Hybrid TOA/AOA Schemes for Mobile Location in Cellular Communication Systems

Chien-Sheng Chen, Szu-Lin Su, and Chuan-Der Lu

Abstract—Wireless location is to determine the mobile station (MS) location in a wireless cellular communications system. When fewer base stations (BSs) may be available for location purposes or the measurements with large errors in non-line-of-sight (NLOS) environments, it is necessary to integrate all available heterogeneous measurements to achieve high location accuracy. This paper illustrates a hybrid proposed schemes that combine time of arrival (TOA) at three BSs and angle of arrival (AOA) information at the serving BS to give a location estimate of the MS. The proposed schemes mitigate the NLOS effect simply by the weighted sum of the intersections between three TOA circles and the AOA line without requiring a priori information about the NLOS error. Simulation results show that the proposed methods can achieve better accuracy when compare with Taylor series algorithm (TSA) and the hybrid lines of position algorithm (HLOP).

Keywords—Time of arrival (TOA), angle of arrival (AOA), non-line-of-sight (NLOS).

I. INTRODUCTION

WIRELESS location systems have received considerable attention and various technologies have been proposed in the past few years. The systems attempt to locate mobile station (MS) by measuring the parameters of radio signals traveling between the vehicle and a set of fixed base stations (BSs). A variety of wireless location techniques include angle of arrival (AOA), signal strength (SS), time of arrival (TOA) and time difference of arrival (TDOA). TOA location scheme measures the propagation time for a radio wave to travel between the MS and a BS. The AOA scheme utilizes an antenna array and a directive antenna to estimate the direction of arrival signal. The signal-strength scheme makes use of a known model to describe the path loss attenuation with distance. The TDOA scheme measures the time difference between the radio signals. The angle-based schemes require a minimum of two BSs to determine the MS location, while the time-based schemes require at least three BSs. But the time-based schemes provide more accuracy than angle-based schemes. Different applications of wireless location services have been well

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documented, including the emergency 911 (E-911) subscriber safety services, location-based billing, fleet management and the intelligent transportation system (ITS) [4-6].

ITS is a next generation transportation system which is a combination of the traditional transportation system and modern technologies such as information communications, electronic technologies, control engineering, computer science and advanced management strategy. ITS uses of vehicle position to decrease the heavy traffic and improve service reliability of public transportation system. Automatic vehicle location (AVL) is a computer-based system for determining the location of a vehicle and transmitting this information of any vehicle equipped with a module to control center. AVL system is often the first step in a more comprehensive ITS implementation. AVL system is a requirement for a variety of applications in ITS implementation like personal navigation, vehicle guidance and public transportation control. A number of categories are available for AVL systems, including dead reckoning, proximity systems and radio location [1].

The use of cellular telephone networks for providing automatic vehicle location information to intelligent vehicle/highway system (IVHS) services [2]. Radio location can be used in IS-95 direct-sequence code-division multiple-access (DS/CDMA) system where the mobile unit transmits the time-based update that is received by three or more BSs. The performance of radio location using TDOA estimates provided by the delay-lock loop in CDMA cellular networks was proposed in [3].

To achieve more accurate measurements of the MS location, it is reasonable to combine two or more schemes to achieve a more accurate position location. A hybrid TDOA/AOA location algorithm gives much better location accuracy for wideband code division multiple access (WCDMA) systems [7]. [8] presented a hybrid TOA/AOA scheme that utilizes nonlinear constrained optimization to estimate the MS location with bounds on the range and angle errors inferred from the geometry.

High location accuracy can be achieved if line-of-sight (LOS) propagation exists between the MS and all BSs. The non-line-of-sight (NLOS) situations, which generally occur in urban or suburban areas, greatly degrade the precision of these location estimation schemes. [9] presented a NLOS identification method by measuring the statistical properties of the range measurements over a period of time and reconstructs the true ranges to estimate the MS location. Based on the NLOS situation and how much a priori knowledge of the NLOS error is available, different NLOS identification and correction

algorithms for mobile user location are proposed [10].

Hearability is the ability to transmit to or receive from the MS signals above a threshold signal level [11]. When the MS is close to its serving BS and in rural area where each BS covers a fairly large area, the hearability of an MS is very low for neighboring BSs except for the serving BS. The lack of available BSs limits the coverage area of the location service and impairs the positioning schemes. Hence, the hybrid TOA/AOA positioning schemes are proposed for such a hearability-constrained environment [15].

In this paper, the proposed hybrid schemes use combinations of TOA and AOA measurements to estimate MS location when only three BSs are available for location purposes. The position of MS is given by the intersections of three circles and a line if TOA measurements from three BSs and the AOA information at the serving BS are available. The proposed schemes mitigate the NLOS effect simply by the weighted sum of the intersections between three TOA circles and an AOA line without a priori information about the NLOS errors. Numerical results show that the proposed schemes always provide much better location estimation than the Taylor series algorithm (TSA) [12][13] and the hybrid lines of position algorithm (HLOP) [14].

The remainder of this paper is organized as follows. The system model is given in Section II. In Section III we describe the positioning methods using TSA and HLOP to locate the MS. The proposed methods are presented in Section IV. In Section V, simulation results are displayed. Conclusion is given in Section VI.

II. SYSTEM MODEL

If the TOA and AOA measurements are accurate, only one BS is required to locate the MS [15]. In reality, the TOA and AOA measurements contain errors due to NLOS propagation. Taking into account the constraint on *hearability*, the number of BSs available for estimating the location is limited to three in this paper. TOA measurements from three BSs and the AOA information at the serving BS can be used to give a location estimate of the MS, as shown in Fig. 1. The coordinates for BS1, BS2, BS3 are given by $(X_1, Y_1) = (0, 0)$, $(X_2, Y_2) = (X_2, 0)$, and (X_3, Y_3), respectively. Let t_i denote the propagation time from the MS to BS i, $i = 1, 2, 3$. The distances between BS i and the MS can be expressed as

$$r_i = c \cdot t_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2} \qquad (1)$$

where (x, y) is the MS location and c is the propagation speed of the signals. Denote by θ as the measured AOA from the serving BS with respect to a reference direction.

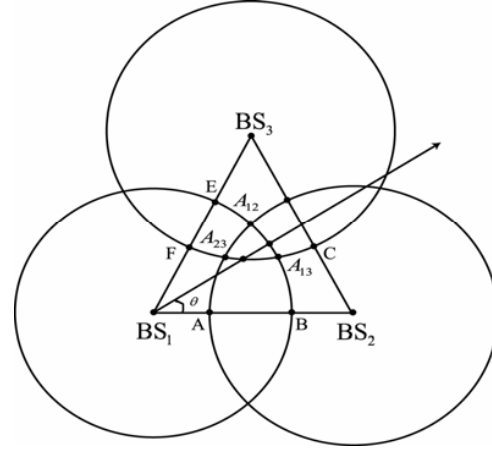$$\theta = \tan^{-1}(\frac{y}{x}) \qquad (2)$$

Fig. 1 Geometric layout of the three circles and a line

III. TAYLOR SERIES ALGORITHM (TSA) AND HYBRID LINES OF POSITION ALGORITHM (HLOP)

A. Taylor Series Algorithm (TSA)

If (x, y) is the true position and (x_v, y_v) is the initial estimated position, let $x = x_v + \delta_x$, $y = y_v + \delta_y$. By linearizing the TOA and AOA equations using a Taylor series expansion in which only the first two terms are retained, the MS location can be expressed in vector form as:

$$A\delta \cong z \qquad (3)$$

where
$$A = \begin{bmatrix} a_{11}, a_{12} \\ a_{21}, a_{22} \\ a_{31}, a_{32} \\ b_{11}, b_{12} \end{bmatrix}, \quad \delta = \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}, \quad z = \begin{bmatrix} r_1 - r_{v1} \\ r_2 - r_{v2} \\ r_3 - r_{v3} \\ \theta - \theta_v \end{bmatrix},$$

and
$$a_{i1} = \frac{\partial r_i}{\partial x}\Big|_{x_v, y_v}, \quad a_{i2} = \frac{\partial r_i}{\partial y}\Big|_{x_v, y_v},$$

$$r_{vi} = \sqrt{(x_v - X_i)^2 + (y_v - Y_i)^2}, i = 1, 2, 3,$$

$$b_{11} = \frac{\partial \theta}{\partial x}\Big|_{x_v, y_v}, \quad b_{12} = \frac{\partial \theta}{\partial y}\Big|_{x_v, y_v}, \theta_v = \tan^{-1}\frac{y_v}{x_v}.$$

Then, the least-square (LS) estimation can be solved by:

$$\delta = (A^T A)^{-1} A^T z \qquad (4)$$

The process starts with an initial estimate for the MS location, and the estimate is updated iteratively until the magnitude of δ falls below a given threshold. This method is recursive and presents a computational burden. Moreover, the iteration may not converge due to a poor initial estimate of the MS location [12][13].

B. Hybrid Lines of Position Algorithm (HLOP)

This scheme makes use of linear lines of position (LOP), rather than circular LOP, to locate the MS. Combining the linear LOP and the AOA line, the MS location is identified by [14]:

$$Gl = h \qquad (5)$$

where $l = \begin{bmatrix} x \\ y \end{bmatrix}$ denotes the MS location,

$$G = \begin{bmatrix} X_2 & 0 \\ X_3 & Y_3 \\ \tan\theta & -1 \end{bmatrix} \text{ and } h = \frac{1}{2}\begin{bmatrix} r_1^2 - r_2^2 + X_2^2 \\ r_1^2 - r_3^2 + X_3^2 + Y_3^2 \\ 0 \end{bmatrix}.$$

Hence, the LS solution to Eq. (5) is given by:

$$l = (G^T G)^{-1} G^T h \qquad (6)$$

IV. THE PROPOSED HYBRID TOA/AOA SCHEMES

It is well known that a TOA measurement can be represented by a circle centered at the BS and that an AOA measurement can be represented by a line from the BS to the MS. As shown in Fig. 1, the equations of the three circles and a line used in location estimation can be expressed as:

$$\text{Circle 1: } x^2 + y^2 = r_1^2 \qquad (7)$$

$$\text{Circle 2: } (x - X_2)^2 + y^2 = r_2^2 \qquad (8)$$

$$\text{Circle 3: } (x - X_3)^2 + (y - Y_3)^2 = r_3^2 \qquad (9)$$

$$\text{Line 1: } \tan\theta_1 \cdot x - y = 0 \qquad (10)$$

The proposed methods utilize three TOA circles and the AOA line to find all the possible intersections to locate the MS. Because the NLOS error is always positive, TOA measurements are always greater than the true values if the measurement error due to noise is neglected. Fig. 1 illustrates a scenario in which the true MS location should be inside the region enclosed by the overlap of the three circles, i.e., the area enclose by $A_{12}A_{13}A_{23}$. The intersections that are within this are defined as feasible intersections. Hence, the feasible intersections must satisfy the following inequalities simultaneously:

$$x^2 + y^2 \le r_1^2 \qquad (11)$$

$$(x - X_2)^2 + y^2 \le r_2^2 \qquad (12)$$

$$(x - X_3)^2 + (y - Y_3)^2 \le r_3^2 \qquad (13)$$

However, not all the feasible intersections provide information of the same value for location estimation. In order to enhance the precision of the location estimation with less effort, several methods which we have proposed in [15] are modified.
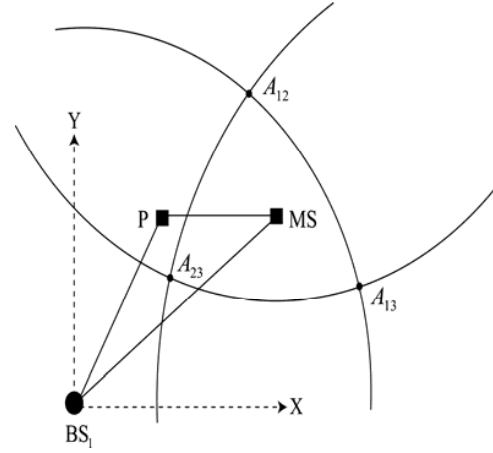

Fig. 2 Geometry of range-based location showing measured range circles and the region of overlap in which the MS lies

(1) Distance-Weighted Method

Step 1. If the scatterer *P* lies outside the region $A_{12}A_{23}A_{13}$, it is evident that the measured AOA oriented in the direction of the scatterer is in error, shown in Fig. 2. If θ_{Aij} is the orientation of the line joining the serving BS and the intersections of the *i*th and *j*th circles, it can be seen that the true AOA satisfies:

$$\theta \in [\min(\theta_{Aij}), \max(\theta_{Aij})], i, j = 1,...,N, i \ne j. \qquad (14)$$

Step 2. Find all the feasible intersections of the three circles and a line.

Step 3. The MS location $(\bar{x}_N, \bar{y}_N)$ is estimated by averaging these remaining feasible intersections, where

$$\bar{x}_N = \frac{1}{N}\sum_{i=1}^{N} x_i \text{ and } \bar{y}_N = \frac{1}{N}\sum_{i=1}^{N} y_i \qquad (15)$$

Step 4. Calculate the distance d_i between each remaining feasible intersection (x_i, y_i) and the average location $(\bar{x}_N, \bar{y}_N)$.

$$d_i = \sqrt{(x_i - \bar{x}_N)^2 + (y_i - \bar{y}_N)^2}, \ 1 \le i \le N \qquad (16)$$

Step 5. Set the weight for the *i*th remaining feasible intersection to $(d_i^2)^{-1}$. Then the MS location (x_d, y_d) is determined by

$$x_d = \frac{\sum_{i=1}^{N}(d_i^2)^{-1} \cdot x_i}{\sum_{i=1}^{N}(d_i^2)^{-1}} \text{ and } y_d = \frac{\sum_{i=1}^{N}(d_i^2)^{-1} \cdot y_i}{\sum_{i=1}^{N}(d_i^2)^{-1}} \qquad (17)$$
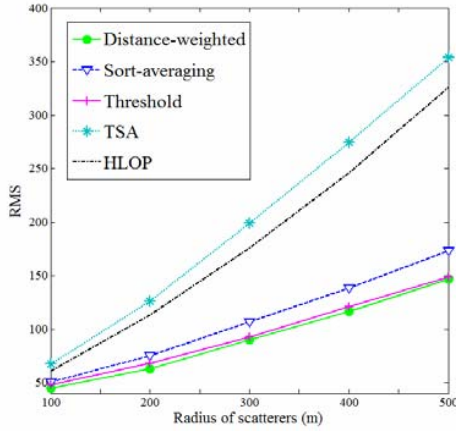
Fig. 3 Average location error versus the radius of scatterers

(2) Threshold Method

Steps 1-3 are the same as those of the distance-weighted method.

Step 4. Calculate the distance d_{mn}, $1 \le m, n \le N$, between any pair of feasible intersections.

Step 5. Select a threshold value D_{thr} as the average of all the distances d_{mn}.

Step 6. Set the initial weight I_k, $I \le k \le N$, to be zero for all remaining feasible intersections.

If $d_{mn} \le D_{thr}$, then $I_m = I_m + 1$ and $I_n = I_n + 1$ for $1 \le m, n \le N$.

Step 7. The MS location (x_t, y_t) is estimated by

$$x_t = \frac{\sum_{i=1}^{N} I_i \cdot x_i}{\sum_{i=1}^{N} I_i} \quad \text{and} \quad y_t = \frac{\sum_{i=1}^{N} I_i \cdot y_i}{\sum_{i=1}^{N} I_i}. \qquad (18)$$

(3) Sort Averaging Method

Steps 1-4 are the same as those of the distance-weighted method.

Step 5. Rank the distances d_i in increasing order and re-label the remaining feasible intersections in this order.

Step 6. The MS location $(\bar{x}_M, \bar{y}_M)$ is estimated by the mean of the first M remaining feasible intersections.

$$\bar{x}_M = \frac{1}{M} \sum_{i=1}^{M} x_i \quad \bar{y}_M = \frac{1}{M} \sum_{i=1}^{M} y_i \quad (M = 0.5 * N \le N) \qquad (19)$$

V. SIMULATION RESULTS

Computer simulations are performed to demonstrate the performance of the proposed location scheme. The coordinates of the BSs are BS1: (0, 0), BS2: (1732 m, 0), and BS3: (866 m,

1500m). The MS location is chosen randomly in accordance with a uniform distribution within the area covered by the triangle formed by the points BS1, BS2, and BS3, shown in Fig. 1. 10,000 independent trials are performed for each simulation. Two different propagation approaches were used to model the measured ranges and angle.
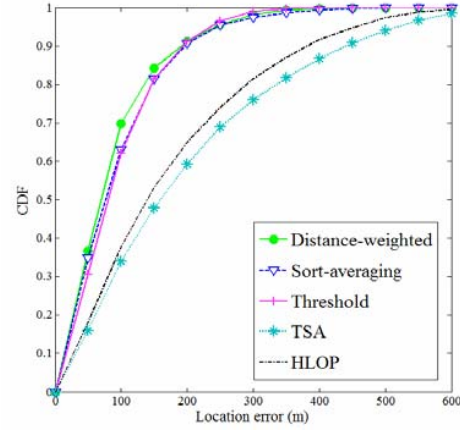

Fig. 4 CDFs of the location error when CDSM is used to model the NLOS error

The first propagation approach considers a circular disk of scatterers model (CDSM) [11]. BS1 is assumed to be the serving BS which provides the more accurate measurements. The radius of CDSM for BS1 is 100 m and the other BSs were taken from 100 m to 500 m. The effect of the radius of the CDSM on the average location error of the various methods is shown in Fig. 3. As the radius of the scatterers increases, the average magnitudes of the NLOS time and angle errors increase. By comparing the root-mean-square (RMS) error, the proposed hybrid TOA/AOA positioning methods still can reduce the RMS errors effectively and provide more accurate positioning. The performance degradation for TSA and HLOP is much more pronounced than that for the proposed methods under harsher NLOS error conditions. The proposed methods deal with large errors more effectively than the other algorithms. Fig. 4 shows cumulative distribution functions (CDFs) of the location error for different algorithms using the CDSM. The radius of CDSM for BS1 and the other BSs were taken to be 100m and 400m, respectively. It can be seen that the proposed methods always provides much better location estimation than TSA and HLOP for the error model considered. The second NLOS propagation model is based on the uniformly distributed noise model [11], in which the TOA measurement error is assumed to be uniformly distributed over $(0, U_i)$, for $i = 1, 2, 3$ where U_i is the upper bound and the AOA measurement error is assumed to be $f_1 = w_1 \cdot \tau_1$, where w_1 is a uniformly distributed variable over [-1, 1] [16]. Fig. 5 shows how the average location error is affected by the upper bound on uniform NLOS error. The upper bound for BS1 is 200 m and the other BSs were taken from 200 m to 700 m. By comparing the RMS error, the proposed method is shown to

have better performance. It can also be observed that the sensitivity of the proposed methods with respect to the NLOS effect is much less than that for TSA, HLOP. The improvement in location accuracy using the proposed method can also be seen in the CDF curves of the location error, as illustrated in Fig. 6. The variables are chosen as follows: $U_1 = 200$ m, $U_2 = 400$ m, $U_3 = 400$ m, and $\tau_1 = 2.5°$. TSA and HLOP offer worst performance and the proposed methods greatly improve location estimate accuracy.
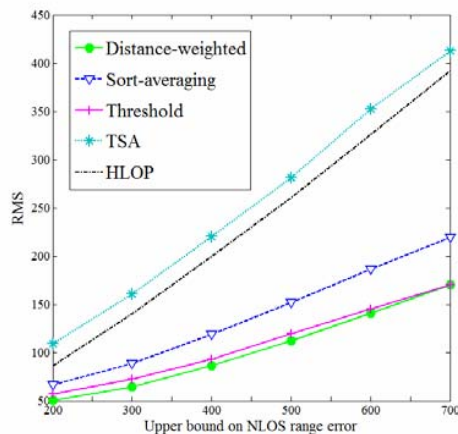

Fig. 5 Performance comparison between the location estimation algorithms when the upper bound is used to model the NLOS
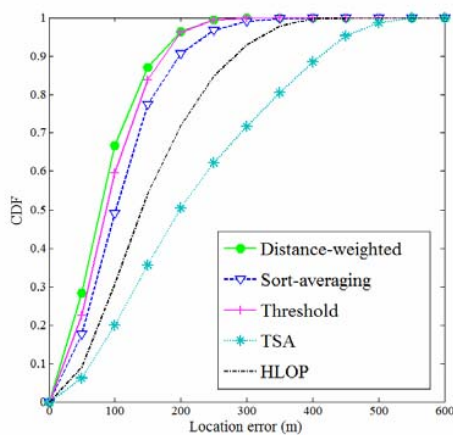

Fig. 6 Comparison of error CDFs when NLOS errors are modeled as the upper bound

VI. CONCLUSION

In this paper, we presented a class of hybrid TOA/AOA geometrical location schemes to estimate the location of an MS from only three BSs. The proposed hybrid methods utilize three TOA circles and the AOA line to find all the possible intersections to locate the MS without requiring a priori information about the NLOS error. The proposed positioning schemes are simply based on the weighted sum of the

intersections of three TOA circles and the AOA line. No matter which NLOS propagation model is considered, the simple geometric positioning methods proposed in this paper give better results than the conventional TSA and HLOP in the MS location estimation.

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