HYBRID TOA/AOA SCHEMES FOR MOBILE LOCATION IN CELLULAR COMMUNICATION SYSTEMS

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ABSTRACT

Wireless location is to determine the position of the mobile station (MS) in wireless communication networks. Due to the measurements with large errors, location schemes give poorer performance in non-line-of-sight (NLOS) environments. This paper illustrates methods to integrate all the available heterogeneous measurements to achieve more accurate location estimation. The proposed hybrid schemes combine time of arrival (TOA) at seven BSs and angle of arrival (AOA) information at the serving BS to give location estimation of the MS. The schemes mitigate the NLOS effect simply by the weighted sum of the intersections between seven TOA circles and the AOA line without requiring priori knowledge of NLOS error statistics. Different NLOS models were used to evaluate the proposed methods. It is shown by the simulation results that the proposed methods provide better location accuracy comparing with Taylor series algorithm (TSA) and the hybrid lines of position algorithm (HLOP).

KEY WORDS

Time of arrival (TOA), Angle of arrival (AOA), Non-line-of-sight (NLOS)

1. INTRODUCTION

Wireless location systems have received considerable attention and various technologies have been proposed in the past few years. 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 uses 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. However, the time-based schemes generally provide better positioning accuracy than angle-based schemes. Different potential applications of wireless location services have been well developed, including the emergency 911 (E-911) subscriber safety services, location-based billing, fleet management and the intelligent transportation system (ITS) [1-2].

ITS is a next generation transportation system which combines the traditional transportation system and electronic technologies, control engineering, computer science and advanced management strategy. ITS incorporates a wide variety of the advanced positioning technologies to improve the efficiency and safety of the transportation systems. ITS applies vehicle position to decrease the heavy traffic and improves the service reliability of public transportation system.

10.5121/ijasuc.2010.1205

Automatic vehicle location (AVL) is a computer-based system to determine and transmit the location of a vehicle equipped with a module to control center. AVL system is often the first step to implement a more comprehensive ITS. AVL system is a requirement for a variety of applications in ITS implementation, such as 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 [3]. Dead reckoning is the process of estimating current position by advancing a previously determined position on the basis of assumed distance and direction moved. To identify the latest signpost passed by the vehicle the proximity system detects the present location of vehicles and applies a radio link from each vehicle to the station. In order to cover a large area with high accuracy, an extraordinary number of signposts are necessary and expensive to operate and maintain. Both of these methods require the additional equipment to the vehicle. Radiolocation systems attempt to locate a vehicle by measuring the parameters of radio signals traveling between the vehicle and some number of fixed stations.

The use of cellular telephone networks can provide AVL information to intelligent vehicle/highway system (IVHS) services [4]. Radiolocation 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 radiolocation using TDOA estimates provided by the delay-lock loop in CDMA cellular networks was proposed in [5].

The accuracy of MS's location estimation highly depends on the propagation conditions of the wireless channels. The line-of-sight (LOS) path between the MS and BS is existent, high location accuracy can be achieved. However, the non-line-of-sight (NLOS) propagation, which will heavily degrade the precision of the location estimation, occurs usually in urban or suburban areas. NLOS propagation results in significant error on the time and angle measurements due to the reflection or diffraction of the signal propagation between the MS and BSs. Extensive research on NLOS-effect mitigation for location estimation has been carried out in past two decades. Wiley and Holzman [6] presented a way to distinguish LOS-BSs and NLOS-BSs by analyzing the statistical properties of collected measurements over a period of time. 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]. Based on the NLOS situation and how much a *priori* knowledge of the NLOS error is available, different NLOS identification and correction algorithms for MS location are proposed [18]. A constrained optimization algorithm was presented in [11] that utilized bounds on the NLOS errors inferred from the geometry of the cell layout and circles depicting the ranges of three BSs. For an unknown NLOS error distribution, an algorithm was proposed in [19] for TOA systems to identify NLOS-BSs, which is based on the weighted residuals for all possible BS combinations. Similar residual schemes were proposed for AOA systems in [20] and for TDOA systems in [21]. All those studies [19][20][21] assumed that there are many BSs available and that only one NLOS-BS exists in the system. However, if signals propagated from all BSs are NLOS, those algorithms cannot accurately estimate the MS location.

To enhance the precision of the location estimation, it is reasonable to combine two or more different schemes. A hybrid TDOA/AOA location algorithm gives much better location accuracy for wideband code division multiple access (WCDMA) systems [7]. A hybrid TOA/AOA algorithm based on a nonlinear constrained optimization aims to locate the MS in a NLOS environment for the case of three participating BSs [8]. Sprito [16] presented a way to combine TDOA and TOA schemes and showed that it is better than TDOA scheme only on the location estimation in Global System for Mobiles (GSM) systems.

This paper proposes hybrid positioning schemes that combine TOA and AOA measurements to locate the MS under the condition that the MS can be heard by only two BSs in [14]. In this paper, we applied the hybrid geometrical positioning schemes to estimate MS location when seven BSs are available for location purposes. The position of MS is given by the intersections of seven circles and a line if TOA measurements from seven BSs and the AOA information at the serving BS are available. The proposed positioning schemes are simply based on the weighted sum of the intersections of seven TOA circles and the AOA line. Simulation 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) [8].

The remainder of this paper is organized as follows. The system model is given in Section 2. In Section 3, we describe the positioning methods using TSA and HLOP to locate the MS. The proposed hybrid TOA/AOA geometrical positioning methods are presented in Section 4. In Section 5, simulation results are given. Conclusion is given in Section 6.

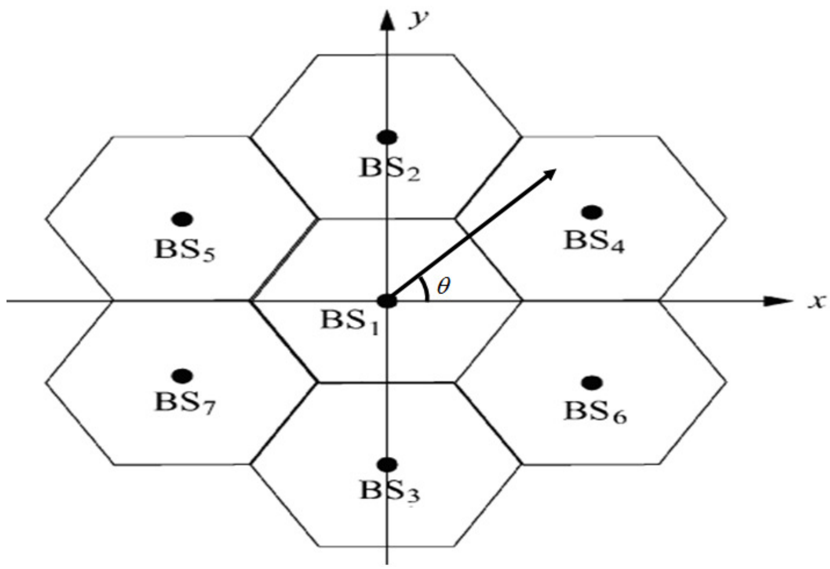

Figure 1. Geometric layout of the seven circles and a line.

2. SYSTEM MODEL

If the TOA and AOA measurements are accurate, then only one BS is required to locate the MS [14]. In reality, due to NLOS propagation, both TOA and AOA measurements contain errors. Thus more than one BS is required for MS location of reasonable accuracy. In this paper TOA measurements from seven BSs and the AOA information at the serving BS is used to give a location estimate of the MS, as shown in Fig. 1. Let t_i denote the propagation time from the MS to BS i, and the coordinates for BS i are given by (X_i, Y_i), $i = 1, 2, ...7$. The distances between BS i and the MS can be expressed as

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

where (x, y) is the MS location and c is the propagation speed of the signals. In Fig. 1 θ is the measured AOA from the serving BS with respect to a reference direction (x-axis) and defined as:

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

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

3.1 Taylor Series Algorithm (TSA)

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

$$A\delta \cong z \tag{3}$$

where $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \vdots & \vdots \\ a_{71} & a_{72} \\ b_{11} & b_{12} \end{bmatrix}$, $\delta = \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$, $z = \begin{bmatrix} r_1 - r_{v1} \\ r_2 - r_{v2} \\ \vdots \\ r_7 - r_{v7} \\ \theta - \theta_v \end{bmatrix}$,

and $a_{i1} = \left.\frac{\partial r_i}{\partial x}\right|_{x_v, y_v}$, $a_{i2} = \left.\frac{\partial r_i}{\partial y}\right|_{x_v, y_v}$, $r_{vi} = \sqrt{(x_v - X_i)^2 + (y_v - Y_i)^2}$, $i = 1, 2, \ldots 7$,

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

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

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

The process starts with an initial guess for the MS location and can achieve high accuracy. This method is recursive and the computational overhead is intensive. Due to the initial guess of the MS location is not accurate enough, the convergence of the iterative process is not assured [12][13].

3.2 Hybrid Lines of Position Algorithm (HLOP)

This scheme makes use of linear lines of position (LOP), rather than circular LOP, to locate the MS. The detail algorithm of the linear LOP approach can be acquired by using the TOA measurements as in [17], and the hybrid linear LOP and AOA measurement (HLOP) in [8]. The method takes the advantage of simpler computation of MS location. The line which passes through the intersection of the two circular LOPs can be found by squaring and differencing the ranges in Eq. (1) for $i = 1, 2,$ which results in

$$2(X_1 - X_2)x + 2(Y_1 - Y_2)y = (r_2^2 - r_1^2 + X_1^2 - X_2^2 + Y_1^2 - Y_2^2). \tag{5}$$

Combining the linear LOP and the AOA line, the MS location is identified by

$$Gl = h \tag{6}$$

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

$$G = \begin{bmatrix} X_1 - X_2 & Y_1 - Y_2 \\ \vdots & \vdots \\ X_1 - X_7 & Y_1 - Y_7 \\ \tan\theta & -1 \end{bmatrix} \text{ and } h = \frac{1}{2}\begin{bmatrix} r_2^2 - r_1^2 + (X_1^2 + Y_1^2) - (X_2^2 + Y_2^2) \\ \vdots \\ r_7^2 - r_1^2 + (X_1^2 + Y_1^2) - (X_7^2 + Y_7^2) \\ 2(X_1 \cdot \tan\theta - Y_1) \end{bmatrix}.$$

Hence, the LS solution to Eq. (6) is given by

$$l = (G^T G)^{-1} G^T h \tag{7}$$

4. THE PROPOSED HYBRID TOA/AOA SCHEMES

From the viewpoint of geometric approach, TOA at any BS can form a circle, centered at the BS. The MS position is then given by the intersection of the circles from multiple TOA measurements. Similarly, a single AOA measurement constrains the MS along a line. Each of the following equations describes a circle for TOA, a line for AOA, as shown in Fig. 1.

$$\text{Circle 1-7: } (x - X_i)^2 + (y - Y_i)^2 = r_i^2, i = 1, 2, \ldots 7 \tag{8}$$

$$\text{Line 1: } \tan\theta_1 \cdot x - y = 0 \tag{9}$$

The intersections of the seven circles and a line will be concentrated near the true MS location if there is no NLOS error. However, NLOS propagation is quite common and it seriously degrades location accuracy. Thus, the intersections may not yield a single common point and will be spread over a region. The proposed methods utilize seven TOA circles and the AOA line to find all the possible intersections to locate the MS. Based on the fact that the NLOS error always appears as a positive bias in TOA measurements, the measured TOA estimated are always greater than the true values due to the excess path length. The true MS location must lie in the region of overlap of the seven circles. The intersections that are within this are defined as feasible intersections. Hence, the feasible intersections must satisfy the following inequalities simultaneously:

$$(x - X_i)^2 + (y - Y_i)^2 \le r_i^2, \ \ i = 1, 2, \ldots 7 . \tag{10}$$

The most straightforward method of estimating the MS location is to utilize these feasible intersections of the circles and the line. However, not all the feasible intersections provide information of the same value for location estimation. In order to achieve high accuracy of MS location with less effort, several better methods which we have proposed in [14] are applied in seven BSs as follows:

4.1 Distance-Weighted Method

The weights can be dynamically adjusted with reference to the distance square between the estimated MS location and the average MS location. The detailed steps are as follows:

Step 1. Find all the feasible intersections of the seven circles and a line.

Step 2. The MS location $(\bar{x}_N, \bar{y}_N)$ is estimated by averaging these remaining feasible intersections, where

$$\bar{x}_N = \frac{1}{N}\sum_{i=1}^{N} x_i \text{ and } \bar{y}_N = \frac{1}{N}\sum_{i=1}^{N} y_i . \tag{11}$$

Step 3. Calculate the distance d_i between each remaining feasible intersection (x_i, y_i) and the average location $(\overline{x}_N, \overline{y}_N)$.

$$d_i = \sqrt{(x_i - \overline{x}_N)^2 + (y_i - \overline{y}_N)^2},\ 1 \le i \le N \qquad (12)$$

Step 4. Set the weight for the ith remaining feasible intersection to $(d_i^{\,2})^{-1}$. Then the MS location (x_d, y_d) is determined by

$$x_d = \frac{\sum_{i=1}^{N} \left(d_i^{\,2}\right)^{-1} \cdot x_i}{\sum_{i=1}^{N} \left(d_i^{\,2}\right)^{-1}} \quad \text{and} \quad y_d = \frac{\sum_{i=1}^{N} \left(d_i^{\,2}\right)^{-1} \cdot y_i}{\sum_{i=1}^{N} \left(d_i^{\,2}\right)^{-1}}. \qquad (13)$$

4.2 Threshold Method

In this method, the weight for a remaining feasible intersection in the MS location estimation is determined by how many "close" remaining feasible intersections it has. The detailed steps are as follows:

Steps 1-2 are the same as those of the distance-weighted method.

Step 3. Calculate the distance $d_{mn},\ 1 \le m,\ n \le N$, between any pair of feasible intersections.

Step 4. Select a threshold value D_{thr} as the average of all the distances d_{mn}.

Step 5. Set the initial weight $I_k,\ 1 \le k \le N$, 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 6. The MS location (x_t, y_t) is estimated by

$$x_t = \frac{\sum_{i=1}^{N} I_i \cdot x_i}{\sum_{i=1}^{N} I_i} \quad \text{and} \quad y_t = \frac{\sum_{i=1}^{N} I_i \cdot y_i}{\sum_{i=1}^{N} I_i}. \qquad (14)$$

4.3 Sort Averaging Method

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

Step 4. Rank the distances d_i in increasing order and re-label the remaining feasible intersections in this order.

Step 5. The MS location $(\overline{x}_M, \overline{y}_M)$ is estimated by the mean of the first M remaining feasible intersections.

$$\overline{x}_M = \frac{1}{M}\sum_{i=1}^{M} x_i \ ,\ \overline{y}_M = \frac{1}{M}\sum_{i=1}^{M} y_i \quad (M = 0.75 * N \le N) \qquad (15)$$

4.4 Sort-Weighted Method

Steps 1-4 are the same as those of the sort averaging method.

Step 5. The MS location is estimated by a weighted average of the first M remaining feasible intersections with weight $=(d_i^{\,2})^{-1}$.

$$x=\frac{\sum_{i=1}^{M}\left(d_i^{\,2}\right)^{-1}\cdot x_i}{\sum_{i=1}^{M}\left(d_i^{\,2}\right)^{-1}}\ ,\quad y=\frac{\sum_{i=1}^{M}\left(d_i^{\,2}\right)^{-1}\cdot y_i}{\sum_{i=1}^{M}\left(d_i^{\,2}\right)^{-1}}\quad (M=0.75*N\le N) \tag{16}$$

5. SIMULATION RESULTS

Computer simulations are performed to demonstrate the performance of the proposed location scheme. We consider a center hexagonal cell (where the serving BS resides) with six adjacent hexagonal cells of the same size, as shown in Fig. 1. The serving BS, that is, BS1, is located at $(0,0)$. Each cell has a radius of 2000 m and the MS locations are uniformly distributed in the center cell [15]. 10,000 independent trials are performed for each simulation. Regarding the NLOS effects in the simulations, two propagation models are performed to assess the performance of all methods, namely, the circular disk of scatterers model (CDSM), and the uniformly distributed noise model [11].

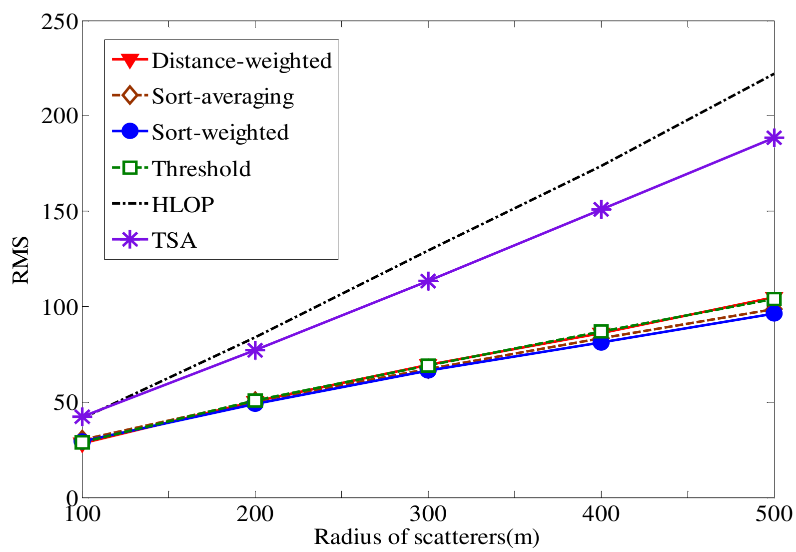

Figure 2. Average location error versus the radius of scatterers.

The CDSM assumes that there is a disk of scatterers around the MS and that signals traveling between the MS and the BSs undergo a single reflection at a scatterer. The measured AOA at the serving BS would in reality be the angle between the BS1 and a scatterer. The measured ranges are the sum of the distances between the BS and the scatterer and between the MS and the scatterer. If BS1 is the serving BS, its measurements should be more accurate. The radius of the scatterers 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. 2. As the radius of the scatterers increases, the average magnitudes of the NLOS time and angle errors increase and lead to less accurate location estimation. The performance of the different methods was measured by comparing the root-mean-square (RMS) error. The proposed hybrid TOA/AOA positioning methods still can reduce the RMS errors effectively and accurately estimate the MS location. The sensitivity of the proposed schemes with respect to the NLOS effect is not obvious. The performance degradation for the proposed methods is not pronounced than that for TSA and HLOP under harsher NLOS error conditions.

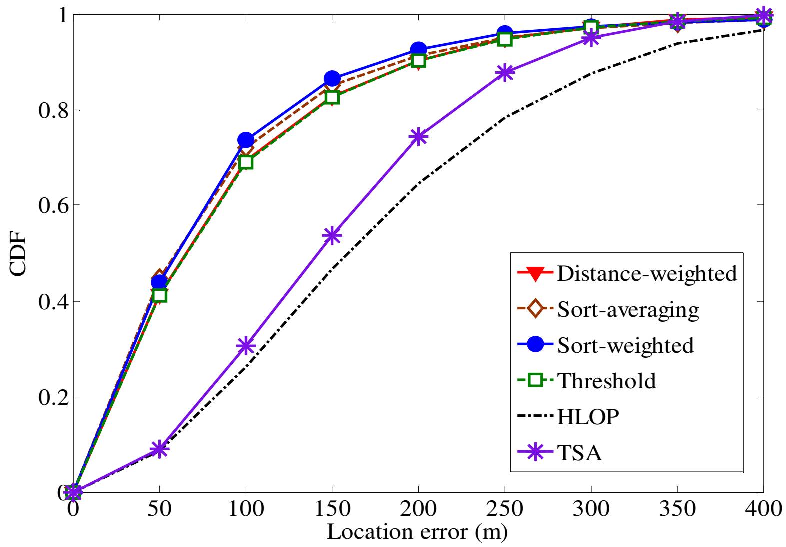

Figure 3. CDFs of the location error when CDSM is used to model the NLOS error.

Figure 3 shows cumulative distribution functions (CDFs) of the location error for different algorithms using the CDSM. The radius of the scatterers for BS1 and the other BSs were taken to be 100m and 400m, respectively. It can be obtained that HLOP gives slightly better performance than TSA. The improvement in MS location accuracy obtained using HLOP was attributed to mitigate the effects of NLOS range errors by the differencing operation. It can be seen that the proposed methods always provides much better position location estimate comparing with other existing methods for the error model considered.

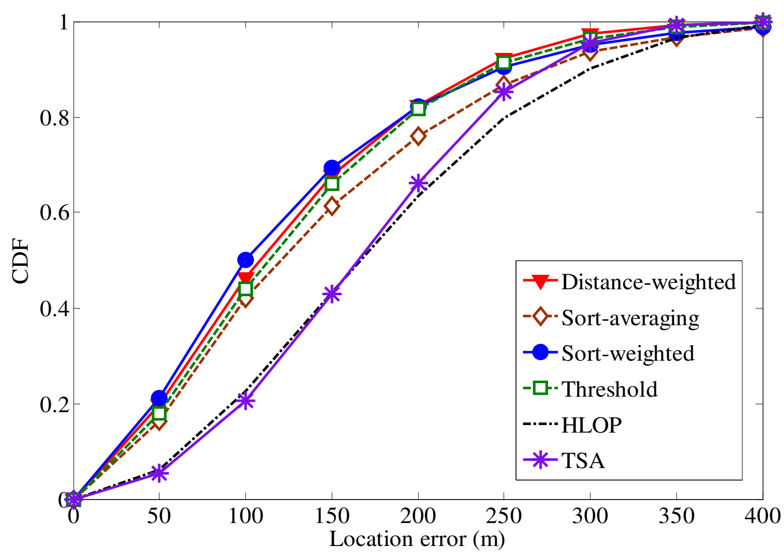

Figure 4. Comparison of error CDFs when NLOS errors are modeled as the upper bound.

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 $i = 1, 2, \ldots 7$ 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] [9]. The improvement in location accuracy using the proposed methods can also be seen in the CDF curves of the location errors, as shown in Fig. 4. The variables are chosen as follows: $U_1 = 200$ m, $U_i = 600$ m, for $i = 2, 3, \ldots 7$, and $\tau_1 = 2.5°$. It can be observed that the proposed methods can promote the location precision effectively and give better accuracy than TSA and HLOP.

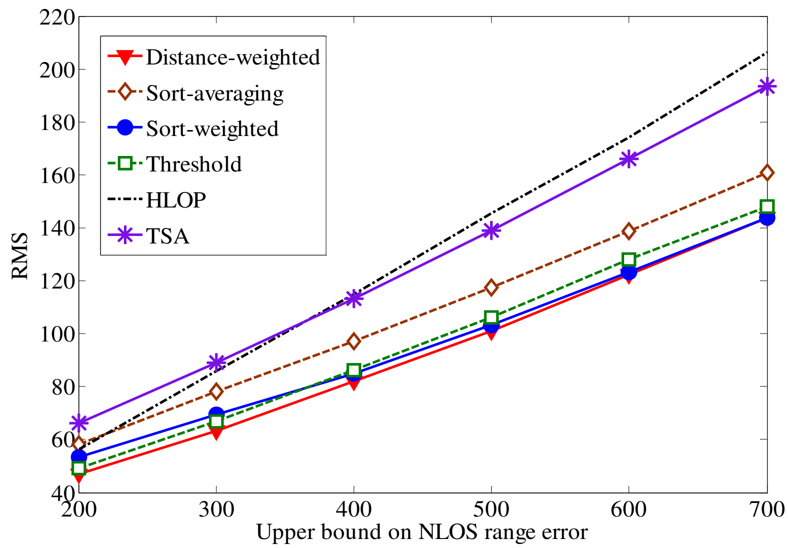

Figure 5. Performance comparison of the location estimation methods when the upper bound is used to model the NLOS.

Figure 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 are taken from 200 m to 700 m. The superior performance for the proposed method can be proved by comparing the RMS error of location prediction. Both TSA and HLOP perform worse location estimation, while the results obtained by the proposed methods have better accuracy of MS location. The sensitivity of the proposed methods with respect to the NLOS effect is much less than those of TSA and HLOP. The proposed methods still can reduce the RMS errors effectively and provide more accurate positioning.

From simulation results, it can be seen that the proposed methods with different weights perform almost equally well. However, no matter which NLOS propagation model is considered, the proposed simple geometric positioning methods can perform better than the conventional TSA and HLOP in the MS location estimation.

6. Conclusions

In this paper a class of hybrid schemes which combine TOA and AOA to estimate MS location from seven BSs. In order to eliminate NLOS errors and improve positioning accuracy, the proposed hybrid methods utilize all the possible intersections of seven TOA circles and the AOA line to locate the MS without requiring a *priori* information about the NLOS error. The proposed schemes mitigate the NLOS effect simply by the weighted sum of the intersections between three TOA circles and an AOA line. A reasonable MS location estimation can be obtained even with the existence of the NLOS errors. Numerical results are given to demonstrate the high MS location accuracy of the proposed hybrid geometrical positioning schemes. This method can acquire precise location estimation compared with the conventional TSA and HLOP regardless of the NLOS error distribution.

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