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Estimating Subscriber Location in Wireless Networks

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ABSTRACT

Location estimation in Wireless networks has become an important feature for improvement in public safety service. Its potential applications include location sensitive billing, asset tracking, fraud protection, mobile yellow pages, fleet management, etc. Several location techniques using terrestrial wireless network elements and radio signals have been proposed over the years, but multipath propagation, multiple access interference (MAI), and non-line-of-sight propagation have impeded the accuracy in mobile station (MS) positioning. Traditional location algorithms have derived location estimates assuming single user environment. However this assumption is not correct as measurement bias is introduced due to MAI. An interference cancellation based delay locked loop (DLL) for MS delay estimation is proposed in this paper, which is subsequently used for radio location. A system model is presented and simulations are carried out that show that proposed method provides better estimate of MS position location even in the presence of MAI.

Index Terms — *Radio Location, Subscriber Location, Successive Interference Cancellation, Delay Locked Loop*

1. INTRODUCTION

Over the past decade, considerable attention has been given to wireless cellular mobile positioning systems, and a plethora of new location-based applications have already started taking advantage of location technology [1]. With the rapid evolution of wireless technologies during the last decade or so, the emphasis on services offered by wireless carriers has shifted from voice-based services to high data rate applications and value-added services. The widespread use of wireless phones has also boosted interest in the area of mobile positioning, especially for vital emergency and personal safety services and commercial applications such as location sensitive billing, fleet management and Intelligent Transportation Systems (ITS) [1-3]. Location based services (LBS) offer wireless device manufacturers and carriers opportunities to increase revenues by offering users attractive services that are tailored to their location. From the standpoint of subscribers, mobile location offers increased safety, access to emergency services, localized information and higher quality of service [4].The driving force behind the development of accurate wireless location techniques is the ever increasing revenue generated from location based services. It was estimated that the location based industry accounted for estimated revenue of about $40 billions in 2006 [5]. Numerous new and novel applications are being implemented to provide range of services to the subscribers. The accuracy requirements for network-based and handset-based technologies have been outlined in [1]. For network-based technologies, these accuracies vary from 100m for 67% of calls as dictated by FCC for E-911 in the USA to 25-125m in urban areas set up by Co-ordination Group on Access to Location Information by Emergency Services (CGALIES) for E-112 in the European Union. As the name suggests, a hand-set based location system uses the mobile station (MS) to measure certain signal characteristics and locates itself while with network-based location, the location determination is done at the base stations (BSs) [1,2]. Both approaches have their advantages and drawbacks [1], but the later takes advantage of the existing wireless communications infrastructure without the need for supplementary technology such as dead reckoning [6]. The location estimation techniques are divided into two categories: unilateral and multilateral. In the former method an MS gathers the data for BS and estimates its position. While in the later technique, MS position is estimated at the network infrastructure. Several methods have been proposed for MS location such as angle of arrival (AoA), time of arrival (ToA), received signal strength (RSS) etc. [7]. This paper examines the feasibility and performance of radio location techniques in code-division multiple-access (CDMA) cellular networks. The code division multiple access (CDMA) is the chosen access scheme, since it is the leading candidate for third-fourth generation cellular networks. The rest of the paper is organized as follows. In Section 2, the successive interference cancellation approach is discussed briefly followed by the signal and channel model in sections 3. Computer simulations and performance discussion in a multiuser scenario are presented in section 4 followed by conclusions in section 5.

2. SUCCESSIVE INTERFERENCE CANCELLATION APPROACH

The proposed receiver is based on successive interference cancellation (SIC) that takes a serial approach to

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canceling interference. Each stage of the detector estimates the parameters of the strongest remaining signal component; then it regenerates and cancels out this component from the received signal. As a result, when the next stage attempts to acquire and track the remaining signals, it sees less MAI. The 1st stage implements the following steps:

a. Detect the strongest signal, s_1 with a conventional detector. The process involves an acquisition stage where a sequential search in Doppler and code offset is used to recover the approximate signal parameters. Coupled code and carrier tracking loops then provide more accurate measurements of the code offset and Doppler. The code tracking loop is typically implemented as a delay lock loop using an "early" and "late" correlator, spaced symmetrically about the desired "prompt" signal. The carrier tracking loop may be a frequency lock loop, or a Costas loop for phase tracking and data recovery.

b. Regenerate an estimate of the strong signal, $\hat{s}_1$, using knowledge of its pseudorandom noise (PN) sequence and estimates of its timing, amplitude and phase. These parameters are derived from the tracking loops in the conventional detector.

c. Subtract $\hat{s}_1$, from the total received signal $r(t)$, producing a relatively cleaned version of the remainder of the received signal with little influence on other users' code tracking loops. If the estimates of the strong signal parameters are accurate, the output of the 1st stage is a correct data decision on the strongest signal and remaining received signal is without the MAI caused by the strongest signal. The process of tracking, demodulating, estimating and canceling results in a received signal which contains no trace of the signal due to the strongest user and the process is repeated in a multistage structure until all the users are demodulated. Such a scheme is illustrated in Figure 1. Canceling the signals in descending order of signal strength is adopted as it is easier to acquire and demodulate the strongest signal hence its removal is advantageous to the remaining weak signals. The result of this algorithm is that the acquisition and tracking of the strongest signal will not benefit from any MA1 reduction, whereas the weakest signals will potentially see a significant reduction in their MAI. The stronger the interferer signal, the better will be its parameter estimates obtained in the tracking loop. Accurate signal parameter estimates result in proper cancellation. However, if the interferer signal becomes weaker due to an increasing distance from the receiver, then the estimates of the signal parameters will deteriorate. This results in inaccurate cancellation and actually has a harmful effect on the subsequent signal acquisition efforts. In order to avoid this, the signal-to-noise (SNR) of the dominant signal may be continuously monitored at the output of the correlator. A threshold may be set to identify the presence of an interference signal that would prevent the acquisition and tracking of weaker signals. When the measured signal level exceeds this threshold the SIC is implemented.

3. SYSTEM MODEL

An asynchronous DS/CDMA system with BPSK modulation is considered here. The binary data signal transmitted by a user k is denoted by $b_k(t)$, which is obtained as follows:

$$b_k(t) = \sum_l A_{k,l} p_T(t - lT) \quad (1)$$

where $A_{k,l} \in \{1,-1\}$ is the information-bearing signal amplitude for the k^{th} user's l^{th} symbol element, and $p_T(t)$ is the rectangular pulse of duration *T*. Let the k^{th} user's signature sequence to be denoted as follows:

$$a_k(t) = \sum_l C_{k,l} p_{Tc}(t - lT_c) \quad (2)$$

where $C_{k,l}$ is the k^{th} user's l^{th} PN chip of duration T_c. The ratio of bit and chip duration is a processing gain $N = T/T_c$. The transmitted signal for each user is then denoted as follows:

$$s_k(t) = \sqrt{2P_k}\, a_k(t) b_k(t) \cos(\omega_c t + \theta_k) \quad (3)$$

with P_k being the signal power and θ_k being a phase for user *k*. For the DS/CDMA system with *K* multiple access users, the received signal $r(t)$ is given as:

$$r(t) = \sum_{k=1}^{K} \sqrt{2P_k}\, a_k(t-\tau_k) b_k(t-\tau_k) \cos(\omega_c t + \phi_k) + n(t) \quad (4)$$

where τ_k is the total delay, ϕ_k is the changed phase given as $\phi_k = (\theta_k - \omega_c \tau_k)$ for the k^{th} user, ω_c is the carrier frequency, and *n(t)* is the additive white Gaussian noise (AWGN) process with a two-sided spectral density $N_o/2$. The τ_k and ϕ_k can be modeled to be independent and identically distributed random variables with the uniform distributions over $[0,T]$ and $[0,2\pi]$,

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respectively. It is also assumed that the spread sequences of all users are known.

In the successive interference cancellation (SIC) scheme the basic idea of detecting a particular user is to cancel the estimated interference of the stronger user signals than itself from the total received signal. At each iteration of the SIC, a user of the strongest correlation value is selected among those obtained from the conventional bank correlators, and its estimated signal is regenerated by estimating its power and re-spreading its detected bit with the corresponding PN chip sequence. This process is iterated until the weakest user is decoded. The Figure 2 shows such a structure.

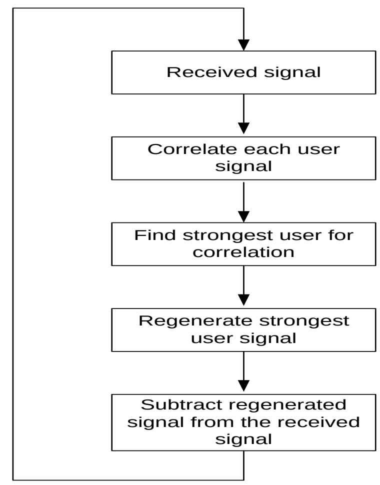

Figure 1: Flow diagram of the interference cancellation scheme

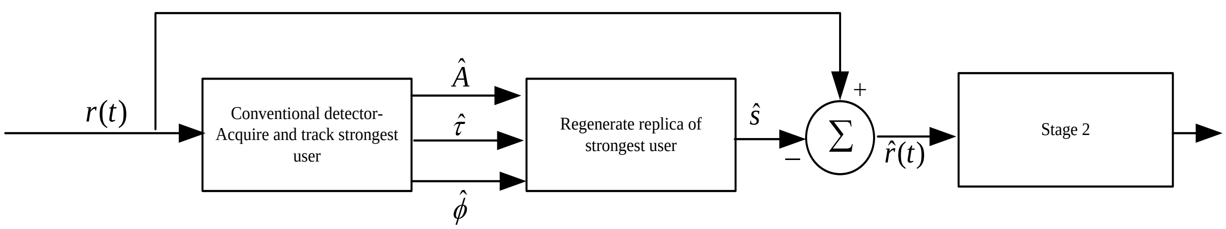

Figure 2: Successive Interference Cancellation Architecture

Denoting the total received signal by $r^1(t) = r(t)$. The initial decision for the l^{th} bit of k^{th} user is given as:

$$Y_{k,l}^{(1)} = \frac{1}{T}\int_{lT+\tau_k}^{(l+1)T+\tau_k} r^{(1)}(t)a_k(t-\tau_k)\cos(\omega_c t+\phi_k)dt \qquad (5)$$

If we denote the remaining signal at the start of *(s-l)*st cancellation stage by $r^{(s-1)}(t)$**,** the corresponding decision variable is given as:

$$Y_{k,l}^{(s-1)} = \frac{1}{T}\int_{lT+\tau_k}^{(l+1)T+\tau_k} r^{(s-1)}(t)a_k(t-\tau_k)\cos(\omega_c t+\phi_k)dt \qquad (6)$$

which is to be used for estimating the signal to be canceled at this stage. For the simplicity of presentation in the following analysis, the user of strongest decision variable is denoted by the index k in each cancellation stage. The estimated signal to be canceled in the $(s-l)^{st}$ stage is given as follows:

$$\hat{s}_k^{(s-1)}(t-\tau_k) = \sum_l \sqrt{2\hat{P}_{k,l}^{(s-1)}}\,a_k(t-\tau_k)\hat{b}_{k,l}(t-\tau_k)\cos(\omega_c t+\hat{\phi}_k) \qquad (7)$$

where $\hat{P}_{k,l}^{(s-1)}$ is unbiased estimate for the power of l^{th} bit for the k^{th} user, $\hat{b}_{k,l}(t) = \hat{A}_{k,l}P_T(t-lT)$ with $\hat{A}_{k,l}$ determined by a hard decision given by $\hat{A}_{k,l} = \mathrm{sgn}(Y_{k,l}^{(s-1)})$. Therefore, the remaining signal at the s^{th} cancellation stage is given as:

$$r^{(s)}(t) = r(t) - \sum_{j=1}^{s-1}\hat{s}_k^{(j)}(t-\tau_k) \qquad (8)$$

For the further simplicity of presentation, without loss of generality, it is assumed that the users are ordered in a descending manner in terms of received signal, i.e., the strongest and the weakest users are denoted in their indices by $k = 1$ and $k = K$ respectively and thus:

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$$r^{(s)}(t) = r(t) - \sum_{j=1}^{s-1} \hat{s}_k^{(j)}(t-\tau_k)$$
$$= \sum_{j=s}^{K} s_j(t-\tau_k) + \sum_{j=1}^{s-1}\{s_j(t-\tau_k) - \hat{s}_j^{(j)}(t-\tau_k)\} + n(t) \qquad (9)$$

In the current sth stage, the decision variable for k^{th} user is determined as in (1) using the remaining signal $r^{(s)}(t)$ and furthermore, can be expressed in terms of MAI components as follows:

$$Y_{k,l}^{(s)} = \frac{1}{T}\int_{lT+\tau_k}^{(l+1)T+\tau_k} r^{(s)}(t)a_k(t-\tau_k)\cos(\omega_c t+\phi_k)dt$$
$$= \sqrt{\frac{P_{k,l}}{2}} + \sum_{j=k+1}^{K} I_{j,k}(\tau_{j,k},\phi_{j,k}) + \sum_{j=1}^{K-1}\left\{I_{j,k}(\tau_{j,k},\phi_{j,k}) - \hat{I}_{j,k}(\tau_{j,k},\phi_{j,k})\right\} + \xi$$

The second term $I_{j,k}(\tau_{j,k},\phi_{j,k})$ constitutes the MAI due to cross-correlation between the j^{th} and k^{th} users and is given by:

$$I_{j,k}(\tau_{j,k},\phi_{j,k}) = \left(\sqrt{\frac{P_{j,l}}{2}}\cos(\hat{\phi}_j-\phi_k)\right)\left(\frac{1}{T}\int_{lT+\tau_k}^{(l+1)T+\tau_k} r^{(s)}(t)a_k(t-\tau_k)\cos(\omega_c t+\phi_k)dt\right)$$

and the third term $\hat{I}_{j,k}(\tau_{j,k},\phi_{j,k})$ is the MAI from cross-correlation between the k^{th} user signal and the estimated signal of j^{th} user, and ξ is a Gaussian random variable defined as:

$$\xi = \frac{1}{T}\int_0^T n(t)a_k(t-\tau_k)dt$$

A structure of the proposed SIC based approach for delay estimation is shown in Figure 3. The idea is to identify and then remove multipath in order to produce a cleaner version of the received signal. The proposed implementation acquires, tracks, and removes the direct as well as the multiple estimates of the strongest signal(s). These multipath signals are summed and cancelled from the incoming signal $r(t)$ to give a partially cleaned-up version of the signal**.** Acquisition and tracking is then performed on $r_c(t)$ to get improved phase and timing estimates.

4. SIMULATION RESULTS

The following parameters have been used for the simulation of the proposed receiver. PN code synchronization follows a procedure of combined tracking/reacquisition/tracking, etc., after an initial acquisition. That is, during tracking whenever |ε| > εmax > 0, a new acquisition will be initiated and a new tracking follows. This value is set to εmax = 0.5. The spreading code is 128 and $\Delta = 1/32$ meaning that the analysis resolution is 1/32.

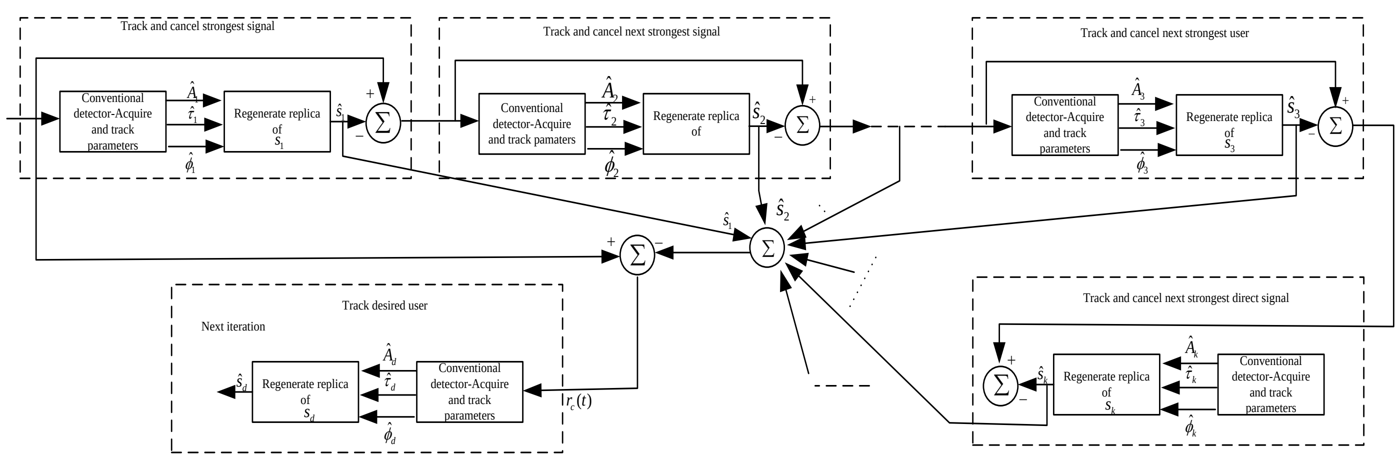

Figure 3: Proposed SIC based tracking

The signals in a cellular network with multipath are simulated. Since the proposed structure is to be employed in the multiuser radiolocation, the system is simulated with 10 users. One third of these belong to the serving BS. Other one third from neighboring BS arrive with the signal power 3dB lower than the users in the serving BS. And the next one- third arrives again from the neighboring BS with signal power 6dB lower than the serving BS. The Rayleigh fading channel is assumed with two path channel from MS to BS. It is also assumed that the initial time estimates are available from the acquisition stage within half of T_c. Due to power control in CDMA systems, all mobiles are

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received with nearly the same power. But the same is not true for the neighboring base stations. An MS served by the 1st base station can be received at much lower power compared than the MS's belonging to that neighboring cell. In fact, only when the mobile to be located is in a soft handover with one or more neighbor cells, its received power is relatively close to the serving cell. ToA measurements strongly depend on the received MAI levels. This issue can be a limiting factor in mobile radio location which typically employs trilateration technique requiring at least participation of three BSs. For example, if the mobile is assumed to be served by the center base station BS_1 and will be radio-located by BS_1, BS_2, and BS_3, then the ratio of its average received power at BS_i compared to BS_1 is given as:

$$\beta_i = P_i / P_1 \qquad (10)$$

It is found that this ratio can fluctuate widely depending on the mobile position relative to the base stations of interest. Here, the work described in [9] is adopted, considering the case where the mobile signal is within 3dB at both BS_2 and BS_3 compared to BS_1. Thus, it is considered that:

$$\beta_1 = 1.0,\ \beta_2 = 0.79,\ \beta_3 = 0.63 \qquad (11)$$

First of all, the case of DLL implementation without interference cancellation is considered. In this respect, the accuracy of DLL-based ToA estimation for two different cases is considered, as shown in Figure 4. The histograms for probability distribution functions (PDFs) of DLL timing error (normalized by T_c) at the mobile serving base station as shown in Figure 4 (Top) is compared with that at another non-serving BS. It can be seen that the DLL timing error remains unaffected with timing error almost uniformly distributed over ± $Tc/2$ which is the same as initially assumed after the acquisition stage. When this is compared with the timing error for the SIC based DLL structure, an improvement is seen. This is shown in Figure 5. The timing error for the serving BS is almost the same as in the previous case. But there is substantial improvement with the timing error converging to zero for the non-serving mobiles. Such timing estimates improve the ToA based mobile location as discussed next.

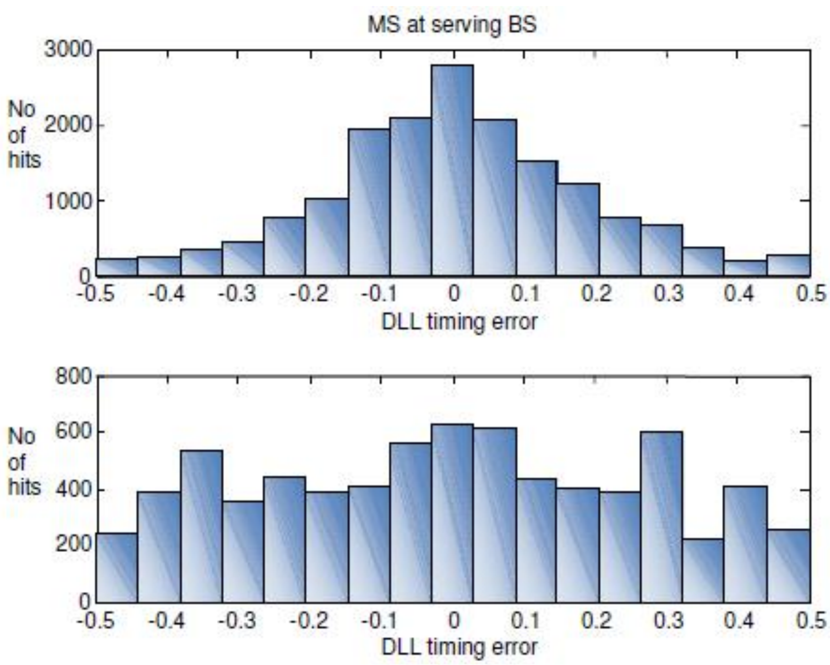

Figure 4: Histograms of DLL Timing Errors (a) Mobile Received at Serving Base Station, and (b) at Non-Serving Base Station

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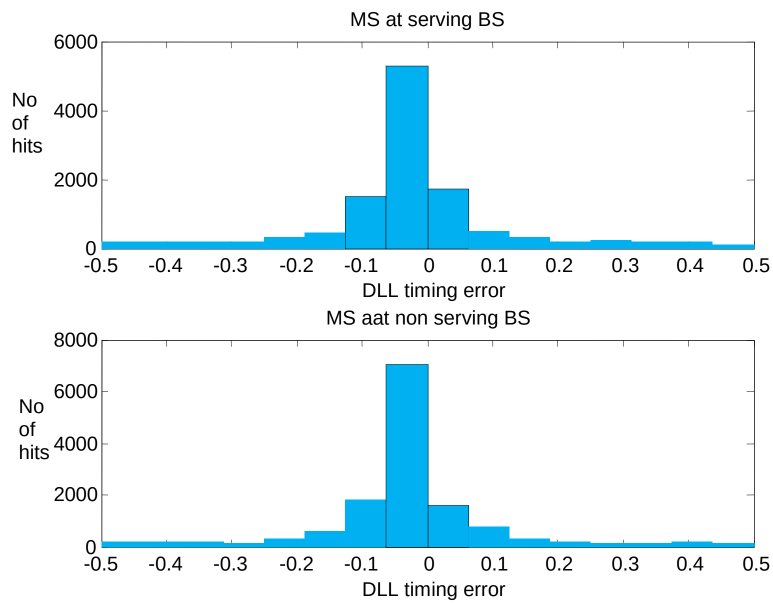

Figure 5: DLL Timing Error with SIC Based Tracking

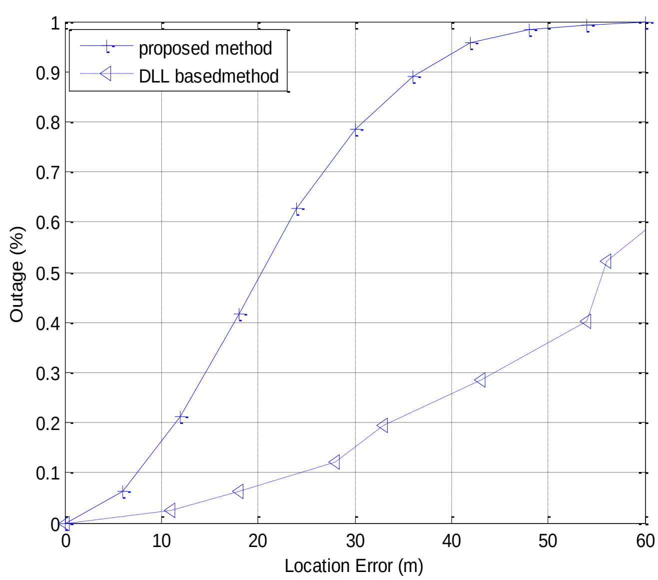

Figure 6: Outage Curve for Location Accuracy

A. Multiuser Radiolocation

For the purpose of radio location, a typical cellular network and ToA algorithm based on approximate maximum likelihood (AML) is considered as described in [8]. The simulation parameters are the same as described earlier. It is assumed that LOS path is available from MS to BS. Outage curve or the cumulative distribution function (CDF) of the mobile position estimation error for the location accuracy is shown in Figure 6. It is seen that for the proposed receiver location, the error is below 36m 90% of time and it is 60m 60% of time for DLL with no interference cancellation. A comparison with the multiple antenna based ToA and ToA/AoA fused method for multiuser case described in [5] shows an approximately 50%

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improvement with the proposed method. The Figure 7 shows position location for the case of three BS. It is seen that the mean of the position location error increases as the MS approaches its serving BS. This is because the MS, closer to the serving BS, needs to transmit at lower power levels to maintain the constant received power at the serving BS. It is also observed that as the distance to the neighboring BSs increases, the signal experiences greater path loss. So the received signal power at the neighboring BSs reaches lower levels, making position location error to sharply rise. This in turn decreases the position location accuracy. The Figure 8 shows in a graphical manner the area around the true MS location where the estimated position is predicted by the method. Again, it can be seen that the uncertainty in true MS location falls within a circle of radius of approximately 15-18 m.

The widely accepted performance measure on the location estimate is Root-Mean-Square-Error (RMSE). The RMSE is defined as:

$$RMSE = \sqrt{\sigma_x^2 + \sigma_y^2}$$

where σ_x^2 and σ_y^2 are the error variances of the location estimate along x and y directions in Cartesian coordinates. Such a plot is shown in Figure 9 for an MS located at (2100, 2100) showing that the RMSE location error is approximately 30m.

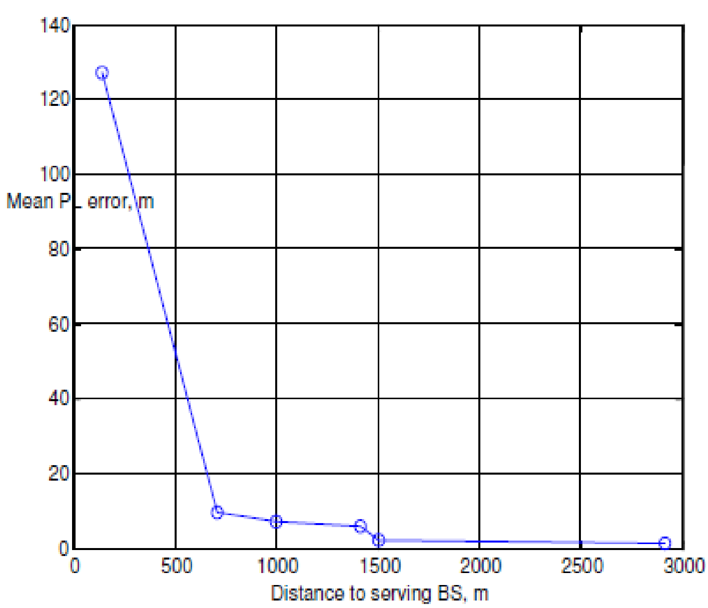

Figure 7: Mean Position Location Error vs. Distance from Serving BS

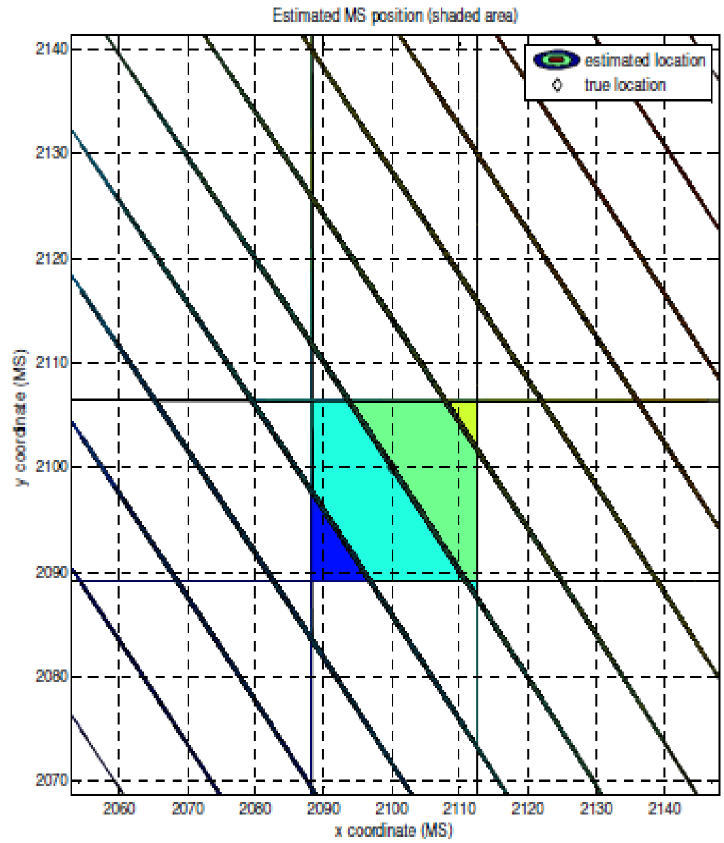

Figure 8: Estimated MS location Around True Location

5. CONCLUSIONS

In this paper, the performance of time of arrival based techniques for mobile positioning in CDMA wireless cellular networks was investigated. The delay locked loop was used as a ToA estimation device with interference cancellation. It was shown that MAI cancellation has a clear impact on the precision of mobile radiolocation, owing to the fact that, with power control, the mobile signal at far-away base stations (not involved in soft handover) can be very weak, and hence its ToA estimation will be noisy, which can be improved by interference cancellation. A mathematical model for the proposed method was presented and a comparison with the DLL based methods was also made. It was shown through simulations that the proposed method provides better location estimates than those obtained by using classical DLL techniques.

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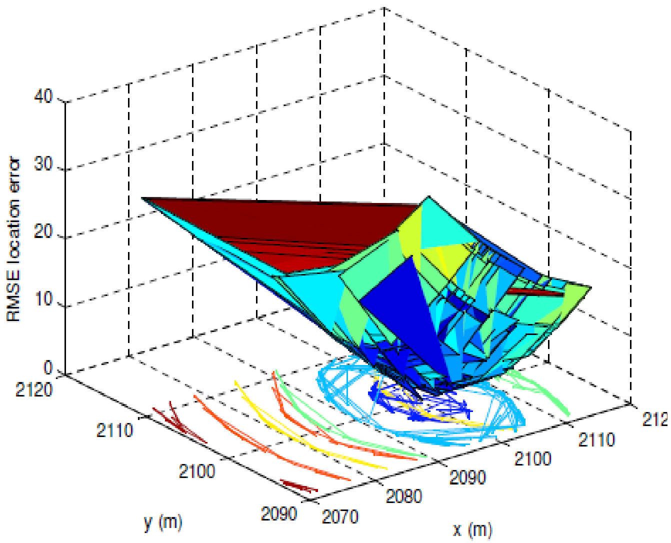

Figure 9: RMSE location error

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