

Evaluation of Multiusers' Interference on Radiolocation in CDMA Cellular Networks

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Abstract

Radiolocation has been previously studied for CDMA networks, the effect of Multiple Access Interference has been ignored. In this paper we investigate the problem of Radiolocation in the presence of Multiple Access Interference. An extensive simulation technique was developed, which measures the error in location estimation for different network and user configurations. We include the effects of lognormal shadow and Rayleigh fading. Results that illustrate the effects of varying shadowing losses, number of base stations involved in position location, early-late discriminator offset and cell sizes in conjunction with the varying number of users per cell on the accuracy of radiolocation estimation was presented.

Keywords: Code Division Multiple Access, Radiolocation, Multiple Access Interference, Base Station, Mobile Station.

1. Introduction

Radiolocation involves: a) identifying the base station (BS) that would participate in the process of subscriber location by selecting a set of BSs within the coverage area that receives intelligible levels of signal from the mobile station (MS) under consideration. b) estimating one-dimensional position which involves each BS, participating in the process, independently producing an estimate of the subscriber location based on its measurements; c) location estimation, that is, estimates from all the participating BSs are used by position location algorithms to produce an accurate estimate of the subscriber location within the coverage area. But, the estimates produced are not always very accurate. The major sources of error in subscriber location systems are: multipath propagation, non-line-of-sight (NLOS), and multiple access interference (MAI). In the case of multipath propagation, accuracy is greatly affected when the reflected rays arrive within a very small period of the first arriving ray. Case is even more worsened when the power of reflected rays is more than the first arriving ray [1]. Several methods have been developed to mitigate the effects of multipath on radiolocation. Typically propagation in wireless communications accrues up to an average of 400-700m [2,3] and biases the estimations. By using the *a priori* information about range error statistics, range estimations made over a period of time and cor-

rupted by NLOS errors can be adjusted to near their correct values. An alternative approach is to reduce the weights of the BSs prone to NLOS reception while estimating location using position location algorithms [4,5]. Co-channel interference is a problem faced by all the cellular systems. In *Code Division Multiple Access* (CDMA) networks, users share the same frequency band, but use unique pseudo-noise (PN) codes. Near far effects in CDMA networks are the biggest source of errors in position estimation. Multiple cellular users who are using the same frequency allocation at the same time cause MAI: it greatly affects the performance of Time of Arrival (ToA) estimation of CDMA systems. In CDMA cellular systems, the MSs are power controlled to combat the near-far effect. Thus, for a CDMA network, time based approach is the most promising technique. This paper investigates the effect of MAI and the accuracy of Radiolocation in CDMA cellular network.

This paper models the intracellular and intercellular multiple access interference (MAI) in Section 2, simulation results are presented in Section 3, and finally in Section 4, the conclusion drawn from the study is summarised.

2. System Model

In a CDMA system all the users share the same frequency band. As a result, at a CDMA receiver signals from users,

other than the intended user, act as interfering signals, thereby giving rise to multiple access interference. Figure 1 represents such a situation.

With reference to Figure 1, the coverage area comprises of cells, C_i, C_j, \dots and C_p . These cells have n_i, n_j, n_k, \dots and C_p users respectively. The BS's i, j, k, \dots and p exercise power control over the users they serve. Let A_i, A_j, A_k, \dots and A_p denote their areas. Only few cells have been considered for simplicity of explanation.

2.1. Modeling Intracellular Multiple Access Interference

In a CDMA system using binary signaling, the radio signal from the k^{th} user, arriving at the BS is given by:

$$S_k(t - \tau_k) = \sqrt{2P_k} c_k(t - \tau_k) b_k(t - \tau_k) \cos(\omega_c t + \phi_k) \quad (1)$$

where, P_k is the power received from the k^{th} user at the BS. Assuming, perfect power control is exercised, we can replace P_k by P , where P represents the nominal power received at the BS from a user under its power control.

$c_k(t)$ is the spreading (or chip) sequence for a user k .

$b_k(t)$ is the data sequence for a user k .

τ_k is the delay for user k relative to a user 0.

ϕ_k is the phase change for user k relative to a user 0.

ω_k is the carrier frequency.

In the above equation we assume that there is no multipath interference in the channel. A PN sequence $c_k(t)$ is of the form: [10]

$$c_k(t) = \sum_{j=-\infty}^{\infty} \sum_{i=0}^{M-1} a_{k,i} \Pi\left(\frac{t - (i + jM)T_c}{T_c}\right) \quad (2)$$

$a_{k,i} \in \{-1, 1\}$

where

T_c represents the chip duration.

MT_c represents the chip repetition period.

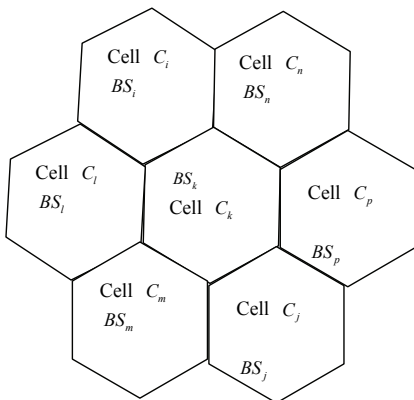


Figure 1. Coverage area.

Π represents the unit pulse function given by

$$\Pi(t) = \begin{cases} 1 & 0 \leq t \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

i is an index to denote a particular chip within a PN cycle. For data sequence $b_k(t)$, T_b is the bit period such that

$$T_b = GT_c$$

where G represents the spreading factor or gain of the CDMA system. It is not necessary that the gain G of a CDMA system be equal to M . In case they are same, a PN sequence would be repeated for every bit period T_b .

The user data sequence $b_k(t)$ is given by

$$b_k(t) = \sum_{j=-\infty}^{\infty} b_{k,i} \Pi\left(\frac{t - jT_b}{T_b}\right) \quad (4)$$

$b_{k,i} \in \{-1, 1\}$

the signal received at the BS is given by

$$r(t) = \sum_{k=0}^{n_p} S_k(t - \tau_k) + n(t) \quad (5)$$

where $n(t)$ represents a zero-mean white Gaussian noise with two sided power spectral density $\frac{N_o}{2}$, and n_p represents the number of users power controlled by BS p .

To derive a decision statistic, the received signal $r(t)$ is mixed with the base band, multiplied with the PN sequence of the desired user, and integrated over the bit period T_b .

Assuming that the receiver is phase and delay synchronized with the k^{th} user, the output of the correlator can be written as [6,7]

$$Z_k = \int_{jT_b}^{(j+1)T_b} r(t) c_k(t) \cos(\omega_c t) dt \quad (6)$$

Assume $\tau_k = 0, \phi_k = 0$, and that the desired user is user 0. Hence $k=0$. Substituting Equations (1) and (5) in Equation (6) we obtain

$$\begin{aligned} Z_0 &= \int_{t=0}^{T_b} [r(t) c_0(t) \cos(\omega_c t) dt \\ &= \int_{t=0}^{T_b} \left[\left(\sum_{k=0}^{n_p-1} \sqrt{2P_k} c_k(t - \tau_k) b_k(t - \tau_k) \cos(\omega_c t - \phi_k) \right. \right. \\ &\quad \left. \left. + n(t) \right) c_0(t) \cos(\omega_c t) dt \right] \quad (7) \end{aligned}$$

Z_0 is a decision statistic for the desired user.

Equation (7) can be expressed as

$$Z_0 = I_0 + \zeta + \eta$$

where

1) I_0 is the contribution from the desired user, i.e.,

$$I_0 = \int_{t=0}^{T_b} \sqrt{2P_k} b_k(t) c_k^2(t) \cos^2(\omega_c t) dt \quad (8)$$

As $c_k \in \{-1, 1\}$, $c_k^2 = 1$

Hence I_0 reduces to

$$I_0 = \sqrt{\frac{P_0}{2}} b_0(t) T_b \quad (9)$$

2) ζ represents the contribution of MAI and is the summation of $n_p - 1$ terms, I_k , where

$$I_k = \sqrt{2p_k} c_k(t - \tau_k) b_k(t - \tau_k) \cos(\omega_c t - \phi_k) c_0(t) \cos(\omega_c t) dt \quad (10)$$

$$\zeta = \sum_{k=0}^{n_p-1} I_k \quad (11)$$

3) η represents the contribution of noise and is given by

$$\eta = \int_{t=0}^{T_b} n(t) c_0(t) \cos(\omega_c t) dt \quad (12)$$

To determine the variance and mean of η

$$\mu_\eta = E[\eta] = \int_{t=0}^{T_b} E[n(t) c_0(t) \cos(\omega_c t)] dt = 0 \quad (13)$$

Variance σ_η^2

$$\begin{aligned} \sigma_\eta^2 &= E[(\eta - \mu_\eta)^2] = E[\eta^2] \\ &= \int_{\lambda=0}^{T_b} \int_{t=0}^{T_b} E[n(t)n(\lambda) \cos(\omega_c \lambda) c_0(t) \cos(\omega_c t) dt d\lambda] \end{aligned}$$

Now,

$$\begin{aligned} E[n(t)n(\lambda)] &= \frac{N_0}{2} \delta(t - \lambda) \\ \sigma_\eta^2 &= \int_{\lambda=0}^{T_b} \int_{t=0}^{T_b} \frac{N_0}{2} c_0(\lambda) \cos(\omega_c \lambda) c_0(t) \cos(\omega_c t) \delta(t - \lambda) dt d\lambda \\ \sigma_\eta^2 &= \int_{t=0}^{T_b} \frac{N_0}{2} c_0^2(t) \cos^2(\omega_c t) dt \\ c_0^2(t) &= 1 \end{aligned}$$

Hence

$$\begin{aligned} \sigma_\eta^2 &= \int_{\lambda=0}^{T_b} \int_{t=0}^{T_b} \frac{N_0}{4} (1 + \cos(2\omega_c t)) dt \\ \sigma_\eta^2 &= \frac{N_0 T_b}{4} \end{aligned} \quad (14)$$

Assuming a large number of interferes, by virtue of the central limit theorem (CLT), the distribution of ζ can be approximated by a zero-mean Gaussian distribution [4,7,8] with variance σ_ζ^2 given by [7]

$$\sigma_\zeta^2 = \frac{GT_c^2 \sum_{k=1}^{n_p-1} P_k}{6} \quad (15)$$

Let,

$$\xi = \zeta + \eta \quad (16)$$

Assuming that the MAI and noise are independent proc-

esses, the variance of ξ can be written as

$$\sigma_\xi^2 = \sigma_\zeta^2 + \sigma_\eta^2 \quad (17)$$

$$= \frac{GT_c^2 \sum_{k=1}^{n_p-1} P_k}{6} + \frac{N_0 T_b}{4} \quad (18)$$

2.2. Modeling Intercellular Multiple Access Interference

Expression for the intercellular interference caused by the users of cell C_i at BS j , represented by I_{ij} can be derived. Let the path loss exponent be m . Let the fading on path from this user to cell C_i be Rayleigh distributed, and represented by x_i . Similarly, let the fading on the path from this user to cell C_j be Rayleigh distributed, and represented by x_j . The average of x_i^2 is the log-normal fading on the path from this user to cell i , i.e., $E[x_i^2 | \zeta_i] = 10^{\zeta_i/10}$, where ζ_i is the decibel attenuation due to shadowing, and is a Gaussian random variable with zero-mean and standard deviation σ_ζ [9,10]. Similarly the average of x_j^2 is the log-normal fading on the path from this user to cell j . Let P_k be the nominal power received at BS i from user n_i . It is assumed that the power control mechanism overcomes both the large scale path loss and shadow fading. However, it does not overcome fast fluctuations of signal power due to Rayleigh fading [8,11]. As BS i exercises a power control over the MS, the actual transmission power P_{ac_i} of the MS would be

$$P_{ac_i} = P_i [r_i(x, y)]^m 10^{\zeta_i/10} \quad (19)$$

where $r_i(x, y)$ is the distance of the MS from BS i . Consequently, assuming uniform user density in the cell, the relative average interference I_{ij} at cell C_j caused by all the users in cell C_i is given by [9]

$$I_{ij} = E \left[\frac{n_i}{A_i} \iint_{C_i} \frac{1}{r_i^m(x, y)} \frac{10^{\zeta_i/10}}{r_j^m(x, y)} dA(x, y) \right] \quad (20)$$

by using iterated expectations,

$$\begin{aligned} E[10^{10} x_j^2] &= E[E[10^{10} x_j^2 | \zeta_i, \zeta_j]] \\ &= E_{\zeta_i, \zeta_j} [E[10^{10} x_j^2 | \zeta_i, \zeta_j]] \end{aligned}$$

Given ζ_i and ζ_j

$$E[x_j^2 | \zeta_i, \zeta_j]$$

is log normal and is equal to

$$10^{-\frac{\zeta_i}{10}}$$

Thus,

$$E[10^{10} \cdot x_j^2] = E[10^{-\frac{(\zeta_i - \zeta_j)}{10}}]$$

Let $X = \zeta_i - \zeta_j$

Thus, X is a Gaussian variable of zero-mean and variance equal to $2\sigma_s^2$

$$\begin{aligned} E[10^{10} \cdot x_j^2] &= E[e^{\gamma X}] \\ E[10^{10} \cdot x_j^2] &= \int_{-\infty}^{\infty} \frac{e^{\gamma x} e^{-\frac{\gamma^2 x^2}{4\sigma_s^2}}}{\sqrt{4\sigma_s^2}} dx \\ E[10^{10} \cdot x_j^2] &= e^{(\gamma\sigma_s)^2} \end{aligned} \quad (21)$$

where $\gamma = \ln(10)/10 = 2.303$. Substituting the result back in (20) we obtain

$$I_{ij} = e^{(\gamma\sigma_s)^2} \frac{n_i}{A_i} \iint_{c_i} \frac{r_i^m(x, y)}{r_j^m(x, y)} dA(x, y) \quad (22)$$

If α denotes the voice activity factor, then the above equation becomes

$$I_{ij} = e^{(\gamma\sigma_s)^2} \frac{n_i \alpha}{A_i} \iint_{c_i} \frac{r_i^m(x, y)}{r_j^m(x, y)} dA(x, y) \quad (23)$$

Let K_{ij} denote inter-cell interference factor due to a user in cell i at BS j .

Hence,

$$K_{ij} = \frac{I_{ij}}{n_i} \quad (24)$$

$$= e^{(\gamma\sigma_s)^2} \frac{\alpha}{A_i} \iint_{c_i} \frac{r_i^m(x, y)}{r_j^m(x, y)} dA(x, y) \quad (25)$$

In our model K_{ii} is zero at cell ii , but not zero otherwise (*i.e.*, $K_{ij} \neq 0$). It is important to point out the importance of K_{ij} . K_{ij} gives the interference at BS j caused by a single user in cell i . Thus, if the total number of users in cell i were to change, the new interference levels can be obtained by simply taking a product of K_{ij} and the number of users. This simplifies our calculations as the interference need not be recalculated for the new number of users. Thus, using Equation (23) we can compute relative average intercellular interference for uniform user distribution. Thus, for an uniform user distribution, we can write the total intercellular interference at BS j due to users in cell i a

$$I_{ij} = n_i \times K_{ij} \quad (26)$$

It should be noted that the above interference calculations are assuming nominal power as unity. If P is the nominal power from a power controlled user received at

home BS, then Equation (26) would be modified as

$$I_{ij} = P \times n_i \times K_{ij} \quad (27)$$

Equation (27) gives the total intercellular interference at cell C_j due to users in cell C_i .

3. Simulation and Results

Simulation was carried out with the following set of fixed parameters:

A chip rate of 1.2288MHz was selected. Hence, $Rc = 1.2288$ Mcps; gain of the CDMA system is 128. Hence $G=128$; Path loss exponent for mobile communications is 4 [11]. Hence, $m=4$; As we are restricting the interference from the first tier of interferer's, number of cells in the coverage area is 7. Hence, $NBS = 7$; Nominal power of MS, $P_k = 1$; Speed of radio signal, $C = 3 \times 10^8$ m/s; Thermal noise, $\frac{N_0}{2} = 10^{-8}$; User distribution per cell is uni-

form and every cell has same number of users N . The variable sets of parameters include:

- a) N : Number of users per cell;
- b) σ_s : The standard deviation of shadowing losses in every cell;
- c) N_{BS} : Number of BS's participating in radiolocation;
- d) Δ : DLL(delay-locked loop) resolution.
- e) R : Radius of the cells.

We studied the effects of varying shadow losses, varying the number of BS's participating in radiolocation, varying the DLL resolution and varying the size of cells on the accuracy of estimation.

3.1. Effect of Varying Shadowing Losses on the Accuracy of Radiolocation

This experiment was conducted to study the combined effect of varying shadowing losses and the number of users per cell on the error in radiolocation.

1) Set $\Delta = 1/8$, number of BS's participating in radiolocation = 3, radius of the cell = 1500m. and integration period, $T_{int} = 128T_c$. Generate a cell site BS database for 7 cells of radius 1500m each, using any computer system that supports the graphical user interface, GUI. Set value of σ_s to 6dB.

2) For the given value of σ_s compute the interference matrix F_{ij} .

3) The number of user is vary per cell from 1 to 100, in steps of 10, and estimate the error in position estimation

4) Similarly, set $\sigma_s = 8$ dB and 10dB, and go to Step 2.

For every setting of σ_s , and number of users per cell, 50

random locations were chosen within the central cell, and estimations were carried out. The final results are an average of the results obtained at the 50 locations. Similar procedure is carried out for the remaining set of experiments.

The plot in Figure 2 shows the variation of error in radiolocation with number of users per cell and σ_s . The mean value of the radiolocation error, tabulated below is determined by taking an average of all the points plotted in the Figure 2. When the number of users is varied from 1 to 100, and other conditions remaining the same, the minimum, maximum and mean values of the observed errors are tabulated in Table 1. The mean error in two-dimensional position estimation remains almost constant when σ_s is increased from 8 dB to 10 dB.

3.2. Effect of Varying the Number of Participating BS's on the Accuracy of Radiolocation

We used 2,3 and 4 BS's to estimate the subscriber location under the above heading. The results are plotted in Figure 3. It was observed that:

1) Accuracy improves drastically if we use more than two BS's for estimation: The accuracy of estimation improves to 71.51m from 697.12m when we employ 3 BS's to estimate the subscriber location instead of 2. Thus, it is very

evident that introducing the third estimator has a significant impact on the estimation accuracy and

2) There is no significant improvement in the estimation accuracy when the number of BS's is increased from 3 to 4: The mean radiolocation error improves by 6m when we increase the number of BS's to 4. This shows that, there is no effect obtained when we increase the number of BS's from 3 to 4. For applications with lower accuracy requirements, 3 BS's would be sufficient for radiolocation. Table 2, derived from Figure 3, outlines the minimum, maximum and mean values of estimation errors for various values of N_{BS} as the number of users per cell is varied from 1 to 100, other conditions remaining same.

3.3. Effect of Varying the Early-Late Discriminator Offset on the Accuracy of Radiolocation

For our work we have used a non-coherent DLL for estimating the TOA of the received signal. The accuracy of estimating the TOA using a DLL depends on how closely the DLL can track the incoming signal, and this is defined by the parameter Δ . To study the effect of variation of Δ on the accuracy of estimation, we have performed experiments with $\Delta = \frac{1}{2}, \frac{1}{4}$ and $\frac{1}{8}$. The results of the experiment are plotted in Figure 4.

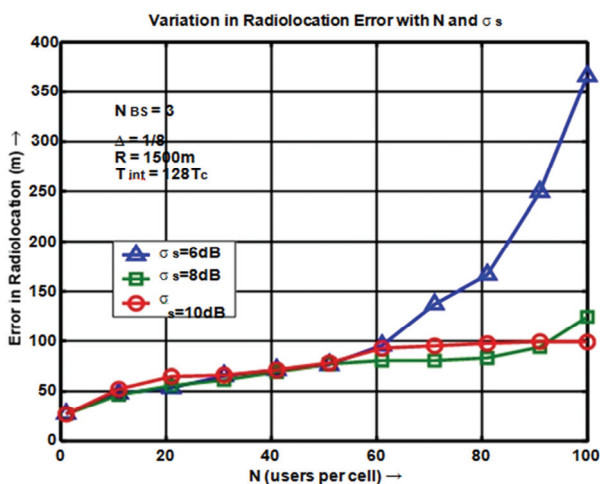


Figure 2. Variation of radiolocation error with N and σ_s .

Table 1. Min and max error in radiolocation for different values of σ_s

| σ_s (dB) | Minimum Error (m) | Maximum Error (m) | mean Error (m) |
|-----------------|-------------------|-------------------|----------------|
| 6 | 26.30 | 364.33 | 122.40 |
| 8 | 25.83 | 122.30 | 71.51 |
| 10 | 25.85 | 96.92 | 75.40 |

Table 2. Min and max error in radiolocation for different values of N_{BS} .

| N_{BS} | Minimum Error (m) | Maximum Error (m) | mean Error (m) |
|----------|-------------------|-------------------|----------------|
| 2 | 543.10 | 721.64 | 697.12 |
| 3 | 26.94 | 24.29 | 71.51 |
| 4 | 24.70 | 111.40 | 65.39 |

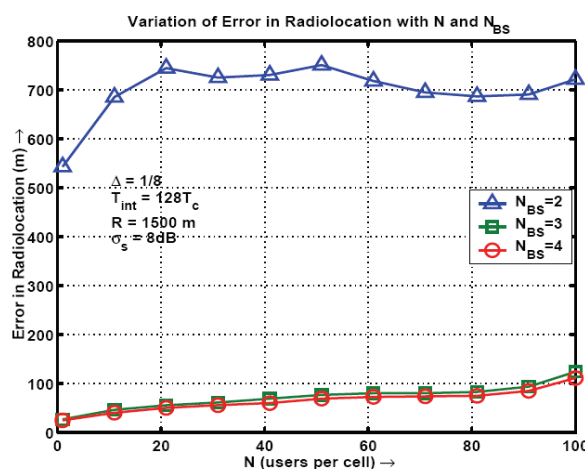


Figure 3. Variation of radiolocation error with N and N_{BS} .

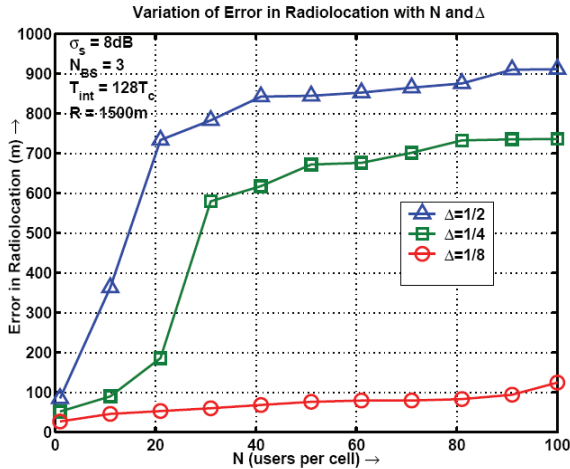


Figure 4. Variation of radiolocation error with N and Δ.

Table 3, derived from Figure 4, outlines minimum and maximum values of errors for different values of Δ as the number of users per cell are increased from 1 to 100, other conditions remaining same. The mean radiolocation error reduces to 524.22m and 70.79m from 733.13m and 524.22m respectively when Δ is reduced from 1/2 to 1/4 and from 1/4 to 1/8. But, the lowest value of Δ is limited by

a) In practice, the locally generated PN sequence will have to be phase delayed to generate the early and late PN sequences. As per IS-95 standards, one chip period corresponds to 813.80 nSec. Thus, if we were to deploy a tracking loop with Δ=1/16, the requirement on the timing resolution capability on the hardware will be

$$\Delta t = T_c \times \Delta = 813.08\text{nSec}/16 = 50.8175\text{nSec}$$

Implementing such high precision tracking loops is both challenging and expensive.

b) If the DLL employ's a serial search technique, it will have to search through all potential code delays until the correct delay is identified. Suppose, the incoming PN sequence is delayed by T_c. If Δ = 1/k, there are k potential delay values between 0 and T_c that the DLL will have to search through before it can lock to the subscriber signal. Thus, the size of the set of potential de-

Table 3. Min and max error in radiolocation for different values of Δ.

| Δ | Minimum Error (m) | Maximim Error (m) | mean Error (m) |
|-----|-------------------|-------------------|----------------|
| 1/2 | 84.86 | 911.02 | 733.13 |
| 1/4 | 51.72 | 735.97 | 524.22 |
| 1/8 | 26.94 | 124.29 | 70.79 |

lays increases as the value of Δ decreases. The bigger the set of potential delays, the longer it will take for the tracking loop to achieve a lock. The situation becomes more complicated, if we are also estimating the velocity of the subscriber. The set of potential delays, soon transforms into a two-dimensional matrix defining the set of potential delays and velocities. A serial search technique would be inefficient for such cases.

Also, accuracy falls as number of users per cell increases. As seen in Figure 4, the accuracy of estimation, falls as the number of users per cell increases. This is because of the degradation of SNR (signal-to-noise) with increasing number of users per cell.

3.4. Effect of Varying the Cell Size on the Accuracy of Radiolocation

All the earlier experiments were carried out with cells, each of radius 1500m. In this case, we simulated coverage areas with cell radii 100m and 500m. Simulations were carried out under the following conditions: Δ = 1/8; σ_s = 8dB; and number of BSs involved in radiolocation = 3. The number of users is varied from 1 to 100 in steps of 10.

The results were then compared with the results of the experiment carried out under identical situation but using cells of 1500m radius. The results indicate that under perfect power control, the degradation in SNR (signal-to-noise) with number of users is independent of the cell size; and the accuracy of estimation is better with smaller cells.

For the experiment conducted with cells of radii 100m, 500m and 1500m, it is found that accuracy of radiolocation is best for cells of radius 100.

4. Conclusions

Our study has investigated the possibility of accurate subscriber location in CDMA cellular networks in the presence of multiple access interference. Earlier works have ignored the effect of non-orthogonality of the pseudo-noise codes on the estimation accuracy. They usually consider the case of a single MS with no interferers, which is not a practical assumption. In our work, we have studied the effect of number of interferers on the accuracy of estimation by varying the number of users in every cell from 1 to 100. To study the effects of multiple access interference on the accuracy of estimation, we have assumed the presence of a line-of-sight component between the MS and the BS. We have studied the effect of MAI in conjunction with varying shadowing environments, varying tracking capability of the DLL, varying number of BSs participating in radiolocation, and varying cell sizes. The results obtained through the simulations carried out under these different conditions are encouraging and show that radiolocation is possible in a CDMA system, even when multiple access interfer-

ence is present.

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