Proceedings of the 2007 IEEE International Conference on Telecommunications and
Malaysia International Conference on Communications, 14-17 May 2007, Penang, Malaysia

Near-Far Problem Impact on Mobile Radiolocation Accuracy in CDMA Wireless Cellular Networks

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Abstract

This paper studies the performance of mobile radiolocation in CDMA wireless cellular networks using Time-of-Arrival (TOA) based techniques. It is shown that the near-far problem due to other-cell multiple-access interference (which cannot be mitigated by power control mechanisms) adversely affects the ability of the other "non-serving" base stations to correctly estimate the TOA of the intended mobile signal. This in turn leads to poor positioning capability, which requires correct timing estimation by the serving base station and at least two additional ones. Different scenarios are examined based on the level of Soft Handover (SHO) connectivity of the mobile. Comparative numerical results are presented in order to illustrate the tradeoffs involved, and it is shown that positioning accuracy is improved when the mobile terminal is in 2-way or 3-way SHO.

Keywords: Radiolocation, CDMA, Time-of-Arrival DLL, Soft Handover

1. Introduction

Recently, wireless mobile communication systems have experienced a tremendous growth and became an integral part of people's daily life worldwide. This global predominance of wireless communications has been even more pronounced with the success of new generations of wireless communication standards that support a rich set of value-added features in addition to basic phone service. Among these features is the possibility to offer radiolocation services whereby the mobile terminal position is determined by combining relevant information (such as signal time of arrival or angle of arrival) from different base stations having radio links with the intended mobile. This positioning capability can support many services ranging from medical emergency help, security and law enforcement, on-the-road assistance, location-dependent commercial advertisement, etc. As such, mobile radiolocation has been mandated by several of the recently introduced wireless standards, and is being widely deployed by cellular network operators worldwide [1].

Several techniques can be adopted for network-based radio-positioning, and are generally based on signal strength, time of arrival or angle of arrival. We mainly focus on the Time-of-Arrival method since it is quite robust in harsh RF environments, and the relevant data required for positioning is readily available from the synchronization systems, without requiring complex hardware as with the Angle-of-Arrival method. There are, however, some well-known limitations that can hinder the performance of positioning algorithms, such as severe multipath and non-line-of sight propagation conditions, as discussed for example in [2,3]. In the case of CDMA systems, there is another special problem due to the fact that power control mechanisms are always operating to maintain the received power from different users at the same level (at their respective *serving* base stations). However, at the other base stations which are also needed for mobile radiolocation, a given mobile received power can be very low compared to other users, and therefore, its TOA estimation will be very noisy, which will in turn affect the accuracy of the mobile positioning algorithms. This problem of "hearability" was described in [6], but in many previous studies, this effect has not been explicitly taken into account. In this paper, we specifically address this problem, and show that radiolocation accuracy can vary considerably depending on the mobile link quality with the base stations involved in its position determination.

The rest of the paper is organized as follows. First, in Section 2, we present the system model. This is followed by a description of the TOA estimation method in Section 3. Then, in Section 4, the positioning algorithm is introduced, and numerical results are presented in Section 5. Final conclusions are given in Section 6.

2. System Model

We consider a cellular network consisting of a central cell with two tiers of surrounding cells as illustrated in Fig.1 (which is sufficient to accurately model interference statistics). Mobile stations are assumed to be uniformly distributed across the network coverage area. For the radio channel between the mobile and base station $\mathrm{BS_i}$, we assume that the mobile signal is subject to attenuation including distance path loss and log-normal shadowing, according to [5]:

$$\alpha(d_{\mathrm{BS_i}}, \xi_{\mathrm{BS_i}}) = p(d_{\mathrm{BS_i}})10^{\xi_{\mathrm{BS_i}}/10} \quad (1)$$

where $p(d)$ is the distance path loss, and ξ is the shadowing variable. The path loss part follows a two-segment model with breakpoint at d_o:

$$p(d) = 10n\log_{10}(d) \quad (2)$$

where n is the path loss slope assumed to take two different values, depending on whether the mobile is within or beyond the given breakpoint. In the subsequent numerical simulations, we use the slopes $n = 2$ or 4, and a breakpoint at 200m, with a cell radius of 2Km. For a given mobile, shadowing vis-à-vis the different base stations is partially correlated, and given by: $\xi_{BS_i} = a\xi_c + b\xi_i$, where ξ_c and ξ_i are the common and independent terms, respectively, and $a^2+b^2=1$. In the numerical results, we assume the shadowing variables are log-normal with σ=8dB, and 50% correlation ($a=b=1/\sqrt{2}$).

Since CDMA systems employ power control mechanisms, at a given base station of interest termed as the "serving" base station, all mobiles are received with nearly the same power (we later assume it to be same, i.e., perfect power control). However, at neighboring base stations, a given mobile served by the first base station can be received at much lower power compared to the mobiles 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 original cell. Since time-of-arrival estimation accuracy (to be discussed next) strongly depends on the received multiple-access interference (MAI) levels, this issue can be a limiting factor in mobile radiolocation which typically requires TOA data from at least three base stations. For example, if we assume that the mobile is served by the center base station $\mathrm{BS_1}$ and will be radio-located by $\mathrm{BS_1}$, $\mathrm{BS_2}$, and $\mathrm{BS_3}$, then defining the ratio of its average received power at $\mathrm{BS_i}$ compared to $\mathrm{BS_1}$,

$$\beta_i = \frac{P_i}{P_1} \quad (3)$$

it is found that this ratio can fluctuate widely depending on the mobile position relative to the base stations of interest. As an illustration, we present examples for three scenarios (cases 1, 2 and 3) that will be used in the subsequent numerical results. Case 1 refers to a mobile in close proximity to its "serving" $\mathrm{BS_1}$, with a signal at least 10dB above that at the other two base stations. Case 2 represents a two-way soft handover scenario, with the mobile power at base station 2 within 3dB (as an example) from that at $\mathrm{BS_1}$, and case 3 denotes the 3-way soft handover situation where the mobile signal is within 3dB at both $\mathrm{BS_2}$ and $\mathrm{BS_3}$ compared to $\mathrm{BS_1}$. It is clearly seen from Table 1 that these β factors can vary considerably across all three cases.

Table 1 also gives another parameter specifying the ratio of other-cell interference to same-cell interference, commonly referred to as the *f*-factor in the CDMA literature [5]. All these parameters depend on the RF model (path loss, shadowing), and will be used subsequently to determine the level of MAI, which directly impacts the accuracy of time-of-arrival estimation.

3. Time-of-Arrival Estimation

For CDMA signals, timing synchronization is typically implemented by a two-step process consisting of coarse acquisition timing search to within a given uncertainty range on the order of one-chip interval, which is then followed by fine time tracking achieved by a delay-locked loop (DLL) mechanism [5]. In this work, we assume perfect time acquisition and focus on the DLL as the main synchronization device. For each base station involved in mobile positioning, a DLL block continuously attempts to bring the local code timing estimate in perfect alignment with the incoming mobile signal. However, this timing estimation will be subject to error due to noise, multipath fading and multiple-access interference. At the DLL input, the composite received signal can be expressed in baseband form as:

$$s(t) = \sum_i \sum_j h_i m_j c_j(t - jT - \tau_i) + n_{th}(t) + n_{\mathrm{int}}(t) \quad (4)$$

where h_i and τ_i are the i-th fading path gain and time delay, T the symbol period, m_j the j-th symbol, and $c(t) = \sum_{n=0}^{N-1} c_n h(t - nT_c)$ the spreading waveform having N chips per symbol, chip sequence $\{c_n\}$ and pulse shaping filter $h(t)$ (assumed to be a root-raised cosine with 22% rolloff, as per 3G UMTS). The signal $n_{th}(t)$ represents additive white Gaussian noise, and $n_{\text{int}}(t)$ the MAI terms which include both same-cell and other-cell interference signals.

In the following, we focus on estimating the TOA of the first arriving path with delay τ_0. As illustrated in Fig.2, we adopt a non-coherent DLL structure [5] (insensitive to data modulation and carrier phase) with two early-late branches. The received signal is correlated with code replicas $c\left(t-\hat{\tau}_o+\Delta\right)$ and $c\left(t-\hat{\tau}_o-\Delta\right)$, where $\hat{\tau}_o$ is the local code timing estimate. The outputs are envelope-detected, and the filtered difference is used to drive the voltage controlled oscillator (VCO) which controls the code timing adjustment. The DLL performance is dependent upon the discriminator output (mainly its slope at the origin)

$$Z_\Delta(\tau)=R^2\left(\tau-\Delta\right)-R^2\left(\tau+\Delta\right) \qquad (5)$$

where the code autocorrelation function is defined as $R(\tau)=1/NT_c\int_0^{NT_c}c(t)c(t+\tau)dt$. The normalized S-curve is often used, as given in [5]:

$$G(\varepsilon)=R^2(\varepsilon-\delta)-R^2(\varepsilon+\delta) \qquad (6)$$

where $\varepsilon=(\tau_o-\hat{\tau}_o)/T_c$ is the normalized timing error, and $\delta=\Delta/T_c$ is the early-late discriminator offset (typically set at $\Delta = T_c/2$). A common figure of merit for analyzing the DLL performance is the timing error variance (or rms jitter). From [5], a close upper-bound approximation of the tracking error standard deviation is obtained for first-order DLL loops and unfaded AWGN channels as

$$\sigma_\varepsilon \approx \frac{2V_o^2+4NE_cV_o}{N^2E_c^2\kappa^2} \qquad (7)$$

where E_c is the received chip energy, κ is the slope of the S-curve at the origin, and V_o is the variance of the thermal noise & MAI signals (considered as AWGN). However, there is no simple equivalent result for the case of frequency-selective multipath fading channels considered in this work. Instead, as will be discussed next, we resort to numerical simulations to characterize the statistics of the DLL timing estimation error that will be later used in the mobile radiolocation algorithm.

4. Mobile Radiolocation Algorithm

In the time-of-arrival radiolocation technique, the distance is calculated as the propagation time divided by the propagation speed. Geometrically, circles can be drawn with the calculated distance as a radius. With the help of three base stations, the mobile location can be found geometrically as the intersection of the corresponding circles. However, in the presence of noise, interference and synchronization problems, the three circles may not intersect at a single point. Therefore, the geometric approach is not suitable, and several other "statistical" techniques have been proposed [2,3] to process the noisy data. Many of these are based on iterative algorithms using least-squares or gradient search minimization.

In this paper, only line-of-sight (LOS) propagation is considered, and base stations are assumed synchronized and the mobile transmission time is known (set to zero for simplicity). The TOA measurements, produced at each base station, are therefore directly proportional to the mobile-base distance separation. In the following, we adopt the notation of [3] to summarize the mobile positioning algorithm in 2-D plane. We only consider three base stations BS$_i$, i=1,2,3 for simplicity (those with the most favorable radio links), although the statistical methods can use data from more base stations. Assuming without loss of generality that BS$_1$ has coordinates (0,0), and the other two base stations are at $(x_{i,},y_i)^{\mathrm{T}}$, i=2,3, with the mobile at $\mathbf{x}=(x_m,y_m)^{\mathrm{T}}$, it is shown in [3] that the mobile coordinates satisfy the set of nonlinear equations **Hx**=**b**, where

$$\mathbf{H}=\begin{bmatrix} x_2 & y_2 \\ x_3 & y_3 \end{bmatrix},\quad \mathbf{b}=1/2\begin{bmatrix} k_2^2-d_2^2+d_1^2 \\ k_3^2-d_3^2+d_1^2 \end{bmatrix} \qquad (8)$$

with $k_i^2=x_i^2+y_i^2$ and $d_i^2=\left(x_i-x_m\right)^2+\left(x_i-x_m\right)^2$.

In the presence of noise, a least squares (LS) solution of this system is obtained as [3]

$$\hat{\mathbf{x}}=(\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\mathbf{b} \qquad (9)$$

The mobile position estimation can be further improved by using this LS solution as an initial guess for an "approximate" maximum likelihood algorithm (AML) [4], which solves a linearized version of the problem expressed by:

$$\begin{bmatrix} \sum g_ix_i & \sum g_iy_i \\ \sum h_ix_i & \sum h_iy_i \end{bmatrix}\begin{bmatrix} x_m \\ y_m \end{bmatrix}=\begin{bmatrix} \sum g_i(s+k_i-\delta_i^2) \\ \sum h_i(s+k_i-\delta_i^2) \end{bmatrix} \qquad (10)$$

$$g_i=\frac{x_m-x_i}{d_i(d_i+\delta_i)},\, h_i=\frac{y_m-y_i}{d_i(d_i+\delta_i)},\, s=x_m^2+y_m^2 \qquad (11)$$

Here, δ_i is the measured (noisy) distance between the base station BS_i and the mobile, while d_i is the true distance. Since the unknowns (x_m, y_m) appear on the RHS of (11), the algorithm can be solved iteratively, starting with an initial guess from (9), as described in [4].

5. Numerical Results

In this section, we present numerical results to illustrate the accuracy of the mobile radiolocation scheme, and its sensitivity to various conditions. We assume a uniformly loaded network, with 20 users per cell. The cell radius is set at 2Km, and the RF propagation model is as described in Section 2. A given desired mobile is radio-located using its TOA's at three base stations subject to MAI as described previously. We also assume slow frequency-selective Rayleigh fading with 2-path links between mobile and base stations (the 2nd path is 3dB below the main one used for time tracking).

In Fig.3, the accuracy of the DLL-based TOA estimation is compared for two different cases. The probability density function (PDF) of the residual timing error at the mobile serving base station is shown in part (a), as compared to the PDF at another non-serving one in part (b), and it is seen that in the latter case, the DLL timing error remains unimproved (nearly uniformly distributed, over +/- $T_c/2$, as with the initially assumed timing acquisition precision). When this TOA data is used for positioning, the timing error will translate into distance error as will be illustrated next.

In Fig. 4, an illustrative view of radio-positioning for the three cases is shown. The dark region at the intersection of the three circles represents a dense scatter plot of the 10^5 mobile noisy position estimates, which are densely packed around the mobile true position. Other plots can be obtained for different scenarios as well. Finally, Fig. 5 shows the cumulative distribution function (CDF) of the mobile position estimation error for the three cases outlined in Section 2 (with their relevant parameters in Table 1). It is clearly seen that the case for 3-way soft handover gives the best performance, followed by 2-way soft handover one, and the case when the mobile is closest to its own base station is worst.

6. Conclusions

This paper dealt with the performance of time-of-arrival based techniques for mobile positioning in CDMA wireless cellular networks. The delay-locked loop was used as a TOA estimation device. Based on TOA measurements from three bases stations, an approximate maximum likelihood estimation algorithm was used for obtaining the mobile coordinates. The impact of mobile link conditions with respect to the base stations involved in its positioning was assessed. It was shown that soft handover radio links with two or three base stations have 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 subsequently degrades the radiolocation precision. Future extensions to this work will consider aspects related of non-line-of-sight propagation, and its mitigation.

Acknowledgment

This work was supported by Grant ARP-24-87 from King Abdul-Aziz City of Science & Technology, Saudi Arabia.

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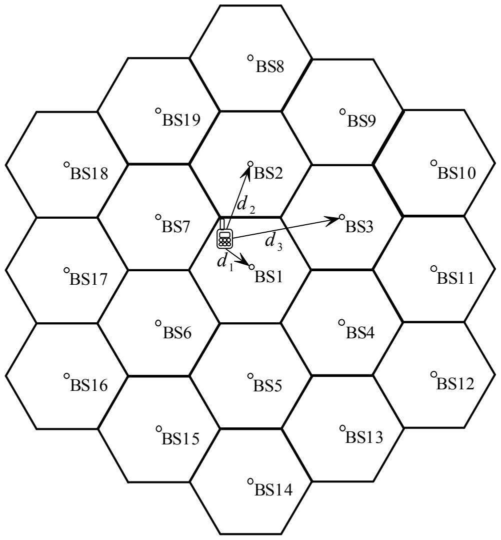

Fig. 1: Cellular network configuration, with center cell and two tiers of interfering cells.

	f-factor	β_1	β_2	β_3
Case 1	0.62	1.0	0.03	0.02
Case 2	0.62	1.0	0.71	0.22
Case 3	0.62	1.0	0.79	0.63

Table 1: Other-cell to same-cell interference, and other-cell-to same-cell desired mobile power ratios for various soft-handover link conditions.

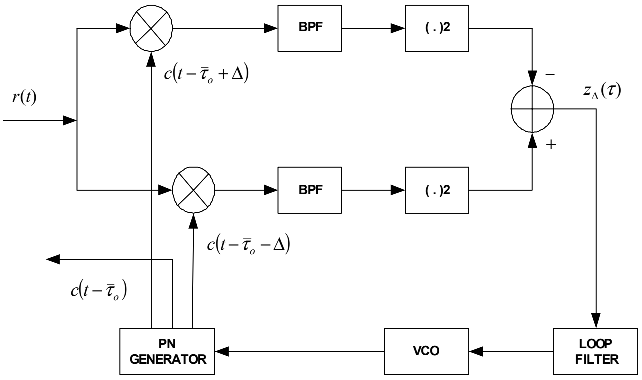

Fig. 2: Delay-locked loop (DLL) block diagram, used for estimation of mobile Time-of-Arrival (TOA).

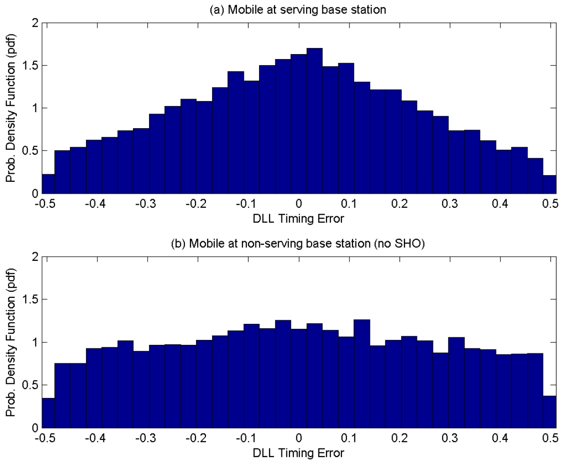

Fig. 3: Histograms for PDF's of DLL timing error (normalized by T_c) for two cases: a) Mobile received at serving BS, and b) at non-serving BS (without SHO).

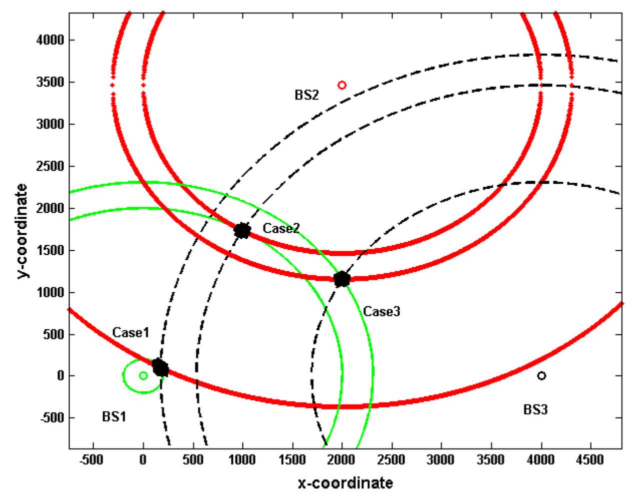

Fig.4: Examples of scatter points for mobile estimated positions in the three different cases.

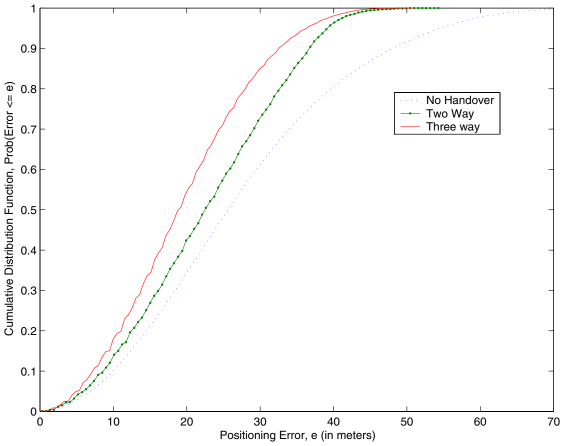

Fig.5: Cumulative distribution function (CDF) for the residual mobile positioning error. Comparison for 3 cases, with various levels of soft-handover connectivity.