Hybrid TDOA/AOA Mobile User Location for Wideband CDMA Cellular Systems

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***Abstract*—This paper proposes a mobile user location scheme for wideband code-division multiple-access (CDMA) wireless communication systems. To achieve high location accuracy and low cost of the mobile receiver, the location scheme combines the time difference of arrival (TDOA) measurements from the forward link pilot signals with the angle of arrival (AOA) measurement from the reverse link pilot signal. High chip rates in wideband CDMA systems facilitate accurate TDOA measurements, and a smart antenna used at the home base station (BS) can provide accurate AOA measurement in a macrocell environment. A two-step least square location estimator is developed based on a linear form of the AOA equation in the small error region. Numerical results demonstrate that the proposed hybrid TDOA/AOA location scheme gives much higher location accuracy than TDOA only location, when the number of base stations is small and/or when the TDOA measurements have a relatively poor accuracy.**

***Index Terms*—Angle of arrival, least square estimator, mobile user location, time difference of arrival, wideband code-division multiple-access.**

I. Introduction

Wireless location is to determine the position of a mobile station (MS) in a wireless cellular communications system. It has received considerable attention over the past few years. In addition to the emergency 911 subscriber safety services, wireless location information can be used for location-sensitive billing and intelligent transport system, and to enhance cellular network performance. The third-generation (3G) wireless systems are currently under development around the globe and will be deployed soon. The current Radio Transmission Technology proposals for 3G wireless mobile systems employ wideband code-division multiple-access (CDMA) technology. The systems will offer a wide range of multimedia communication services and user location service. However, how to implement the location service in such systems remains an open area for research, as the previous work on MS location mainly aimed at the first and second-generation wireless systems. The main challenge is to achieve high location accuracy at low implementation cost, taking account of the hostile wireless propagation environment.

Various wireless location schemes which have been extensively investigated [1]–[3] can be classified to two categories: 1) time based location, where the time of arrival (TOA) or the time difference of arrival (TDOA) of the incoming signals is measured and 2) angle based location, where the angle of arrival (AOA) of the received signals is measured. Both categories have their own advantages and limitations. For example, TDOA schemes require at least three properly located base stations (BSs) for two-dimensional (2-D) MS locations, and generally have better accuracy than AOA schemes; AOA schemes, on the other hand, requires only two BSs minimum for a location estimate. However, it is highly range dependent. A small error in the angle measurement will result in a large location error when the MS is far away from any BSs involved.

The equations of the location estimator based on the measurements are usually nonlinear and the solution is nontrivial particularly when the measurements are noisy and/or inconsistent. In [4] and [5], the solution to TDOA equations is obtained by linearizing the equations via a Taylor-series expansion. The Taylor-series approach can achieve high accuracy, but requires an initial location guess and may suffer from the convergence problem if the initial guess is not accurate enough. Furthermore, it is an iterative approach and is computationally intensive as it needs to determine the local linear least-square (LS) solution in each iteration. To overcome the drawbacks, a two-step LS estimator for the TDOA location is proposed in [6]. The LS estimator is an approximation of the mnaximun-likelihood (ML) estimator when the TDOA measurement errors are small, and is able to provide a near optimum solution [2].

As TDOA and AOA location methods complement each other in most BS layouts, in this paper, we propose a hybrid TDOA/AOA location scheme which combines TDOA location with AOA location. The proposed location scheme makes use of the salient features of 3G wireless systems for low signaling overhead and implementation cost. Furthermore, it has the advantages of both TDOA and AOA methods to achieve high location accuracy. For location estimator, we extend the two-step LS estimator originally developed for TDOA location to obtain the solution of the nonlinear TDOA/AOA location equations. Numerical results are obtained to demonstrate the high location accuracy of the proposed scheme. In Section II, we describe the wideband CDMA system model under consideration. Section III proposes the hybrid TDOA/AOA location scheme for the system. Section IV gives the derivation of the LS estimator for the TDOA/AOA location. The performance of the proposed scheme is evaluated via computer simulation in Section V, followed by the conclusion in Section VI.

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II. The Wideband CDMA System Model

We consider a macrocell wideband CDMA system with frequency division duplex. The system model has many common features as those specified in 3G wireless system proposals for IMT-2000/UMTS,[1] including cdma2000 from North America [7], WCDMA from Europe [8] and Japan [9], and Global CDMA from Korea [10], [11]. In particular, with respect to mobile location, the system has the following characteristics: 1) BSs are precisely synchronized in time based on the global positioning system (GPS) time reference to facilitate accurate TDOA measurements in the forward link. In the cdma2000 [7] and Global CDMA I [10] proposals, network synchronous mode (where the BSs are synchronized to each other in time) has been fundamentally made to reduce the system complexity and to make the soft handoff schemes convenient. Even though the proposals from Europe [8], Japan [9], and Korea [11] adopt network asynchronous mode, it is specifically indicated in these proposals that "synchronous operation is also possible"; 2) similar to the 3G system proposals, a dedicated reverse-link pilot channel is assigned to each active MS to facilitate the initial acquisition, time tracking, coherent reference recovery, and power-control measurements for the MS. The BS serving a particular MS is called the home BS for that MS. The reverse pilot signal from the MS is sent in a continuous waveform to its home BS and is power controlled by the BS; 3) each BS is equipped with antenna arrays for adaptive beam steering. This allows the BS to dedicate a spot beam to a single MS under its jurisdiction by dynamically changing the antenna pattern as the MS moves. In the 3G system proposals, the reverse-link pilot signal is also used for beamforming. For example, the adaptive beam steering is proposed in [7] for spatial division multiple access to reduce the impact of high-rate MSs on the aggregate cell capacity and to mitigate high propagation losses; 4) in the forward link, each BS has a pilot channel to continuously broadcast its pilot signal to provide timing and phase information for all MSs in the cell. All the in-phase and quadrature components of the pilot signals are modulated with the same pair of pseudorandom noise (PN) codes, and each BS can be identified by its unique phase offset of the PN code sequences [12]. Each MS keeps monitoring the pilot signal levels from nearby BSs, and reports to the network those which cross a given set of thresholds (for soft hansoffs); and 5) both the forward-link and reverse-link transmissions are power controlled, except the forward-link pilot signals.

As the system model is based on the IMT/UMTS proposals for the 3G systems, it does not impose much (if any) of extra implementation complexity for the mobile location.

III. The Proposed TDOA/AOA Location Scheme

A. Measurements for Mobile Location

Consider 2-D MS location. It is assumed that, at any time, the MS to be located can receive forward-link pilot signals from its home BS and at least one neighboring BS. Upon receiving the location service request, two types of measurements are carried out for the location purpose: 1) TDOA measurements at the MS receiver—As all BSs are time synchronized, the MS receiver can measure the time arrival difference between the pilot signals of a nonhome BS and the home BS by a PN code tracking loop which cross correlates the pilot signal from the nonhome BS with the pilot signal from the home BS. The pilot signal from each of the neighboring BSs can be used in the MS location, provided the signal-to-noise ratio (SNR) of the received signal at the MS from the BS is above a certain threshold. The TDOA measurements can be obtained with an accuracy better than half chip duration if wireless propagation channel impairments are not severe [13]. The high chip rate in the 3G systems enables high accuracy TDOA measurements. The effect of interference and noise on the TDOA measurement accuracy can be reduced by increasing the integration time of the tracking loop. On the other hand, the Doppler shift puts a limit on the integration time, and other channel impairments such as fading and delay spread from the nonhome BSs can increase the TDOA measurement errors and 2) AOA measurements at the home BS—With an adaptive antenna array, the home BS steers its antenna spot beam to track the dedicated reverse-link pilot signal from the MS for improved reception. This provides the arriving azimuth angle of the signal from the MS. The forward-link TDOA measurements will be forwarded to the home BS via the wireless channel, where both the forward-link TDOA and reverse-link AOA measurements are combined to give a location estimate of the MS, as described in Section IV.

B. AOA Modeling for Macrocell

The AOA measurement accuracy is critical to the location accuracy of the proposed scheme, and is dependent on the wireless propagation environment. A wireless channel contains objects (referred to as scatterers) which randomly scatter the energy of the transmitted signal. The scattered signals arrive at the receiver from various directions [14]. In a macrocell environment, the scatterers surrounding the MS are about the same height as or are higher than the MS. This results in the MS received signal arriving from all directions after bouncing from the surrounding scatterers. The AOA at the MS antenna can be modeled as a random variable uniformly distributed over $[0, 2\pi]$ [14]. On the other hand, the BS antennas are usually mounted at a level much higher than the surrounding scatterers. Hence, the received signal at the home BS mainly results from the scattering process in the vicinity of the mobile. The incoming waves from the mobile seen at the BS antenna are restricted to a small angular region [15], and the AOA is no longer uniformly distributed over $[0, 2\pi]$. For macrocell environments with relatively large BS antenna heights, a popular model for AOA at the home BS is that the effective scatterers are evenly spaced on a circular ring about the mobile [16], [17], as shown in Fig. 1, where $\theta_{\rm BW}$ denotes the angle spread, R is the radius of the scatterer ring, D is the distance between the MS and the home BS, and β is the AOA of the reverse-link pilot signal. In general, $\theta_{\rm BW}$ decreases as the BS antenna height increases. The circular model predicts a relatively high probability of multipath components within a small range of angles. Measurements reported in [18] suggest that AOA is Gaussian distributed and typical angle spreads are

[1] International Mobile Telecommunications System 2000/Universal Mobile Telecommunications System.

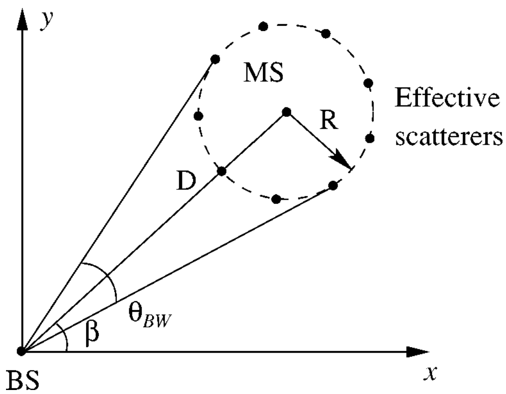


Fig. 1. The circular model of scatterers in a macrocell environment.

approximately two to six degrees for $D = 1$ km. Simulation results for outdoor multipath environments indicate that AOA can be measured with an accuracy better than four degrees [3]. For wideband radio channels, measurements (with a 10 MHz bandwidth centered at 1840 MHz) confirm that most of the received signal energy is concentrated in a small AOA region in rural, suburban, and even many urban environments [19]. In general, with wideband signaling, reflected signals are likely to arrive at the BS in a finite number of clusters, and the Gaussian wide sense stationary uncorrelated scattering (GWSSUS) model [20] is widely used to characterize this situation. An extension of GWSSUS to multiantenna AOA case is introduced in [21] and verified by field measurements. From the modeling and measurements, it is expected that, in a wideband macrocell environment, the home BS with a relatively large receiving antenna height is able to see a wave cluster containing the LOS component (called the LOS cluster) of the reverse-link pilot signal from the target MS. The LOS cluster is dominant in power and is mainly caused by local scatterers located close to the MS. Using the antenna array, the home BS is able to measure the AOA of the incoming pilot signal with an error within a few degrees.

C. Advantages of the TDOA/AOA Location

The proposed hybrid TDOA/AOA location scheme exploits the signaling and system resources as given in the 3G system proposals for high location accuracy at a low implementation cost. It has the following advantages: 1) it has the merits of both TDOA and AOA methods. With the AOA information, the proposed location scheme requires only two BSs minimum for a location estimate. On the other hand, when there are more than two BSs available for location estimate, it will achieve the high accuracy of the TDOA approach. In the case of a one-dimensional (1-D) BS layout, the AOA information will solve the ambiguity problem that the TDOA approach has, as to be discussed in Section IV; 2) it can avoid the drawbacks of AOA only location. In fact, AOA only location is not suitable for the 3G wireless systems. First, the AOAs cannot be measured at the MS, because of the uniformly distributed (over $[0, 2\pi]$) AOA seen at the MS antenna and the complex antenna array required; Second, as the reverse-link pilot signal from the MS is power controlled by its home BS, the signal received by neighboring BSs has poor quality due to the near–far effect, resulting in poor AOA measurement accuracy. The AOA accuracy is likely to be further reduced as the BS antenna may not see an LOS cluster. With the neighboring BSs being far away from the MS, the location accuracy degradation due to the AOA measurement error is significantly increased; Third, in order for the neighboring BSs to measure the AOA of the reverse-link pilot signal from the MS, the BS antennas need to track the MS movement, which imposes a large extra cost on the antennas as the MS is not under the jurisdiction of the neighboring BSs. In the proposed location scheme, the AOA is measured only at the home BS, so that the signal quality degradation due to the near–far effect does not exist. In addition, as the MS is relatively close to its home BS, there usually exists an LOS cluster of the received signal at the home BS (resulting in small AOA measurement errors) and the range-dependent AOA location error can be reduced; 3) the measurements are based on the forward-link and reverse-link pilot signals already existing in the wideband CDMA system proposals. No extra network signaling is required for the location scheme, except forwarding the TDOA measurements to the home BS over the reverse data link. For soft handoffs in 3G systems, the MS receiver is required to monitor the forward-link pilot signal levels from the nearby BSs. The TDOA measurements are based on the signaling and PN code tracking for soft handoffs at the MS receiver. Since the forward pilot signals are not power controlled, the scheme alleviates the impact of near–far effect caused by the power control mechanism. As the forward and reverse pilot signals are transmitted continuously, long duration measurement of TDOA/AOA is possible for improved accuracy. The location scheme does not interrupt the ongoing information transmission between the home BS and the MS; and 4) with the TDOA approach, the MS is not required to be synchronized with the BSs, resulting in a simpler MS receiver as compared with that using a TOA approach.

The performance of the proposed location scheme will be evaluated using both root mean squared (RMS) and Crámer–Rao lower bound (CRLB) of the location error in Section V. The CRLB defines the *optimum performance* for a linear estimator [4], [5].

IV. Solution to TDOA/AOA Equations

In this section, we derive a location estimator to solve the nonlinear TDOA/AOA equations for the MS location. It is assumed that: 1) the TDOA and AOA measurement errors are independent Gaussian random variables with zero-mean and known variances and 2) there exists an LOS cluster in the AOA measurements.

A. Two BSs With Accurate Measurements

If the TDOA and AOA measurements are accurate, we need only the home BS and another BS to location an MS using the proposed location scheme. Consider the case as shown in Fig. 2(a), where $\mathrm{BS\_1}$ is the home BS, $\mathrm{BS\_2}$ is the other BS, β is the measured AOA at $\mathrm{BS\_1}$ with respect to a reference direction (represented by the horizontal axis). From the AOA and TDOA measurements and the known location coordinates (x'_1, y'_1) and (x'_2, y'_2) of BS_1 and BS_2, respectively, the MS

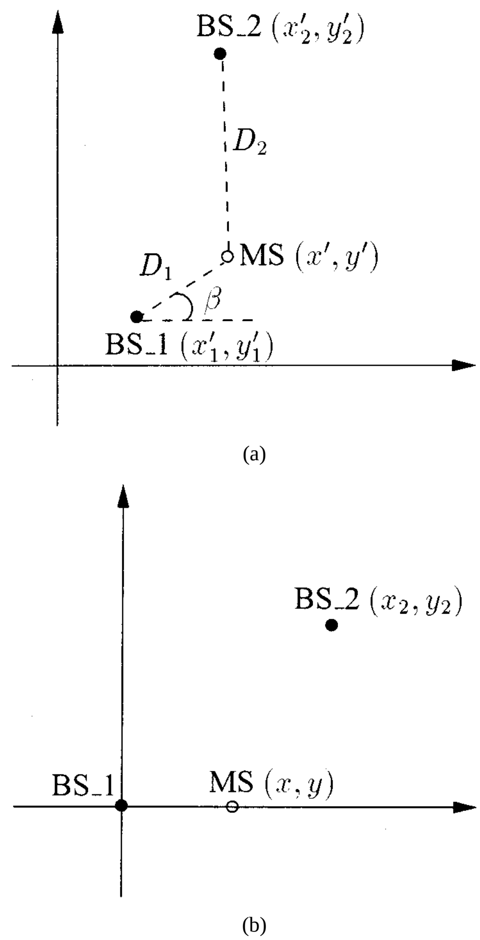


Fig. 2. Location with two BSs and accurate measurements. (a) Original coordinates. (b) New coordinates.

location (x', y') can be obtained by solving the following equations:

$$t_2 = \frac{1}{c}(D_2 - D_1), \quad \beta = \tan^{-1}\left(\frac{y' - y_1'}{x' - x_1'}\right) \tag{1}$$

where t_2 is the TDOA between the pilot signals from BS_2 and BS_1, $D_k = \sqrt{(y_k' - y')^2 + (x_k' - x')^2}$ $(k = 1, 2)$ is the distance between the MS and BS_k, and c is the speed of light. The closed form solution to (1) is quite complex. For simplicity of analysis, we define a new coordinate system as illustrated in Fig. 2(b), which is obtained by rotating the axes of the old coordinate system clockwise by the angle β and by defining the BS_1 location as the origin. In the new coordinate system, the MS location is denoted by (x, y), BS_2 location by (x_2, y_2). Equation (1) corresponds to

$$c \cdot t_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2} - \sqrt{x^2 + y^2}, \quad y = 0 \tag{2}$$

and the solution is

$$x = \frac{x_2^2 + y_2^2 - c^2 t_2^2}{2(x_2 + ct_2)}, \quad y = 0. \tag{3}$$

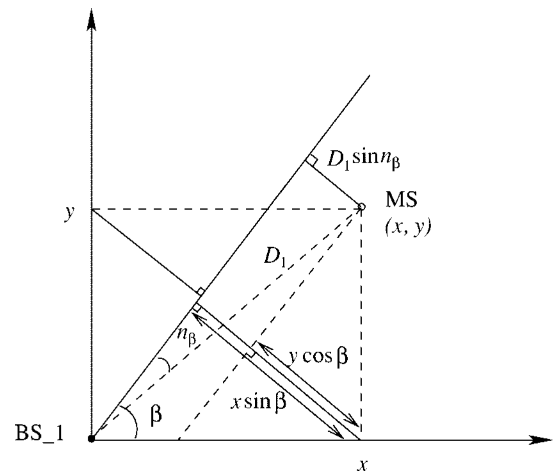


Fig. 3. Linear approximation of the AOA equation.

Note that (x_2, y_2) is in fact a function of the measured AOA, β, given by

$$\begin{aligned} x_2 &= \sqrt{(x_2' - x_1')^2 + (y_2' - y_1')^2} \cos\left(\arctan\frac{y_2' - y_1'}{x_2' - x_1'} - \beta\right) \\ y_2 &= \sqrt{(x_2' - x_1')^2 + (y_2' - y_1')^2} \sin\left(\arctan\frac{y_2' - y_1'}{x_2' - x_1'} - \beta\right). \end{aligned} \tag{4}$$

In reality, due to propagation channel impairments, the TDOA and AOA measurements contain errors. As a result, there may not exist a solution to (1), i.e., the measurements involving only two BSs may not lead to an MS location estimate. More than two BSs are usually required for a location estimate of reasonable accuracy.

B. $K(\geq 3)$ BSs With 2-D Array Layout

When there are $K(\geq 3)$ BSs available for the MS location, we have a set of overdetermined nonlinear location equations. The equations incorporating the measurement errors are given by

$$t_k = \frac{1}{c}(D_k - D_1) + n_k, \quad \beta = \tan^{-1}\left(\frac{y - y_1}{x - x_1}\right) + n_\beta \tag{5}$$

where $k = 2, \ldots, K, n_k$ is the TDOA measurement error associated with BS_k and the home BS, and n_β is the measurement error of the AOA. In the following, we discuss the LS solution to this problem, which is an ML estimator when the measurement errors are small.

1) Taylor-Series Linearization: Consider the AOA equation in (5). Using the home BS as the coordinate origin, we have the following geometrical relationship, as shown in Fig. 3:

$$D_1 \sin n_\beta = x \sin\beta - y \cos\beta. \tag{6}$$

Using the fact that $\sin n_\beta \approx n_\beta$ when $|n_\beta| \ll 1$, we can approximately rewrite the AOA equation in a linear form as

$$0 \approx -x \sin\beta + y \cos\beta + D_1 n_\beta. \tag{7}$$

As a result, (5) can be rewritten in a matrix form as

$$\boldsymbol{m} = \boldsymbol{f}(\boldsymbol{\theta}) + \boldsymbol{n}. \tag{8}$$

where

$$\boldsymbol{\theta} = \begin{bmatrix} x \\ y \end{bmatrix}, \quad \boldsymbol{m} = \begin{bmatrix} t_{2,1} \\ t_{3,1} \\ \vdots \\ t_{K,1} \\ 0 \end{bmatrix}$$

$$\boldsymbol{f}(\boldsymbol{\theta}) = \begin{bmatrix} (D_2 - D_1)/c \\ (D_3 - D_1)/c \\ \vdots \\ (D_K - D_1)/c \\ -x\sin\beta/D_1 + y\cos\beta/D_1 \end{bmatrix}$$

and

$$\boldsymbol{n} = \begin{bmatrix} n_{2,1} \\ n_{3,1} \\ \vdots \\ n_{K,1} \\ n_\beta \end{bmatrix}.$$

The measurement error $\boldsymbol{n}$ is assumed to be a multivariate random vector with zero mean and a $K \times K$ positive definite covariance matrix given by

$$\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{Q}_t & 0 \\ 0 & \sigma_\beta^2 \end{bmatrix}$$

where $\boldsymbol{Q}_t$ is the covariance matrix for TDOA measurement errors, and σ_β^2 is the variance of the AOA measurement error. Equation (8) can be solved by the Taylor series expansion method [6].

2) Two-Step LS Approach: The linearized LS estimator using Taylor series expansion is an ML estimator and can achieve high accuracy, provided the linearization error is small and the initial guess of the MS location is accurate enough. The estimator is computationally intensive and has a convergence problem [2]. To solve this problem, we extend the two-step LS approach for TDOA equations [6] to the hybrid TDOA/AOA location, which requires the AOA equation to be a linear function of x, y, and D_1. Equation (7) is the required format. Let $\boldsymbol{\theta}_a = [x, y, D_1]^T$ be the unknown vector. Let superscript 0 denote the error-free value of a variable. The matrix form of the TDOA/AOA equations in the presence of the measurement error $\boldsymbol{n}$ is

$$\boldsymbol{m}_a = \boldsymbol{G}_a \boldsymbol{\theta}_a^0 + \boldsymbol{\psi}_a \tag{9}$$

where

$$\boldsymbol{m}_a = \frac{1}{2} \begin{bmatrix} D_{2,1}^2 - L_2 \\ D_{3,1}^2 - L_3 \\ \cdots \\ D_{K,1}^2 - L_K \\ 0 \end{bmatrix}$$

$$\boldsymbol{G}_a = -\begin{bmatrix} x_2 & y_2 & D_{2,1} \\ x_3 & y_3 & D_{3,1} \\ & \cdots & \\ x_K & y_K & D_{K,1} \\ -\sin\beta & \cos\beta & 0 \end{bmatrix}$$

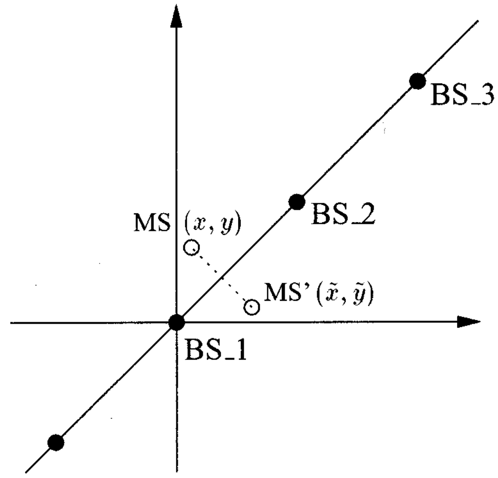


Fig. 4. The 1-D array layout of the BSs.

$$\boldsymbol{\psi}_a = c\boldsymbol{B}\boldsymbol{n} + \frac{c^2}{2}\boldsymbol{n} \odot \boldsymbol{n} \begin{bmatrix} \boldsymbol{I}_{K-1} & 0 \\ 0 & 0 \end{bmatrix}$$
$$\boldsymbol{B} = \mathrm{diag}\left\{D_2^0, \ldots, D_K^0, D_1^0/c\right\}$$

$\boldsymbol{I}_{K-1}$ is the $K-1 \times K-1$ identity matrix, and $\odot$ represents the Schur product (element-by-element product). We can then use an approach similar to that given in [6] to solve the LS estimation problem.

3) $K(\geq 3)$ BSs With 1-D Array Layout: When the BSs are arranged in a 1-D array layout such as in a highway environment, as depicted in Fig. 4, the matrices containing x_k and y_k become singular because the BS positions satisfy $y_k = ax_k, k = 1,2,\ldots,K$, where a is a constant. To solve the TDOA/AOA equations, we first use the 1-D TDOA LS estimator [6] to obtain the location estimate $(\hat{x}, \hat{y})$ with estimation error (e_x, e_y). By incorporating the additional AOA measurement, we have

$$\boldsymbol{m}_l = \boldsymbol{G}_l \boldsymbol{\theta} + \boldsymbol{\psi}_l \tag{10}$$

where

$$\boldsymbol{m}_l = \begin{bmatrix} \hat{x} \\ \hat{y} \\ 0 \end{bmatrix}, \quad \boldsymbol{G}_l = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -\sin\beta & \cos\beta \end{bmatrix}, \quad \boldsymbol{\psi}_l = \begin{bmatrix} e_x \\ e_y \\ D_1 n_\beta \end{bmatrix}.$$

The final location estimate is

$$\boldsymbol{\theta} = \left(\boldsymbol{G}_l^T \boldsymbol{Q}_l \boldsymbol{G}_l\right)^{-1} \boldsymbol{G}_l^T \boldsymbol{Q}_l \boldsymbol{m}_l \tag{11}$$

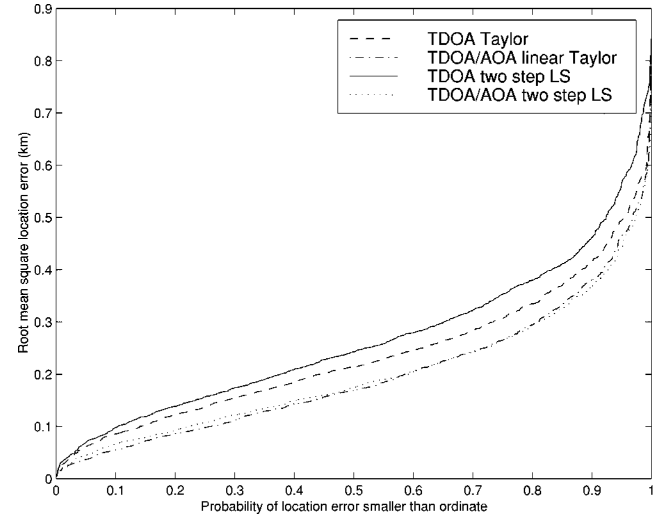
where

$$\boldsymbol{Q}_l = \begin{bmatrix} \boldsymbol{Q}_t & 0 \\ 0 & D_1^2\sigma_\beta^2 \end{bmatrix}.$$

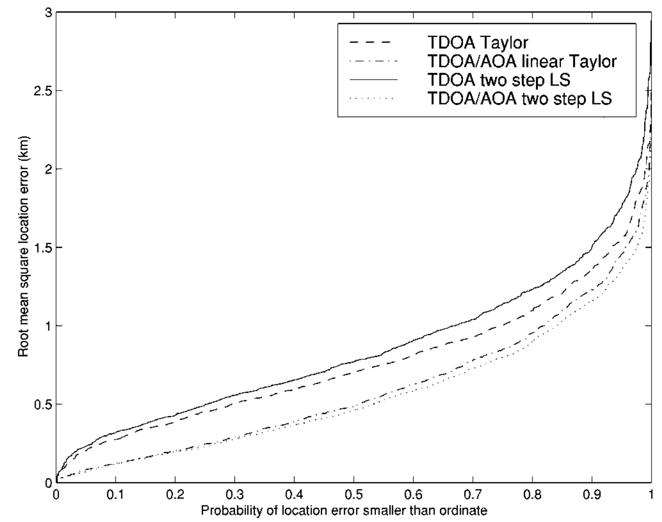
The performance of the estimator can be evaluated by the covariance matrix of $\boldsymbol{\theta}$ given by $\boldsymbol{\Psi}_l = (\boldsymbol{G}_l{}^T \boldsymbol{Q}_l^{-1} \boldsymbol{G}_l)^{-1}$. There is always an ambiguity in the MS location if only TDOA measurements are used. In Fig. 4, both the true MS location and its mirror image MS' at $(\tilde{x}, \tilde{y})$ satisfy the TDOA hyperbolic equation. By adding the AOA measurement, this ambiguity is eliminated.

V. Simulation Results

Computer simulations are performed to demonstrate the performance of the proposed location scheme. We assume



(a)



(b)

Fig. 5. Performance comparison between the TDOA/AOA location and TDOA only location, four BSs, true MS location at (3, 3) km. (a) $c\sigma_t$ =0.1 km, $\sigma_\beta = 1°$. (b) $c\sigma_t = 0.316$ km, $\sigma_\beta = 1°$.

that the TDOA and AOA measurement errors are independent Gaussian random variables with zero-mean and that variances of the TDOA measurement errors associated with different BSs are identical unless otherwise specified. For the 2-D location, we consider a hexagonal test cell surrounded by 6 neighboring cells with radius of 5 km. The RMS error is computed based on 10 000 independent runs. The initial position guess in the Taylor-series method is chosen to be the true solution to allow for convergence. Simulations show that at least three iterations are required for Taylor-series solutions to convergence. In the simulations, the variances of the measurement errors are given. In practice, the variances depend on the chip rate, the propagation environment, and the home BS antenna parameters. They can be estimated based on the received signal SNRs and their typical values for various propagation conditions.

A. The Effect of TDOA and AOA Measurement Accuracy

Fig. 5 shows the location accuracy of the proposed TDOA/AOA location as compared with that of the TDOA only location, with $c\sigma_t = 0.1$ and 0.316 km, respectively, and $\sigma_\beta = 1$ degree. The MS is located at the coordinates (3, 3) km. It is observed that: 1) the TDOA/AOA location always performs better than TDOA only location for both the Taylor series estimator and the two-step LS estimator; 2) for TDOA only location, the Taylor series estimator generally gives slightly better performance than the two-step LS estimator, provided it converges. However, for the hybrid TDOA/AOA location, the performance of the two-step LS estimator is very close to that of the Taylor series estimator; and 3) with larger TDOA measurement errors, the performance improvement introduced by additional AOA is more significant. Fig. 6 shows the performance comparison for the MS located at (0.4, 0.4) km. When the MS is close to the home BS, the Taylor series method has convergence problem if the initial guess is not accurate enough. It is observed that the TDOA/AOA two-step LS estimator gives best performance, followed by the TDOA/AOA Taylor series estimator. Additional AOA information is very useful here to reduce the otherwise large location estimation error. Fig. 7 shows the comparison when the variance of the TDOA measurement error associated with $\mathrm{BS\_2}$ is ten times of that associated with $\mathrm{BS\_3}$ and $\mathrm{BS\_4}$. The TDOA/AOA location using both the Taylor series estimator and the two-step LS estimator gives an RMS error almost 0.2 km smaller than that of the corresponding TDOA only location. The TDOA/AOA two-step LS estimator performs slightly better than the TDOA/AOA Taylor series estimator. In the case that some of the BSs have a larger TDOA measurement error variance than others, the AOA information greatly reduces the RMS location error. Table I gives the RMS errors and the CRLB of the location methods with various numbers of the BSs. It is observed that, for all the numbers of the BSs, the proposed TDOA/AOA location outperforms TDOA only location. Fig. 8 shows the location accuracy comparison versus σ_β. It is observed that: 1) a large performance improvement by the TDOA/AOA location is achieved when the AOA measurement is accurate and 2) the TDOA/AOA location always performs better than the TDOA only location. However, when the AOA measurement error

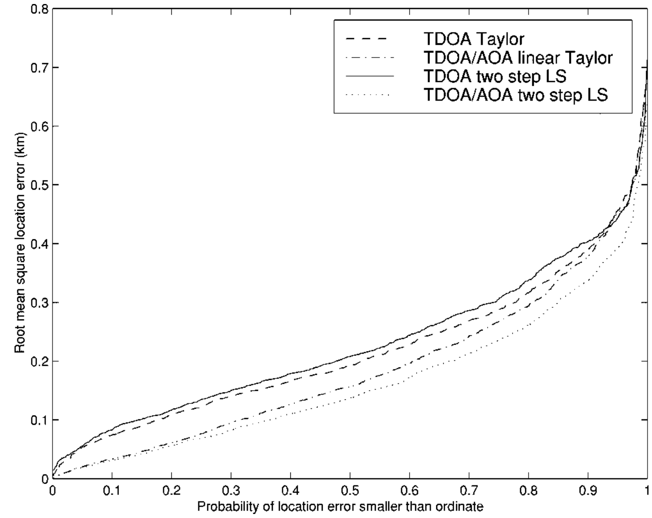


Fig. 6. Performance comparison between the TDOA/AOA location and TDOA only location, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1°$, four BSs, true MS location at (0.4, 0.4) km.

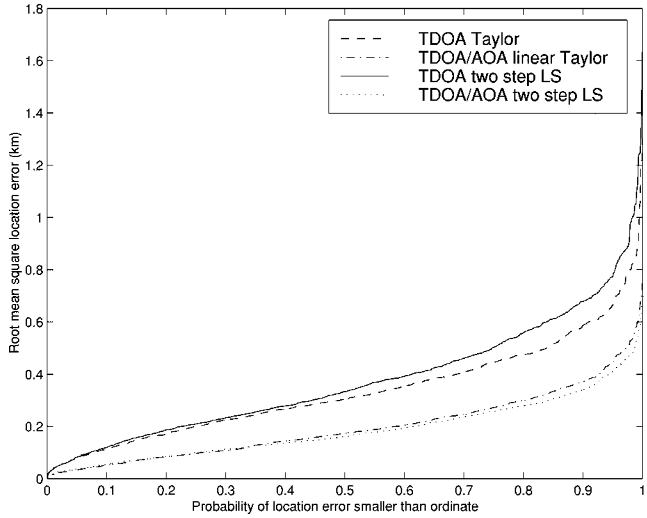


Fig. 7. Performance comparison between the TDOA/AOA location and TDOA only location, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1^\circ$, $c\sigma_{t2} = 0.316$ km, four BSs, true location (3, 3) km.

TABLE I
COMPARISON OF 2-D ARRAY RMS ERROR FOR DIFFERENT METHODS, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1^\circ$, TRUE MS LOCATION (3, 3) km

RMS (km)	M = 4	M = 5	M = 6	M = 7
TDOA CRLB	0.0805	0.0765	0.0725	0.0537
TDOA/AOA CRLB	0.0668	0.0652	0.0631	0.0513
TDOA Taylor	0.0812	0.0766	0.0726	0.0537
TDOA/AOA Taylor	0.0667	0.0654	0.0632	0.0513
TDOA LS	0.1142	0.1134	0.0951	0.0703
TDOA/AOA LS	0.0915	0.0907	0.0823	0.0652

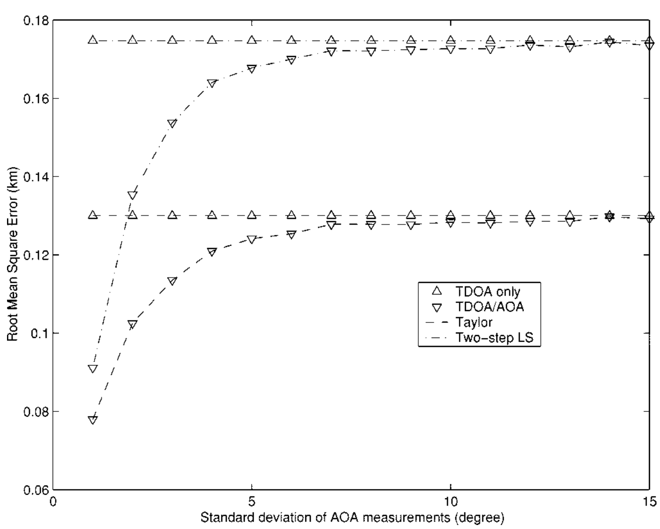
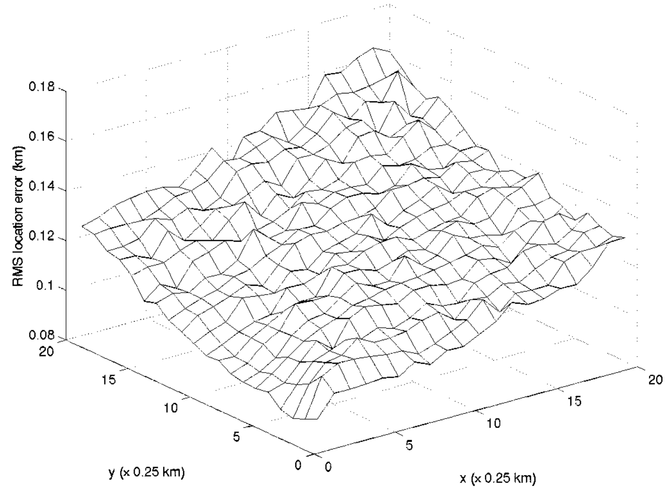


Fig. 8. Performance comparison between the TDOA/AOA location and TDOA only location, four BSs, true MS location at (3, 3) km, $c\sigma_t = 0.1$ km.

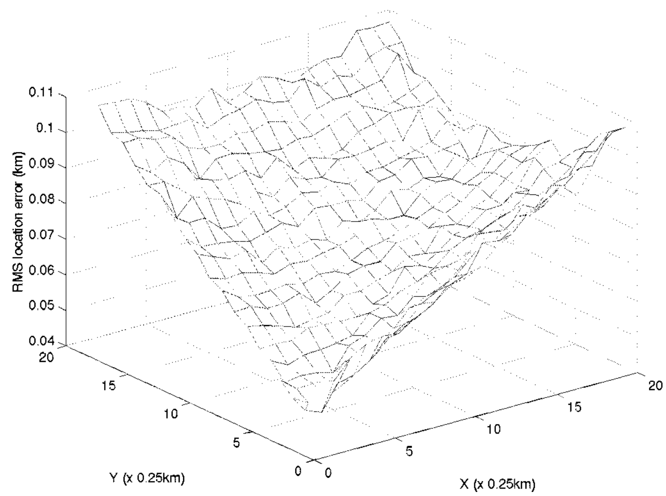
increases to a certain level, the performance improvement becomes negligible.

B. The Performance Dependence on the MS Location

To give a comparison among the location methods on their performance dependence on the MS location, the RMS location



(a)



(b)

Fig. 9. RMS location error for the TDOA/AOA location and TDOA only location using Taylor series approach, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1^\circ$, four BSs. (a) TDOA Taylor series linearization approach. (b) TDOA/AOA Taylor series linearization approach.

errors for four BSs in the 2-D array layout case is studied by varying the MS location. The results are illustrated in Figs. 9–10, where the x and y axes are the location coordinates of the MS. It is observed that: 1) the TDOA/AOA location consistently outperforms the TDOA only location; 2) the results using the two-step LS approach are almost as good as those using the Taylor series linearization approach; and 3) when the MS is relatively close to the home BS, the RMS location error becomes smaller, especially for the TDOA/AOA location.

C. The 1-D Array BS Layout Case

Fig. 11 show the performance comparison between the TDOA/AOA location and TDOA only location with four BSs. We assume that the TDOA only estimator is able to pick up the solution closer to the true location. It is observed that: 1) when the AOA measurement is accurate, as in Fig. 11(a) where $\sigma_\beta = 1^\circ$, there is a clear advantage of the TDOA/AOA location

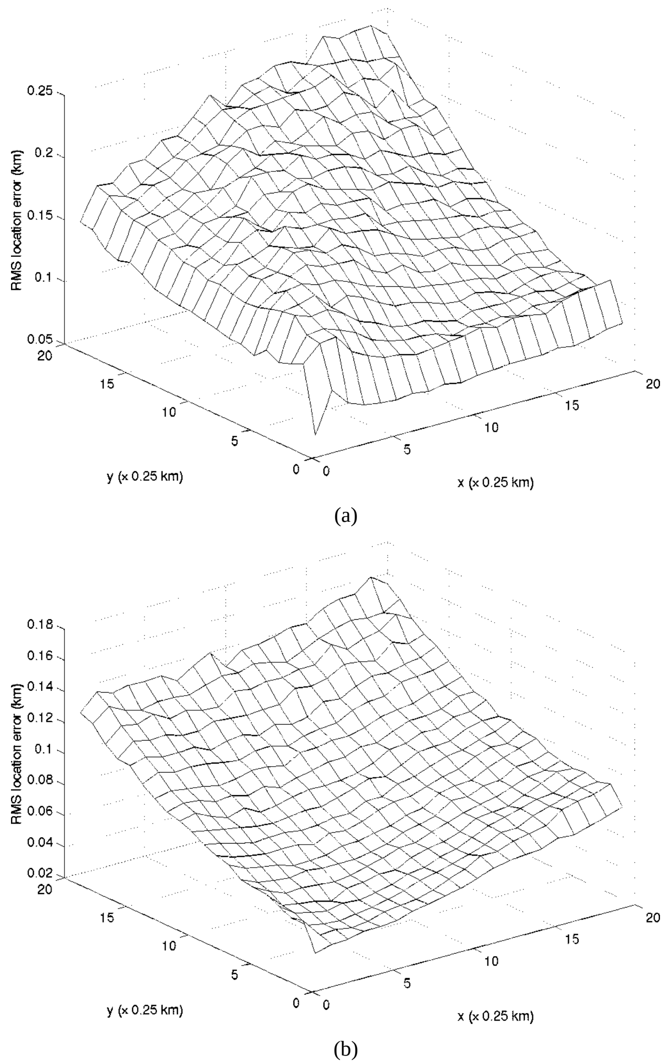


Fig. 10. RMS location error for the TDOA/AOA location and TDOA only location using two-step LS approach, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1°$, four BSs. (a) TDOA two-step LS approach. (b) TDOA/AOA two-step LS approach.

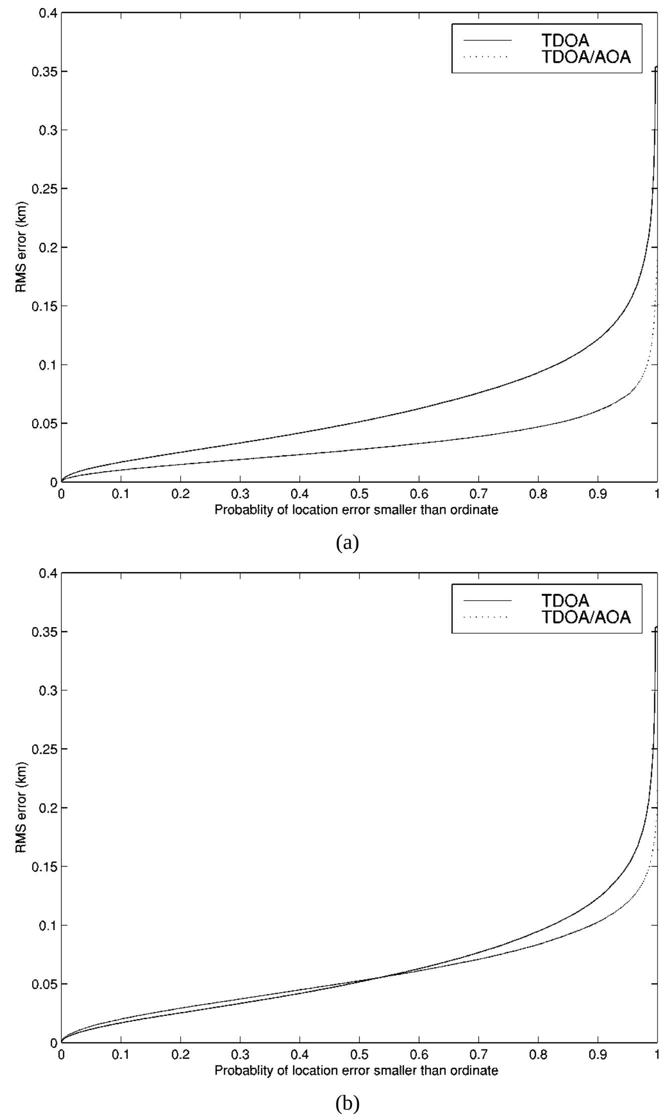


Fig. 11. Performance comparison between the TDOA/AOA location and TDOA only location with 1-D array BS layout, four BSs, true MS location at (0.25, 0.75) km. (a) $c\sigma_t = 0.1$ km, $\sigma_\beta = 1°$. (b) $c\sigma_t = 0.1$ km, $\sigma_\beta = 4°$.

and 2) when σ_β is increased to 4°, as in Fig. 11(b), the performance difference between the TDOA/AOA and AOA location schemes is reduced. In general, if the AOA measurement has a large error and the TDOA measurements are accurate, the TDOA/AOA location may give poorer performance than the TDOA only location. However, the TDOA approach for the 1-D array BS layout always has the ambiguity problem, and additional AOA information can solve this problem. Table II compares the RMS errors when the number of BSs is increased from three to seven. It shows that: 1) as the number of BSs increases, the RMS error decreases and 2) when the number of available BSs is small, TDOA/AOA greatly improves location accuracy.

TABLE II
COMPARISON OF LINEAR ARRAY RMS ERROR FOR DIFFERENT METHODS, $c\sigma_t = 0.1$ km, $\sigma_\beta = 1°$, TRUE MS LOCATION (0.25, 0.75) km

RMS (km)	M = 3	M = 4	M = 5	M = 6	M = 7
TDOA	0.1775	0.1083	0.0587	0.0522	0.0450
TDOA/AOA	0.0872	0.0609	0.0280	0.0267	0.0220

VI. CONCLUSION

This paper proposes a mobile user location scheme using both TDOA and AOA measurements in the wideband CDMA communications system. By introducing a linear form of the AOA equation, we extend the previous TDOA only location estimators to solve the TDOA/AOA equations for the 2-D array BS layout case. A solution for the 1-D array BS layout case is also given. Simulation results demonstrate that: 1) the proposed hybrid TDOA/AOA location scheme generally performs better than TDOA only location schemes, especially when the AOA measurement is accurate; 2) the additional AOA information solves the ambiguity problem in the 1-D array BS layout case; 3) the Taylor series algorithm has slightly better accuracy when compared with the two-step LS algorithm, but it requires an initial guess of the MS location and may have convergence problem; and 4) the two-step LS algorithm performs well in most situations, even when the MS is close to the home BS.

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