x, y)\) to the zeroth cell’s base station as \(r_0(x, y)\) and that to any other cell’s base station as \(r_1(x, y)\) (Fig. 1). Since the user at \((x, y)\) is communicating through the nearest base station to that position, it will also be power controlled by that base station so that the user’s transmitter power gain equals the propagation loss (1). Consequently, the relative average interference at the given cell due to all users in all other cells, denoted as the region \( S_0 \),

\[
I_{S_0} = E \int_{S_0} \left[ \frac{r_1^\mu(x, y)10^{\xi_1/10}}{r_0^\mu(x, y)10^{\xi_0/10}} \right] \kappa dA(x, y) \tag{14}
\]

where the subscript 0 refers to the given cell, so that \(r_0(x, y)\) is the distance from the user to the given cell’s base station, while the subscript 1 refers to the cell of occupancy, so that \(r_1(x, y)\) is the distance from the user to the nearest base station to \((x, y)\). \(\xi_0\) and \(\xi_1\) correspond to the respective random propagation components in dB, as defined in (1) and (2). Thus the denominator of the bracketed term in the integrand of (14) is the propagation loss while the numerator is the gain adjustment through power control by the nearest base station. \(S_0\) is the entire area outside the given zeroth cell, which consists of all other cells. Note also that for each cell in \(S_0\), \(r_1(x, y)\) refers to the distance to a different (nearest) base station. Note finally that all parameters in (14) are position dependent and deterministic except \(\xi_0\) and \(\xi_1\) which are random but do not depend on position. Then defining

\[
R_1(x, y) = r_1(x, y)/r_0(x, y) \text{ and } \beta = \ln(10)/10
\]

we may rewrite (14) as

\[
I_{S_0} = E^{e^{\beta(\xi_1 - \xi_0)}} \int_{S_0} R_1^\mu(x, y) \kappa dA(x, y). \tag{16}
\]

But from (3), we have

\[
\xi_1 - \xi_0 = b(\xi_1 - \xi_0)
\]

which is a Gaussian random variable with zero mean and, since \(\xi_1\) and \(\xi_0\) are independent, \(\text{Var}(\xi_1 - \xi_0) = b^2 \text{Var}(\xi_1 - \xi_0) = 2b^2 \sigma^2\).

Letting \(x = \xi_1 - \xi_0\),

\[
E^{e^{\beta(\xi_1 - \xi_0)}} = E^{e^{\beta x}} = \int_{-\infty}^{\infty} e^{bx} e^{-x^2/4\sigma^2} dx = e^{b^2(\sigma^2)^2}. \tag{17}
\]

Consequently, from (16) and (17), using (13), we obtain for the mean other-cell interference normalized by the number of

\[
\int_{S_0} I_{S_0} \kappa dA(x, y) = e^{b^2(\sigma^2)^2} \left[ \frac{2}{3\sqrt{3} \kappa} \int_{S_0} R_1^\mu(x, y) dA(x, y) \right]. \tag{18}
\]

The results of numerical integration for \(\mu = 3, 4, \text{ and } 5\) and several values of \(\sigma\), with \(b = 1/\sqrt{2}\), are given in Table II.

### Table II

<table>
<thead>
<tr>
<th>(\mu)</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Standard Deviation, (\sigma)</td>
<td>0.77</td>
<td>0.44</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>0.48</td>
<td>0.33</td>
</tr>
<tr>
<td>4</td>
<td>1.18</td>
<td>0.67</td>
<td>0.46</td>
</tr>
<tr>
<td>6</td>
<td>2.01</td>
<td>1.13</td>
<td>0.78</td>
</tr>
<tr>
<td>8</td>
<td>4.21</td>
<td>2.38</td>
<td>1.64</td>
</tr>
<tr>
<td>10</td>
<td>10.9</td>
<td>6.17</td>
<td>4.27</td>
</tr>
<tr>
<td>12</td>
<td>35.1</td>
<td>19.8</td>
<td>13.7</td>
</tr>
</tbody>
</table>

#### B. Soft Handoff Reception by Better of Two Nearest Cells

To approach the performance of a soft handoff system, we next consider other-cell interference when the user is permitted to be in soft handoff to only its two nearest cells. Again taking the zeroth cell as the one under consideration, the region for which this cell can be in soft handoff, which we denote \(S_0\), is the six-pointed star which contains the cell, shown as the hatched area in Fig. 2. Within any user which is communicating with one of the six nearest neighbors will introduce interference into the zeroth base station. But this happens only if the propagation loss to that neighbor is less than to the zeroth base station,\(^3\) in which case it is power-controlled by the former. Thus the mean total interference to the zeroth base station from within the \(S_0\) region is

\[
I_{S_0} = \int_{S_0} \int_{S_0} R_1(x, y)^\mu E^{10^{(\xi_1 - \xi_0)/10}};
\]

where the expectation is over the sample space for which the inequality is satisfied.

Defining the logarithmic (dB) attenuation to each user as

\[
M(x, y) = 10\mu \log_{10} R_1(x, y)
\]

and using the definitions of (15), we obtain, dropping for convenience the notation of dependency on \(x\) and \(y\),

\[
I_{S_0} = \int_{S_0} \int_{S_0} R_1^\mu E^{10^{(\xi_1 - \xi_0)/10}} = (M_0 - M_1)/b \kappa dA
\]

where \(b = 1/\sqrt{2}\). Note that in the hard handoff there is no other-cell user interference from the \(S_0\) region because, by definition, all users therein are controlled by the zeroth cell’s base station.
\[ \begin{align*}
\int_{\mathcal{S}_0} \int_{\mathcal{S}_0} e^{b\xi_2} \left( \frac{(M_0-M_1)b}{2b\sigma^2} \right) e^{-(x-2b\sigma)^2/4\sigma^2} \kappa dA \\
= e^{b^2(\beta\sigma)^2} \int_{\mathcal{S}_0} \int_{\mathcal{S}_0} R_1^\mu E\left[ x^{\xi_2} \left( \frac{b^2}{2\sigma^2} \right) \right] e^{-x^2/2\sigma^2} dx_1 \kappa dA \\
= e^{b^2(\beta\sigma)^2} \int_{\mathcal{S}_0} \int_{\mathcal{S}_0} R_1^\mu Q\left( \frac{b\beta}{\sqrt{2}} + \frac{M_1 - M_0}{\sqrt{2b\sigma}} \right) \kappa dA \tag{20}
\end{align*} \]

where the last equality follows from the circular symmetry of the joint density function and the linear boundary of the region of integration.

Now the second integral \( I_2 \) is the same as \( I_1 \), with \( M_1 \) and \( M_2 \) interchanged. Thus combining (20), (21), and (22) and using (13), we obtain, for \( b = 1/\sqrt{2} \), the relative interference at the zeroth base station from all users not controlled by its base station

\[ f = \frac{I_{\mathcal{S}_0} + I_{\overline{\mathcal{S}_0}}}{k_u} = \frac{2e^{b(\beta\sigma)^2/2}}{3\sqrt{3}} \times \left[ \int_{\mathcal{S}_0} \int_{\mathcal{S}_0} R_1^\mu Q\left( \frac{M_1 - M_0}{\sigma} \right) dA \right. \\
+ \int_{\mathcal{S}_0} \int_{\mathcal{S}_0} R_1^\mu Q\left( \frac{M_1 - M_2}{\sigma} \right) dA \left. \right. \\
+ \int_{\mathcal{S}_0} \int_{\mathcal{S}_0} R_1^\mu Q\left( \frac{M_2 - M_1}{\sigma} \right) dA \right]. \tag{23} \]

Again in the spatial integrals over \( \mathcal{S}_0 \) and \( \overline{\mathcal{S}_0} \), \( R_1(x, y), R_2(x, y) \) and \( M_1(x, y), M_2(x, y) \) refer to the base stations nearest and second nearest to the user at \( (x, y) \).

The value of relative interference, \( f \), is evaluated numerically and shown in Table III. For all \( \mu \) and \( \sigma \), the value is greatly reduced from the single cell (hard handoff) case of Table II.

C. Soft Handoff Reception by Best of Multiple \((N_c)\) Cells

Though soft handoff is generally between two cells, it may be among three or more and, in any case, it should always be possible to change the set. We may generalize the results of the last section by increasing the candidate set for handoff
TABLE III  
RELATIVE OTHER-CELL INTERFERENCE FACTOR, $f$ FOR $\mu = 3, 4, \text{AND} 5$  
(SOFT HANDOFF BETWEEN TWO CELLS)  

<table>
<thead>
<tr>
<th>Total Standard Deviation</th>
<th>$\mu = 3$</th>
<th>$\mu = 4$</th>
<th>$\mu = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.77</td>
<td>0.44</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.78</td>
<td>0.43</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>0.87</td>
<td>0.47</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>1.09</td>
<td>0.56</td>
<td>0.36</td>
</tr>
<tr>
<td>8</td>
<td>1.60</td>
<td>0.77</td>
<td>0.47</td>
</tr>
<tr>
<td>10</td>
<td>2.80</td>
<td>1.28</td>
<td>0.73</td>
</tr>
<tr>
<td>12</td>
<td>5.93</td>
<td>2.62</td>
<td>1.42</td>
</tr>
</tbody>
</table>

$e^{r^2(\beta_0)^2} \int \frac{\sum_{j=1}^{N_c-1} R_j^\mu}{\sum_{j=1}^{N_c-1} \int_{S_0} R_j^\mu \left[ \int_{-\infty}^{\infty} e^{-((\xi_j - b\beta_0)^2)/2\sigma^2} \frac{d\xi_j}{\sqrt{2\pi}\sigma} \right] d\xi_j}$

$\times \prod_{i=1, i \neq j}^{N_c-1} \int_{S_0} e^{-((\xi_j - b\beta_0)^2)/2\sigma^2} d\xi_j$

$x \in \mathbb{R}, (M_j - M_i)/b$

$N_c-1 \prod_{i=1, i \neq j}^{N_c-1} Q \left( z + \frac{M_j - M_i}{b\sigma} + b\beta_0 \right) dz \right] k dA$  

Similarly, for the mean total interference to the zeroth base station from all users in the $S_0$ region, we have

$I_{S_0} = \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ 10^{(\xi_j - \xi_0)/10} \right] d\xi_j$

for all $i \neq j, i > 0$  

$= \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ e^{(\xi_j - \xi_0)} \right] d\xi_j$

for all $i \neq j, i > 0$  

$= \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ e^{(\xi_j - \xi_0)} \right] d\xi_j$

for all $i \neq j, i > 0$  

$= e^{r^2(\beta_0)^2} \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ \int_{\infty}^{\infty} e^{-((\xi_j - b\beta_0)^2)/2\sigma^2} \frac{d\xi_j}{\sqrt{2\pi}\sigma} \right] d\xi_j$

$\times \prod_{i=1, i \neq j}^{N_c-1} \int_{S_0} e^{-((\xi_j - b\beta_0)^2)/2\sigma^2} d\xi_j$

$\times \prod_{i=1, i \neq j}^{N_c-1} Q \left( z + b\beta_0 + \frac{M_j - M_i}{b\sigma} \right) dz \right] k dA$.  

From these we obtain the relative interference at the zeroth cell from all users not controlled by its base station as

$f = I_{S_0} / k_{du}$

where $I_{S_0}$ and $I_{S_0}$ are by given (24) and (25), respectively, with $k = 2k_{du}/(3\sqrt{3})$ and as previously we assume that

Fig. 3. Region $S_0$ (hatched) and distances for $N_c = 3$. to $N_c$ cells, including the zero and the base stations in the $N_c - 1$ cells nearest to the zero cell. Thus the $S_0$ region expands; for example, Fig. 3 shows that $S_0$ for $N_c = 3$ is a large hexagon which circumscribes the six-pointed star (which is $S_0$ for $N_c = 2$, as shown in Fig. 2.)  

Generalizing the analysis of the last section, we find that the mean total interference to the zeroth base station from within the $S_0$ region is

$I_{S_0} = \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ 10^{(\xi_j - \xi_0)/10} \right] d\xi_j$

$= \int \int \sum_{j=1}^{N_c} R_j^\mu \left[ e^{(\xi_j - \xi_0)} \right] d\xi_j$

$\xi_j > \xi_i + (M_j - M_i)/b \text{ for all } i \neq j, i \neq 0 \right] k dA$
TABLE IV
RELATIVE OTHER-CELL INTERFERENCE FACTOR, $f$ for $N_c = 1, 2.3$ and 4 ($\mu = 4$)

<table>
<thead>
<tr>
<th>$N_c$</th>
<th>$N_c = 1$</th>
<th>$N_c = 2$</th>
<th>$N_c = 3$</th>
<th>$N_c = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
<td>0.44</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>0.67</td>
<td>0.47</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>6</td>
<td>1.13</td>
<td>0.56</td>
<td>0.49</td>
<td>0.49</td>
</tr>
<tr>
<td>8</td>
<td>2.38</td>
<td>0.77</td>
<td>0.57</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>6.17</td>
<td>1.28</td>
<td>0.75</td>
<td>0.66</td>
</tr>
<tr>
<td>12</td>
<td>19.8</td>
<td>2.62</td>
<td>1.17</td>
<td>0.91</td>
</tr>
</tbody>
</table>

$h = 1/\sqrt{2}$. This general result specializes to the previous expressions (23) for $N_c = 2$ and (18) for $N_c = 1$. Table IV contains the results of numerical integrations of (24) and (25) for $N_c = 3$ and 4, along with those for $N_c = 2$ and $N_c = 1$ of Tables III and II, respectively, for $\mu = 4$ and several values of $\sigma$. The validity of the numerical results is supported by the consistency of the values obtained in the various tables as well as by experimental evidence. It is clear that for $\sigma \leq 6$ dB the two nearest neighbors suffice to obtain most of the soft handoff advantage. For $\sigma = 8$ dB, use of three neighbors (to better deal with the cell's corners) provides an additional significant advantage.

It is clear, therefore, from Table IV that soft handoff among three cells reduces the relative other-cell user interference, $f$, to 0.57 from 2.38 for hard handoff, (for $\mu = 4$ and $\sigma = 8$ dB), which implies that the capacity, which is inversely proportional [8] to $1 + f$, is increased by the factor $3.38/1.57 = 2.15$. Even when soft handoff is limited to $N_c = 2$ cells the increase, $3.38/1.77 = 1.91$, is still quite significant.

V. CONCLUSION

It has been established by a simple analytical approach, using the generally accepted propagation model with log-normal shadowing, that soft handoff in CDMA improves coverage by a factor of 2 to 2.5 in cell area. Coupled with power control, soft handoff increases reverse link capacity by a factor of better than 2. It bears repeating that these improvements are possible only because of the universal frequency reuse capability inherent in CDMA.

REFERENCES


Andrew J. Viterbi (S'54-M'58-SM'63-F'73) received the S.B. and S.M. degrees from the Massachusetts Institute of Technology, Cambridge, in 1957, and the Ph.D. degree from the University of Southern California in 1962.

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Dr. Viterbi is a member of the U.S. National Academy of Engineering. He has chaired the Visiting Committee for the Electrical Engineering Department of Technion-Israel Institute of Technology, has been Distinguished Lecturer at the University of Illinois and at the University of British Columbia, and is a member of the M.I.T. Visiting Committee for Electrical Engineering and Computer Science. In 1986 he was recognized with the Annual Outstanding Engineering Graduate Award by the University of Southern California, and in 1990 he received an honorary Doctor of Engineering Degree from the University of Waterloo, Ont., Canada. He presented the Shannon Lecture at the 1991 International Symposium on Information Theory. He has received several paper awards including the 1968 IEEE Information Theory Group Outstanding Paper Award and the 1994 Stephen O. Rice Award (co-recipient). He has also received several major international awards: the 1975 Christopher Columbus International Award; the 1984 IEEE Alexander Graham Bell Medal; the 1990 Marconi International Fellowship Award; was co-recipient of the 1992 NEC C&C Foundation Award and the 1994 Eduard Rhein Foundation Award for basic research.

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