Adaptive Soft-Handoff Thresholds for CDMA Systems with Spatial Traffic

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In this paper we examine the interactions of the soft-handoff thresholds with the traffic load of a CDMA cell. We assume a user distribution following a spatial homogeneous Poisson process and determine the joint probability distribution for the radii of the two cells and the minimal overlapping area which will be interpreted as the area of soft-handoff. With these values, we can obtain the optimal soft-handoff thresholds obeying the fluctuations in cell radius for an expected target traffic and show the implications on CDMA coverage planning. Since soft-handoff regions are determined by the pilot signal level of the base station, we will only focus in our analysis on the forward link coverage areas.

1. INTRODUCTION

Cellular networks employing code division multiple access (CDMA) technology have gained enormously in acceptance over the last few years. This is mainly due to its superior system capacity as compared to more traditional systems based on frequency or time division (F/TDMA), see [1]. Since communication channels in F/TDMA systems are separated by different time and frequency slots, interference from other users can be neglected. In CDMA, each communication channel is separated by modulating the data signal with a noise-like carrier which is unique for the link and then spreading the modulated signal over the same frequency bandwidth. Since the signal appears like noise over the channel, all other users' signals will also be received as noise and constitute a certain level of interference.

However, the *universal frequency reuse* in all CDMA cells can also be seen as advantage with respect to handoffs, i.e., how an active connection is handled when a *mobile station* (MS) leaves one cell and enters another. *Soft-handoff* in CDMA is driven by the mobile and is performed by comparing the forward link pilot signal strength to certain system thresholds. When a MS is near the cell boundary, the received signal from its cell site will become lower due to propagation loss, but additionally it will receive stronger signals from neighboring *base stations* (BS) at the same time. The MS will then communicate with these several BS simultaneously. The advantages of this path diversity due to soft-handoff are less call droppings and increased coverage areas. However, since there are two or more traffic channels involved for one connection, there should not be too many users in soft-handoff in order to keep the capacity loss at an acceptable level.

The performance of soft-handoff has been studied by many authors. Viterbi [2] examined the gains in cell coverage and reverse link capacity with soft-handoff compared to conventional hard handoff. In [3] and [4] analytical models for soft-handoff have been presented that include sophisticated mobility models, however, without really considering in their models the CDMA-specific behavior of the cells. Other papers like [5] used models including soft-handoff to show that this additional diversity results in a better system performance in terms of lower outage probabilities at the cell boundaries. In [6] a similar approach was taken, but here the users in the cell were modeled as independent random variables in order to illustrate the tradeoff between cell coverage area and capacity. Besides, those random variables were artificial since they didn't take into account the interaction between the cell coverage and the spatial distribution of the users. Furthermore, only few papers, e.g. [7], show the importance of a correct setting of the soft-handoff thresholds.

In this paper, we describe the relationship between coverage and capacity by using a spatial Poisson process for modeling the user distribution. We show that for a given maximum tolerated capacity loss we obtain the optimal distances between the BS and the appropriate soft-handoff thresholds. This issue is extremely important with respect to avoiding overload conditions and outage events and gives valuable insight in network planning.

The paper is organized as follows. Section 2 gives an overview of the soft-handoff mechanism currently implemented in the IS-95 standard. Here, the thresholds that the MS uses to determine the soft-handoff state will be introduced. In Section 3 we present our Poisson traffic model and derive the joint probability distribution for the cell radii of two cells. We also describe the minimal overlapping area for a given traffic load. Following this, we present the computation of the traffic dependent soft-handoff thresholds in Section 4 based on the cell radius obtained in the previous section. The numerical results and their implications on network planning are shown in Section 5, followed by the conclusion and outlook on future work in Section 6.

2. IS-95 SOFT-HANDOFF MODEL

In CDMA, the mobile triggers the soft-handoff process by taking measurements of the forward link quality and notifying the BS of the current condition. Based on this information the handoff decision will be taken. The next sections will describe the interactions involved in this *mobile-assisted handoff* (MAHO).

2.1. Soft-Handoff Set Maintenance and Thresholds

The soft-handoff mechanism as described in the IS-95 standard [8] is initiated from the measurements on the forward link channel at the MS. For this the mobile station registers the pilot signal strength in terms of the chip-energy-to-interference ratio (E_c/I_0) of each BS it receives and stores it in one of four exclusive sets [9]: the *active*, *candidate*, *neighbor*, and *remaining* sets. Pilots are added and removed from the sets by comparing them to the following thresholds:

`T_ADD` A pilot in the neighbor or remaining set is moved to the candidate set, if its E_c/I_0 is greater than `T_ADD`.

`T_DROP` A pilot in the active or candidate set is moved to the neighbor set, if its E_c/I_0 falls below `T_DROP` for a period of `T_TDROP` seconds.

The reason for using two different threshold values is to have a hysteresis to avoid a ‘ping pong’ effect of a pilot continuously being added and removed from soft-handoff.

When a MS is in soft-handoff, i.e., two or more pilot signals are in its active set, the mobile simultaneously maintains traffic channel connections with these cells. On the forward link the mobile uses the RAKE receiver to demodulate and combine the separate signals. On the reverse link, the signal from the MS is received by both BS and the frames are sent back independently to the mobile switching center (MSC). We can see that during a two-way soft-handoff the MS is utilizing channel resources from two different cells at the same time. Therefore, soft-handoff not only results in a gain in coverage, but also in a loss in capacity. A tradeoff between this loss and the gain in connection quality has to be considered [10]. Thus, the soft-handoff regions should not be too large, otherwise the loss in capacity due to the extra links would be too high.

2.2. Derivation of E_c/I_0

In the following, we will use the model presented in [5] to describe the chip-energy-to-interference ratio E_c/I_0. In line with [5] the path loss attenuation from a base station to a MS at distance r will be (in *dB*):

$$l(r) = C + 10\mu \log(r) + \gamma \tag{1}$$

where C is the constant loss at unit distance, μ is the path loss exponent and γ the log-normal shadowing loss with zero mean and standard deviation σ. Due to the variations near the mobile, the signals received will be partially correlated. Therefore, the log-normal shadowing can be expressed as $\gamma_i = a\zeta + b\zeta_i$ with i.i.d. random variables ζ and ζ_i with zero mean and standard deviation of σ.

The chip-energy-to-interference ratio E_c/I_0 for user i at distance r_i can now be given as:

$$\epsilon_i = \frac{\alpha_i S_i L(r_i) 10^{\frac{\gamma_i}{10}}}{S_i L(r_i) 10^{\frac{\gamma_i}{10}} + \sum\limits_{j \neq i} S_j L(r_j) 10^{\frac{\gamma_k}{10}} + N_0 W} \tag{2}$$

where S_i is the total effectively radiated power (ERP) of cell i, α_i is the fraction of the cell power allocated to the pilot signal and $N_0 W$ is the background noise power in bandwidth W. The propagation loss from Eqn. (1) in linear space is denoted by $L(r)$.

Neglecting the term for background noise $N_0 W$, we may now define $C_j = \frac{S_j}{S_i} \left(\frac{r_i}{r_j}\right)^{\mu}$ and with $(\gamma_j - \gamma_i) = b(\zeta_j - \zeta_i)$ we obtain a new log-normal random variable X_i:

$$X_i = \sum_{j \neq i} C_j 10^{\frac{b(\zeta_j - \zeta_i)}{10}}. \tag{3}$$

The first and second moments of X_i can be obtained as follows:

$$E[X_i] = \exp(\lambda^2 \sigma^2) \sum_{j \neq i} C_j \tag{4}$$

$$E[X_i^2] = \exp(4\lambda^2 \sigma^2) \sum_{j \neq i} C_j^2 + \exp(3\lambda^2 \sigma^2) \sum_{j \neq i} \sum_{k \neq j \neq i} C_j C_k \tag{5}$$

where $\lambda = \frac{b}{10}\ln(10)$. Transforming X_i to logarithmic space, we get the normal random variable Z_i with mean $E[Z_i]$ and standard deviation σ_{Z_i}:

$$E[Z_i] = 10\log\left(\frac{E[X_i]^2}{\sqrt{E[X_i^2]}}\right) \qquad \text{and} \qquad \sigma_{Z_i} = \lambda 10\log\left(\frac{E[X_i^2]}{E[X_i]^2}\right) \tag{6}$$

Therefore, Eqn. (2) can now be written as:

$$\epsilon_i = \frac{\alpha_i}{1 + 10^{\frac{Z_i}{10}}} \tag{7}$$

3. SOFT-HANDOFF AREA SIZE WITH SPATIAL TRAFFIC

Let us assume a spatial Poisson process directing the user distribution over the plane, at a fixed time t. According to the expected traffic load in each cell, the corresponding cell's radius can be derived along with the soft-handoff area size (i.e. the overlapping region of the cells).

We propose here to first recall the Poisson process model by highlighting its main characteristics of interest here. Secondly, we derive the joint distribution of the radius of two cells when the expected traffic load in each cell is specified. We finally provide some discussion about the behavior of the minimum soft-handoff area size with an expected user load in the system.

3.1. Spatial User Distribution Model

Suppose now that customers are randomly located over the plane according to a homogeneous Poisson process of rate λ (see Kingman [11] for a formal introduction). In such a process, the number $N(A)$ of active users in some cell A depends only on the area of the cell in the following manner:

$$P[N(A) = k] = \exp\{-\lambda|A|\}\frac{(\lambda|A|)^k}{k!}, \tag{8}$$

where $k \in I\!N$ and $|A|$ denotes the area of the set A. Another important feature is that non-overlapping cells do not interact on each other's capacity, i.e., if the cells A and B are disjoint, then

$$P[N(A) = k, N(B) = l] = P[N(A) = k]\ P[N(B) = l], \tag{9}$$

where both $k, l \in I\!N$. Due to these two properties, the Poisson process is first completely stationary, i.e., the process keeps the same characteristics under any translation or rotation of the plane. Secondly, users will be observed as homogeneously spread over any studied area A.

The independence assumption between sets of users is only met when those sets do not overlap. In case A and B overlap, the joint distribution of $N(A)$ and $N(B)$ depends on the actual number of points lying in the overlapping area $A \cap B$, denoted by V. The distribution is then simply obtained by conditioning on $N(V)$. So we have

$$P[N(A) = k, N(B) = l] = \sum_{j=0}^{\min(k,l)} P[N(A) = k, N(B) = l \mid N(V) = j]\ P[N(V) = j]$$

$$= \sum_{j=0}^{\min(k,l)} P[N(V) = j]\ P[N(A \setminus V) = k - j]\ P[N(B \setminus V) = l - j] \tag{10}$$

using relation (9).

Given the observed number of users both in A and B, the conditional distribution of $N(V)$ can then be obtained using

$$P[N(V)=k \mid N(A)=l, N(B)=m] = \frac{P[N(V)=k]}{P[N(A)=l, N(B)=m]}\, P[N(A)=l, N(B)=m \mid N(V)=k]. \tag{11}$$

3.2. Radius of Cells According to the Expected Traffic Load

Let $\mathcal{C}(a_1, r_1)$ and $\mathcal{C}(a_2, r_2)$ be two cells of circular shape where a_i is the center and r_i the radius of cell i, for each $i \in \{1,2\}$. The distance between the two base stations located at the center of each cell is fixed to be equal to d.

Let $P_{k_1 k_2}(r_1, r_2)$ be defined as

$$P_{k_1 k_2}(r_1, r_2) = P[N(\mathcal{C}(a_1, r_1)) \geq k_1, N(\mathcal{C}(a_2, r_2)) \geq k_2], \tag{12}$$

It states that $\mathcal{C}(a_1, r_1)$ and $\mathcal{C}(a_2, r_2)$ must contain at least k_1 and k_2 users, respectively. It implies that for example r_1 can be viewed as the minimum radius of the cell $\mathcal{C}(a_1, r_1)$ when exactly k_1 users are expected to be located in that cell. We can then heuristically interpret $P_{k_1 k_2}(r_1, r_2)$ in the following manner

$$P_{k_1 k_2}(r_1, r_2) = P[\text{radius of cell } 1 < r_1, \text{radius of cell } 2 < r_2 \mid \text{cell 1 contains } k_1 \text{ users}, \text{cell 2 contains } k_2 \text{ users}]. \tag{13}$$

It follows that according to fixed k_1 and k_2, we can derive the minimum corresponding radius of each cell.

We then have

$$P_{k_1 k_2}(r_1, r_2) = \sum_{j_1=k_1}^{\infty} \sum_{j_2=k_2}^{\infty} P[N(\mathcal{C}(a_1, r_1)) = j_1, N(\mathcal{C}(a_2, r_2)) = j_2]. \tag{14}$$

Two cases now have to be distinguished according to the values of r_1 and r_2.

If $r_1 + r_2 \leq d$, then the two cells have no intersection, and the two random variables corresponding to the number of points in $\mathcal{C}(a_1, r_1)$ and $\mathcal{C}(a_2, r_2)$ are independent, as stated before. We can then simply use the expression (9).

If now $r_1 + r_2 > d$, the random variables are dependent and we should use expression (10). In this computation, the area of the overlapping area V is needed as a function of the radius r_1 and r_2, denoted as $V(r_1, r_2)$. Without loss of generality, we assume $a_1 = (0,0)$ and $a_2 = (d, 0)$. The area $V(r_1, r_2)$ is equal to the sum of V_1 and V_2, where

$$V_1 = \alpha\, r_1^2 - (\tilde{X}\, \tilde{Y}), \qquad \text{and} \qquad V_2 = \beta\, r_2^2 - ((d - \tilde{X})\, \tilde{Y}). \tag{15}$$

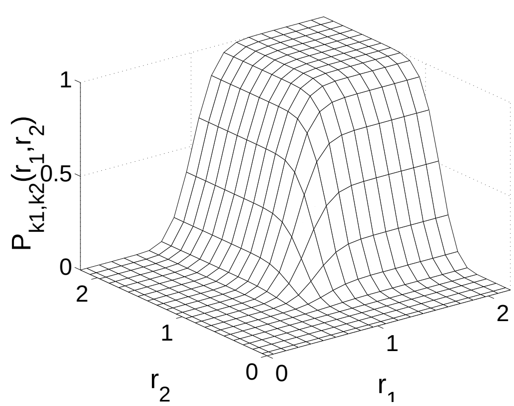
The following quantities have to be defined as

$$\tilde{X} = \frac{d^2 + r_1^2 - r_2^2}{2d}, \quad \tilde{Y} = \sqrt{r_1^2 - \tilde{X}^2}, \quad \alpha = \arccos \frac{\tilde{X}}{r_1}, \quad \text{and } \beta = \arccos \frac{d - \tilde{X}}{r_2}. \tag{16}$$

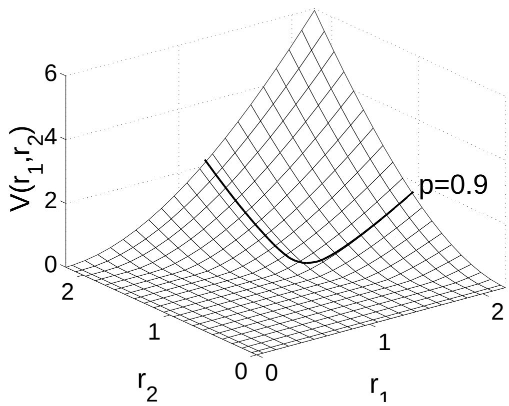
3.3. Minimum Soft-Handoff Area Size

Algorithms have been implemented that compute values of $P_{k_1 k_2}(r_1, r_2)$ for some fixed k_1 and k_2. We propose here to look at a simple case where d is fixed to 2.2 km. We also assume that in the average case, 3 users/km^2 are observed; it implies that λ is equal to 3.0. Due to the geographical and teletraffic properties of the region, we would like the first base station to be able to manage at least 10 customers and the second one 7.

Figure 1(a) represents the numerical results obtained for the joint distribution of r_1 and r_2. It is obvious that the greater the radii, the greater the probability to observe at least the desired number of customers. The curve shown here is not symmetrical, this is explained by the introduction of different parameters k_1 and k_2.



(a) Joint radius probability distribution



(b) Size of overlapping area

Figure 1. Radius distribution and overlapping area

The corresponding area size $V(r_1, r_2)$ is presented in Figure 1(b). Also shown on that picture is a curve identifying all values of r_1, r_2 for which the probability is at 90% to observe at least 10 customers in cell $\mathcal{C}(a_1, r_1)$ while at least 7 customers lie inside the second cell. The quantity of interest here is the minimum overlapping area size, since it represents the worst case where soft-handoff occurs. In this case, where $d = 2.2$ km, the minimum soft-handoff region would be about 0.14 km^2. One should then expect to encounter 0.42 users in such a region.

Figure 2 illustrates different values of soft-handoff area size according to the distance d, separating the two studied base-stations, given that the other parameters keep the same value. One can observe that the greater d, the smaller the value of the minimum overlapping area of the two cells. Indeed the Poisson process keeps the same properties for whatever d. We can also immediately observe in Figure 2 that the soft-handoff area decreases as λ increases. That is intuitive since in the same area, one can observe more users when the density is high.

4. THRESHOLDS WHILE MAINTAINING TRAFFIC LOAD

Let us suppose we have another user entering the system at the margin of the cells, see point D in Fig. 3. The user here has a probability p_d to leave the cell 1 at this point, i.e., $p_d = P(E_c/I_0 < \texttt{T\_DROP})$. In the same way, at point A we can consider the probability p_a of

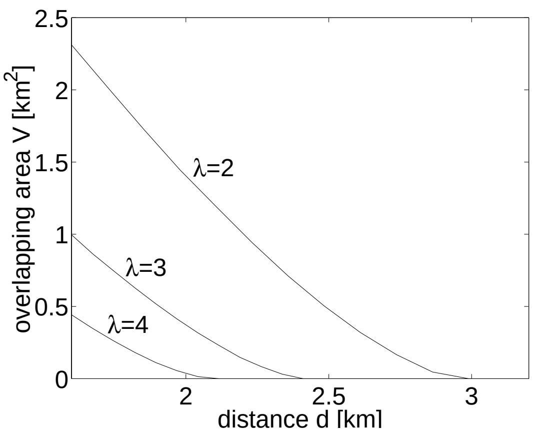


Figure 2. Minimum soft-handoff region for different traffic intensities

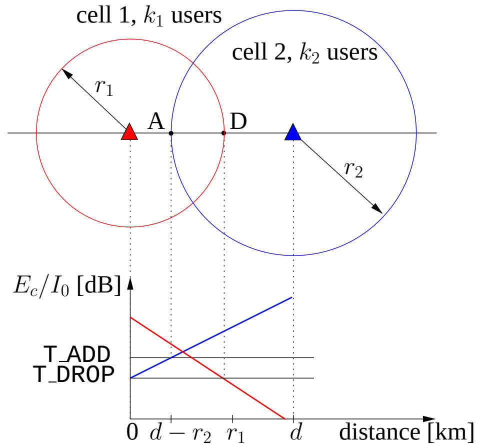


Figure 3. Variations of soft-handoff thresholds due to fluctuations of traffic

not adding cell 2 to the active set to be $p_a = P(E_c/I_0 < \texttt{T\_ADD})$. The probabilities p_d and p_a should be proportional to the cell loading of cell 1 and 2, respectively:

$$p_d = k_1/k_{\text{pole}} \qquad \text{and} \qquad p_a = k_2/k_{\text{pole}} \tag{17}$$

where k_i is the number of users in cell i and k_{pole} is the pole capacity, i.e., the theoretical maximum number of users in each cell. If the loading of cell 1 is high, the user should leave the cell with a higher probability than if it is low. Equivalently, if the load of cell 2 is high, we want the probability of cell 2 participating in soft-handoff to be low.

The probability for leaving the cell 1 at point D is given in Eqn. (18).

$$\begin{aligned} P(\epsilon_1 < \texttt{T\_DROP}) &= P\left(\frac{\alpha_1}{1+10^{\frac{Z_1}{10}}} < \texttt{T\_DROP}\right) = P\left(Z_1 > 10\log\left(\frac{\alpha_1}{\texttt{T\_DROP}} - 1\right)\right) \\ &= Q\left(\frac{10\log\left(\frac{\alpha_1}{\texttt{T\_DROP}} - 1\right) - m_{Z_1}}{\sigma_{Z_1}}\right) = p_d. \end{aligned} \tag{18}$$

If we give a p_d from Eqn. (17), we can solve Eqn. (18) in order to obtain T_DROP as

$$\texttt{T\_DROP} = \frac{\alpha_1}{1+10^{\frac{\sigma_{Z_1} Q^{-1}(p_d)+m_{Z_1}}{10}}}. \tag{19}$$

We can perform the same kind of computation for T_ADD at point A and obtain Eqn. (20):

$$\texttt{T\_ADD} = \frac{\alpha_2}{1+10^{\frac{\sigma_{Z_2} Q^{-1}(p_a)+m_{Z_2}}{10}}}. \tag{20}$$

We now have an expression for T_DROP that depends on the random variable Z_1, which in turn contains the distance r_1 to cell 1. In T_ADD we have the distance r_2 to BS 2. Our next section will describe how we can use the size of the overlapping area from Section 3 to obtain the values of r_1 and r_2. This will permit us to set T_DROP and T_ADD in an optimal way.

5. THRESHOLD VALUE AS A FUNCTION OF CAPACITY LOSS

In Section 3, we have obtained the minimum soft-handoff area when the desired traffic load in each cell was observed with a probability equal to 90%. A curve has been drawn in Fig. 2 where this minimum soft-handoff area was studied according to the inter-BS distance d.

To each minimum soft-handoff area correspond some given values of the radii r_1 and r_2. With this pair of radii, we can compute the variations of the T_DROP and T_ADD thresholds as a function of the inter-BS distance d using Eqns. (19) and (20).

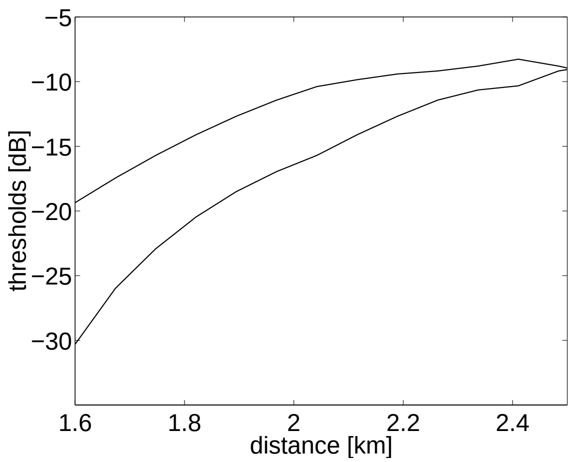


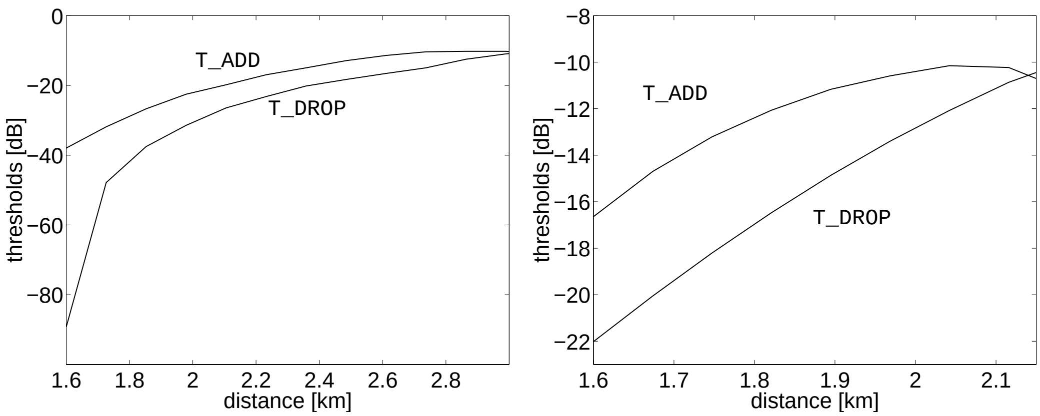
Figure 4. Soft-handoff thresholds depending on the inter-BS distance ($\lambda = 3$)

Figure 4 shows the thresholds obtained in the same conditions as described in Section 3, i.e., $k_1 = 10$, $k_2 = 7$ and the intensity λ of the Poisson process is set to 3 users/km^2. Results corresponding to an inter-BS distance greater than 2.5 km are not shown here. Indeed there is no overlapping area in such conditions as depicted in Figure 2. There is then no point in studying the probability that a user participates in soft-handoff as soon as he is out of the range of the other BS. An expected effect (see [9] for details) is that T_ADD should be greater than T_DROP whatever the inter-BS distance d. Moreover the greater d becomes, the smaller the difference between the two considered thresholds.

We can now propose a way to set the thresholds according to an accepted loss of capacity due to soft-handoff. As assumed in Section 3, the minimum traffic load handled by cell 1 and cell 2 is k_1 and k_2, respectively. Moreover users in the overlapping region V (i.e., in soft-handoff conditions) are using two channels, one in each cell. It implies a loss of as many channels as the number of users in V (say k), in the whole system. So the percentage of channel loss is

$$\mathrm{L} = k/(k_1 + k_2). \tag{21}$$

Let us fix the loss percentage at 7%, let k_1 and k_2 be respectively equal to 10 and 7. It implies using (21) that the number of users in soft-handoff conditions is 1.2. Because users are randomly located through the plane according to a Poisson process of rate $\lambda = 3$, a soft-handoff region containing 1.2 users is expected to have an area equal to 0.4 km^2. According to Figure 2, it corresponds to a distance $d = 2.0$ km. Using the results we have presented above (see Figure 4), we can propose the network designer to separate the BS by a distance of 2.0 km and fix the thresholds T_ADD to -10.38 dB and T_DROP to -15.71 dB.



(a) Lower traffic density ($\lambda = 2$)

(b) Higher traffic density ($\lambda = 4$)

Figure 5. Soft-handoff thresholds depending on inter-BS distances

It is clear that the traffic density will be varying over the time of the day. Thus, we now propose that the thresholds change with the traffic conditions. In Figures 4, 5(a), and 5(b), corresponding thresholds versus inter-BS distance are shown for different values of λ. One major comment is that the greater the traffic density λ the smaller the value of corresponding thresholds. Let us take the case we have discussed above, where the inter-BS distance has been fixed to 2.0 km. Table 1 contains the results for the corresponding thresholds.

	$\lambda = 2$	$\lambda = 3$	$\lambda = 4$
T_DROP [dB]	-31.45	-15.71	-12.08
T_ADD [dB]	-22.51	-10.38	-10.15

Table 1
Threshold values for a fixed inter-BS = 2.0 km, according to varying traffic density

6. CONCLUSION

In this paper we have presented a new approach for setting the soft-handoff thresholds in a CDMA system considering a spatial user distribution model. With the use of a spatial Poisson process for the user distribution, we obtain the minimum overlapping area which constitutes the minimal soft-handoff region. If the target traffic load of both cells is known, this gives us the optimal inter-BS distance obeying these conditions. We also showed how to compute the soft-handoff thresholds T_ADD and T_DROP for this case. With this method we are able to maintain the traffic load in both cells at our desired target level. This not only gives a more predictable behavior of the system load, it also facilitates improvements in the overall capacity when planning the network of cells with varying target loads. Other papers, e.g. [12] and [13], have shown that if one keeps the target traffic at not equal levels, a further increase in capacity can be reached for the potential *hot cells*.

Current research projects include the consideration of overlapping areas of 3 or more BS. This will remarkably increase the complexity of the proposed analysis. It is also planned to enhance our model by observing non-homogeneous spatial processes or processes with interacting users [14]. With the application of spatio-temporal processes it will be possible to also include a more dynamic view of the system and not only to look at the stationary behavior. These processes will reflect the realistic traffic conditions even better.

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