

Dilution of Position Calculation for MS Location Improvement in Wireless Communication Systems

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Abstract—Geometric dilution of precision (GDOP) represents the geometric effect of base stations (BSs) and mobile station (MS) on the relationship between measurement error and positioning determination error. When the measurement variances are equal to each other, GDOP could be the most appropriate selection criterion of location measurement units. GDOP expression has simpler form if all the measurements are with the same variance. For time of arrival (TOA) schemes, the maximum volume method of GDOP calculation doesn't guarantee the optimal selection of the four measurement units. The conventional method for calculating GDOP is to use matrix inversion to all subsets. GDOP was originally used as a criterion for selecting the right 3D geometric configuration of satellites in global positioning systems (GPS). In this paper, we employ GDOP using the matrix inversion method to select appropriate BSs in cellular communication systems. The proposed BS selection criterion performs better than using the random subsets of four or five BSs chosen from all seven BSs. After BS selection, the proposed distance-weighted method and threshold method for TOA schemes can yield superior MS location estimation accuracy. For time difference of arrival (TDOA) schemes, the proposed BS selection criterion provides better MS location estimation. From simulation results, the performances of MS location strongly depend on the relative position of the MS and BSs. Therefore, it is very important to select a subset with the most appropriate BSs rapidly and reasonably for positioning.

Index Terms—geometric dilution of precision, time of arrival, time difference of arrival, non-line-of-sight

I. INTRODUCTION

Geometric dilution of precision (GDOP) can be applied as a criterion for choosing the right geometric configuration of the measurement units such as base stations (BSs) and mobile station (MS). The smaller

value of GDOP is calculated, the better geometric configuration we have. When enough measurements are available, the optimal measurements selected with the minimum GDOP can not only eliminate the adverse geometry effects but improve the positioning accuracy. GDOP is defined under the assumption of equal pseudo-range error variance [1]. GDOP can be approximately inversely proportional to the volume of the tetrahedron formed by four satellites [2-3]. The four satellites evenly distributes with the maximum volume which gives the more accurate location estimation. The maximum volume method requires less computing time which selects a subset with maximum volume of tetrahedron to yield minimum GDOP. However, one cannot use the method because it doesn't guarantee the optimal selection of the four satellites with minimum GDOP. On the other hand, the conventional matrix inversion method can be applied to all subsets and guarantee the optimal subset.

The problem of determining the location of a MS in a wireless network has been investigated extensively in recent years. The popular schemes for estimating the location of MS include angle of arrival (AOA) [10], time of arrival (TOA) [11], and time difference of arrival (TDOA) [12] techniques. The AOA scheme utilizes an antenna array and a directive antenna to estimate the direction of arrival signal. TOA location scheme measures the propagation time for a radio wave to travel between the MS and BS. The TDOA scheme measures the time difference between the radio signals. To select the most appropriate set of BSs, which will give the minimum positioning error, GDOP effect must be considered. Poor BSs geometric configuration can lead to high GDOP and affect the accuracy of MS location. If the geometric relationship of the BSs relative to the MS is poor, the location estimation of MS performs much worse.

The global positioning systems (GPS) uses TOA of terrestrial-based positioning methods, where the TOA circle becomes the sphere in space and the fourth measurement is required to solve the receiver-clock bias for a three-dimensional (3D) solution. The bias is caused by the unsynchronized clocks between the receiver and the satellite. In practice, the time of user is significantly less accurate than an atomic clock. Therefore, measurement from a fourth satellite is employed to correct the clock bias errors present at receiver of the users end. GPS is a worldwide navigation system formed from a constellation of 24 satellites, each 11,000 nautical miles above the Earth. The GPS satellites each take 12 hours to orbit the earth. GPS satellites transmit two carrier frequencies. Typically, only one is used by civilian receivers. From the perspective of these civilian receivers on the ground, GPS satellites transmit at 1575.42 MHz using code division multiple access (CDMA) technique, which uses a direct-sequence spread-spectrum (DS-SS) signal at 1.023 MHz (Mchips/s) with a code period of 1 ms. Each satellite's DS-SS signal is modulated by a 50-bit/s navigation message that includes accurate time and coefficients (ephemeris) to an equation that describes the satellite's position as a function of time [15].

Ranging error of GPS is caused by many sources, such as the effect of ionospheric delay, tropospheric delay, date of ephemeris, satellite clock, satellite orbit, selective availability (SA) and multipath. Range and range-rate corrections are applied to the raw pseudo-range measurements in order to create a position solution that is accurate to a few meters in open environments. A method called differential GPS (DGPS), can significantly reduce these errors and enhance the accuracy of the GPS system [1]. DGPS involves the cooperation of a reference receiver whose location is known. It uses a reference receiver at a surveyed position to send correcting information to a mobile receiver over a communications link. If better position accuracy is required for certain applications, DGPS correction data must be transmitted to the MS.

The basic idea of assisted GPS (AGPS) is to establish a GPS reference network whose receivers have clear views of the sky and can operate continuously. This reference network is also connected with the cellular system architecture, and continuously monitors the real-time constellation status and provides precise data such as satellite visibility, ephemeris and clock correction, Doppler, and even the pseudo random noise code phase for each satellite at a particular epoch time. The data derived from the GPS reference network are transmitted to the mobile phone GPS receiver at the request of the MS or location-based application, to aid fast startup and to increase the sensor sensitivity. Acquisition time is reduced because the Doppler versus code phase uncertainty space is much smaller than in conventional GPS due to the fact that the search space has been predicted by the reference receiver and network. This allows for rapid search speed and for a much narrower signal search bandwidth, which enhances sensitivity and

reduces mobile receiver power consumption. Once the embedded GPS receiver acquires the available satellite signals, the pseudo-range measurements can be delivered to network-based position determination systems for position calculation or used internally to compute position in the MS [15-16].

GDOP was initially developed as a measure to help selecting the optimal geometric configuration of satellites in GPS. To select the most appropriate set of BSs and give the minimum positioning error, GDOP effect must be considered. For both TOA and TDOA schemes, in this paper we employ the subset with the minimum GDOP to determine the MS location estimation. The matrix inversion method is used to calculate GDOP value and only a subset with minimum GDOP is selected for location process. In the simulations, we only consider the subsets of four or five measurements. By using the BS selection criterion, the improvement in MS location accuracy is very obvious. Simulation results show that the proposed BS selection criterion always gives better MS location accuracy comparing with the random subsets of four or five BSs. It is enough for selecting four BSs for the compromise between completeness of data and simplification of computation. In addition, with the proposed BS selection criterion, the proposed distance-weighted method and threshold method can provide much better MS location estimation for TOA schemes.

The remainder of this paper is organized as follows. In Section II, we describe the mobile location methods for TOA schemes. The TDOA schemes are presented in Section III. Section IV briefly describes GDOP calculation for TOA and TDOA schemes. In Section V, we propose BS selection criterion. Next, Section VI compares the performance of the proposed algorithm with the other methods through simulation result. Finally, Section VII draws conclusions.

II. MOBILE LOCATION METHODS FOR TOA SCHEMES

With the proposed BS selection criterion, MS location can be estimated by the Taylor series algorithm (TSA) [4-5], linear lines of position algorithm (LLOP) [6], distance-weighted method and threshold method which we have proposed in [7].

A. Taylor Series Algorithm (TSA)

Several methods have been presented to solve the nonlinear problem. TSA is the most useful one in linearizing the non-linear equations. By measuring the propagation times of the signals traveling between the MS and various BSs, then the distances between the MS and BSs can be obtained. Let t_i denote the propagation time from the MS to BS i and the corresponding distances can be expressed as

$$r_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2}, \quad i = 1, 2, \dots, 7 \quad (1)$$

where (x, y) and (X_i, Y_i) are the locations of the MS and BS i , respectively. 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 MS location can be estimated by linearizing the TOA equation using Taylor's series expansion and neglecting the higher order terms.

$$r_i \cong r_{vi} + a_{i1}\delta_x + a_{i2}\delta_y \tag{2}$$

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

$$a_{i1} = \left. \frac{\partial r_i}{\partial x} \right|_{x_v, y_v} = \frac{x - X_i}{r_i}, \quad a_{i2} = \left. \frac{\partial r_i}{\partial y} \right|_{x_v, y_v} = \frac{y - Y_i}{r_i}.$$

δ_x, δ_y are respectively, coordinate offset of x, y .

The linearized TOA equations can be expressed in matrix form as

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

where $z = \begin{bmatrix} r_1 - r_{v1} \\ r_2 - r_{v2} \\ \vdots \\ r_i - r_{vi} \end{bmatrix}$, $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \vdots & \vdots \\ a_{i1} & a_{i2} \end{bmatrix}$, $\delta = \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix}$, and

$$r_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2}.$$

The vector variable δ in Eq. (3) can be solved as follows

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

Calculation starts with an initial guess for the MS location, and update this value iteratively until the magnitude of δ below a given threshold value. This method is recursive and the computational overhead is intensive. It requires a proper initial position guess close to the true solution, and convergence is not guaranteed [4-5].

B. Linear Lines of Position Algorithm (LLOP)

The new geometrical interpretation makes use of LLOP to replace the circular LOP for estimating the MS location [6]. The line which passes through the intersections of the two circular LOPs for two TOA measurements can be found by squaring and subtracting the distances obtained by Eq. (1) for $i = 1, 2$ and can be expressed as

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

The MS location is identified by

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

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

$$G = \begin{bmatrix} X_1 - X_2 & Y_1 - Y_2 \\ X_1 - X_3 & Y_1 - Y_3 \\ \vdots & \vdots \\ X_1 - X_i & Y_1 - Y_i \end{bmatrix} \text{ and}$$

$$h = \frac{1}{2} \begin{bmatrix} r_2^2 - r_1^2 + (X_1^2 + Y_1^2) - (X_2^2 + Y_2^2) \\ r_3^2 - r_1^2 + (X_1^2 + Y_1^2) - (X_3^2 + Y_3^2) \\ \vdots \\ r_i^2 - r_1^2 + (X_1^2 + Y_1^2) - (X_i^2 + Y_i^2) \end{bmatrix}.$$

Hence, the solution to Eq. (6) can be obtained by

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

C. Proposed Distance-Weighted Method and Threshold Method

From the viewpoint of geometric approach, TOA value measured at any BS can be used to form a circle, centered at the BS. The MS position is then given by the intersections of the circles from multiple TOA measurements. In order to achieve high accuracy with less effort, the distance-weighted method and threshold method proposed in [7] can be applied to determine MS.

III. MOBILE LOCATION METHODS FOR TDOA SCHEMES

For TDOA approach, TSA [4] and least square (LS) method [13] are used to determine the MS location.

A. Taylor Series Algorithm (TSA)

TDOA measurement is obtained from subtracting two TOA measurements. The range difference between the i th BS and BS1 can be expressed as

$$r_{i1} = r_i - r_1 = \sqrt{(x - X_i)^2 + (y - Y_i)^2} - \sqrt{(x - X_1)^2 + (y - Y_1)^2} \tag{8}$$

Equation (8) into Taylor series and retaining the first two terms produce

$$r_{i1} \cong r_{vi1} + b_{i1}\delta_x + b_{i2}\delta_y \tag{9}$$

where $r_{vi1} = \sqrt{(x_v - X_i)^2 + (y_v - Y_i)^2} - \sqrt{(x_v - X_1)^2 + (y_v - Y_1)^2}$,

$$b_{i1} = \frac{\partial r_{i1}}{\partial x} = \left(\frac{x - X_i}{r_i} - \frac{x - X_1}{r_1} \right), \quad b_{i2} = \frac{\partial r_{i1}}{\partial y} = \left(\frac{y - Y_i}{r_i} - \frac{y - Y_1}{r_1} \right).$$

The linearized TDOA equations can be described by

$$\gamma \cong B\delta \tag{10}$$

where $\gamma = \begin{bmatrix} r_{21} - r_{v21} \\ r_{31} - r_{v31} \\ \vdots \\ r_{i1} - r_{vi1} \end{bmatrix}$, $B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ \vdots & \vdots \\ b_{i1} & b_{i2} \end{bmatrix}$.

The MS location is obtained through the use of a TSA expansion and the solution to Eq. (8) can be obtained by

$$\delta = (B^T B)^{-1} B^T \gamma. \tag{11}$$

B. Least Square Method (LS)

By squaring Eq. (1), we can obtain the following equations

$$(x - X_i)^2 + (y - Y_i)^2 = r_i^2 \tag{12}$$

$$(x - X_i)^2 + (y - Y_i)^2 = r_i^2 = (r_{i1} + r_1)^2, \quad i = 2, 3, \dots, 7 \quad (13)$$

Subtracting the Eq. (12) from Eq. (13) result in

$$E\delta = F \quad (14)$$

where $E = \begin{bmatrix} X_2 - X_1 & Y_2 - Y_1 \\ X_3 - X_1 & Y_3 - Y_1 \\ \vdots & \vdots \\ X_i - X_1 & Y_i - Y_1 \end{bmatrix},$

$$F = \frac{1}{2} \begin{bmatrix} (X_2^2 + Y_2^2) - (X_1^2 + Y_1^2) - r_{21}^2 - r_{21} \cdot r_1 \\ (X_3^2 + Y_3^2) - (X_1^2 + Y_1^2) - r_{31}^2 - r_{31} \cdot r_1 \\ \vdots \\ (X_i^2 + Y_i^2) - (X_1^2 + Y_1^2) - r_{i1}^2 - r_{i1} \cdot r_1 \end{bmatrix}.$$

The LS solution for TDOA scheme is [13]

$$\delta = (E^T E)^{-1} E^T F \quad (15)$$

IV. CALCULATION OF GDOP FOR TOA AND TDOA SCHEMES

GDOP was initially developed as a criterion to select the optimal 3D geometric configuration of satellites in GPS. High GDOP describes a situation in which a relatively small ranging error can result in a large position location error. GDOP is a task of choosing the appropriate measurement units, which results in a better geometric configuration and the more accurate position estimate. In order to improve the positioning accuracy, we should minimize GDOP among the selected measurement units. In the range measurements, the accuracy varies with the error, as well as the relative positions of the MS and BSs. If the measurement errors are uncorrelated and have equal variances, GDOP can be defined as [14]

$$GDOP = \sqrt{\text{trace}(H^T H)^{-1}}. \quad (16)$$

The geometry matrix for TOA schemes and TDOA schemes are

$$H = \begin{bmatrix} \partial r_1 / \partial x & \partial r_1 / \partial y & 1 \\ \partial r_2 / \partial x & \partial r_2 / \partial y & 1 \\ \vdots & \vdots & \vdots \\ \partial r_i / \partial x & \partial r_i / \partial y & 1 \end{bmatrix}, \text{ and } H = \begin{bmatrix} \partial r_{i1} / \partial x & \partial r_{i1} / \partial y \\ \partial r_{i2} / \partial x & \partial r_{i2} / \partial y \\ \vdots & \vdots \\ \partial r_{ij} / \partial x & \partial r_{ij} / \partial y \end{bmatrix},$$

respectively.

V. PROPOSED BS SELECTION CRITERION

To select the most appropriate set of BSs, which will give the minimum positioning error, GDOP effect must be considered in cellular communication systems. When enough measurements are available, the optimal measurements selected with the minimum GDOP can prevent the poor geometry effects, thereby improving the MS location accuracy. The excessive measurement increases the computational load and can not improve the location accuracy. To further reduce the computational

overhead and improve location performance, the selection of optimal measurement units is necessary.

In general, the subset with smallest GDOP provides more accurate MS location results. We use a set of four or five BSs selected among seven to estimate MS location in cellular communication systems, as shown in Fig.1. Those BSs are the ones with the minimum GDOP. The proposed BS selection criterion is as follows: Select n measurements among seven BSs to generate different subset, there are divided into $C(7, n)$ measurement subsets. GDOP is computed for all subset and the subset which gives the smallest GDOP is selected. Finally, n measurement units of this subset are used to find out the MS location solution.

VI. SIMULATION RESULTS

This section is used to demo how to improve the performance of the MS location estimate. 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. Each cell has a radius of 1 km and the MS location is uniformly distributed in the center cell [8]. The serving BS, that is, BS1, is located at (0, 0). Different methods based on GDOP to select the best subset of four or five BSs are applied to estimate the MS location. The dominant error for wireless location systems is usually due to the non-line-of-sight (NLOS) propagation effect. The NLOS propagation model is based on the circular disk of scatterers model (CDSM) [9]. The measured ranges are the sum of the distances between the BS and the scatterer and between the MS and the scatterer.

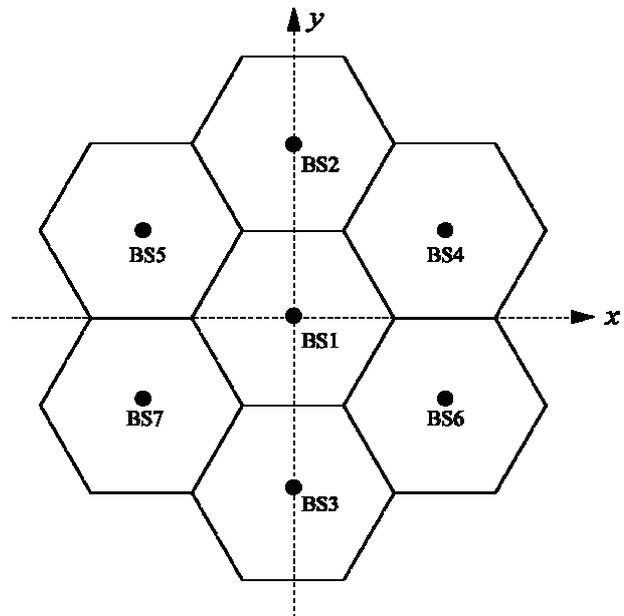


Figure 1. Seven-cell system layout in cellular communication systems.

Based on the above BS selection criterion, the most straightforward location method employs the BSs with minimum GDOP to estimate the MS location. To give a comparison of different subsets, Fig. 2 provides the root mean square (RMS) error varies as the radius of CDSM.

Four BSs selected randomly with poor geometry perform can extremely degrade the performance of location estimation and the accuracy of mobile location. In order to eliminate the poor geometry effects, the selecting BSs with minimum GDOP criterion can be used and the optimal geometric configuration with four measurements is obtained.

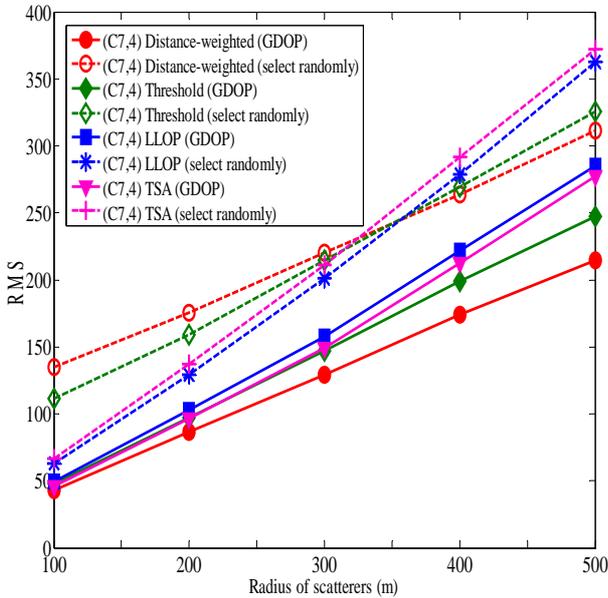


Figure 2. Average location error versus the disc radius of CDSM.

Figure 3 was applied to examine the performances of the proposed BS selection criterion and the subset selecting five BSs randomly when the radii of CDSM are varied. The subset with minimum GDOP always provides much better location estimation than the other subsets with five BSs taken randomly regardless of the different methods.

Figure 4 compares the results of the subset with minimum GDOP and using all seven BSs method. The radius of the scatterers of CDSM is assumed to be 100 m. The larger the number of the selected BSs, the more accurate the positioning is. By using LLOP, distance-weighted method and threshold method, the positioning precision of using all seven BSs are slightly better than those of the minimum GDOP subsets with five BSs. For TSA, the optimal subset with five BSs gives the nearly equal level of performance as using all seven BSs method. From simulation results, it is enough to select four BSs for the best geometry to reduce the positioning error quietly.

In TDOA schemes, the NLOS propagation model is based on the uniformly distributed noise model [5], in which the TOA measurement error is assumed to be uniformly distributed over $(0, U_i)$, for $i = 1, 2, \dots, 7$, where U_i is the upper bound. The improvement in MS location estimation by using the proposed BS selection criterion can be seen in Fig. 5. It can be seen that LS performs better than TSA method. Thus even four BSs are randomly selected with relatively poor accuracy, but the

geometric configuration between BSs and MS can affect the positioning accuracy seriously.

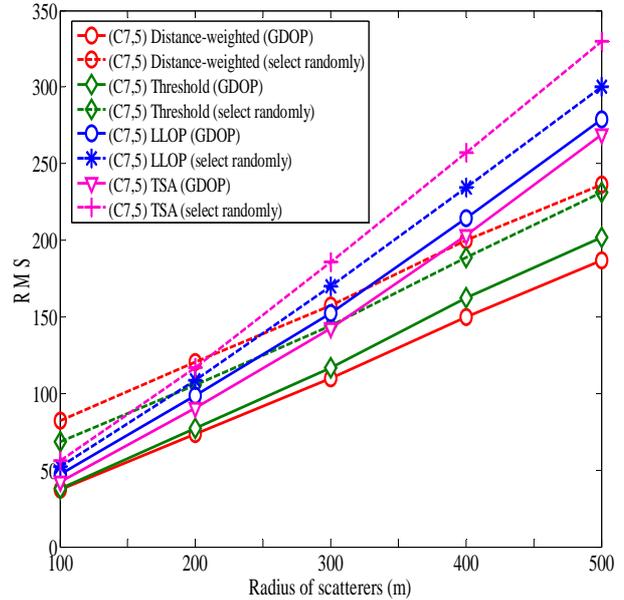


Figure 3. Comparison of RMS errors when NLOS errors are modeled as CDSM.

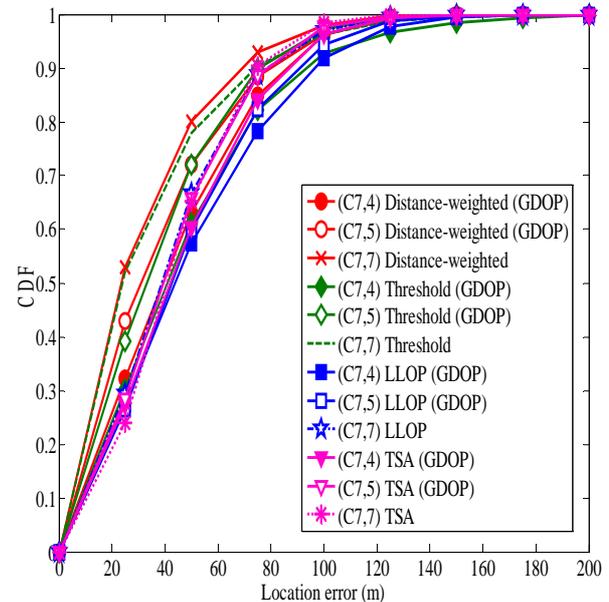


Figure 4. Comparison of location error CDFs using all seven BSs and the subset with minimum GDOP.

Figure 6 shows how the average location error is affected by NLOS errors. The superior performance for the proposed BSs criterion has been demonstrated by comparing the RMS error. Five randomly selected BSs with poor geometry yield bad location estimation and the proposed BSs criterion can provide more precise location estimation even in severe NLOS conditions.

Figure 7 shows the CDF of the average location error with the minimum GDOP subset and using all seven BSs method. The upper bound of NLOS error is chosen as 300 m. If more BSs are involved in the subset, these

methods can give better location performance improvement. Both the minimum GDOP subset with five BSs and using all seven BSs method provide a comparable level of accuracy in MS location estimation.

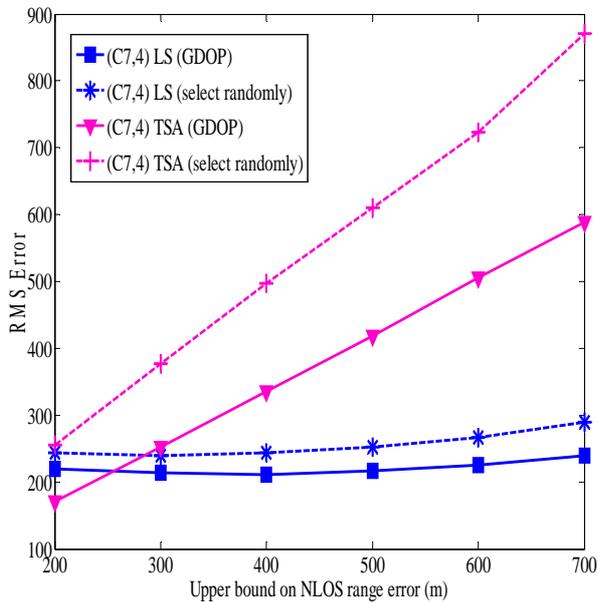


Figure 5. Average location error versus the upper bound of NLOS errors.

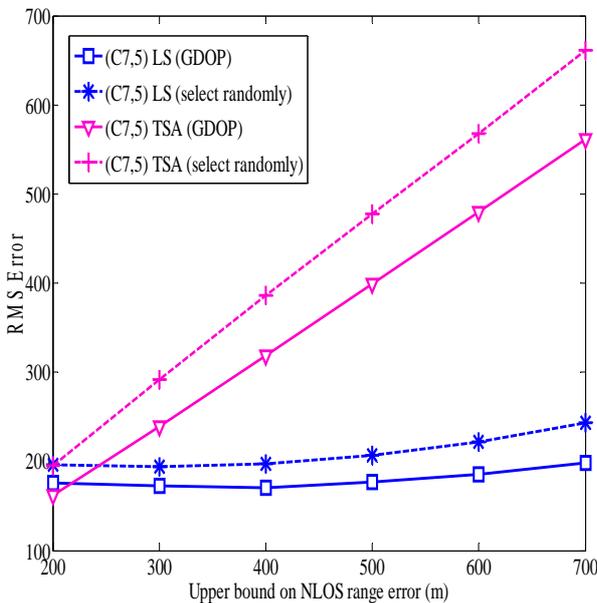


Figure 6. Performance comparison between the location estimation methods in which the measurement errors are assumed to be uniformly distributed.

VII. CONCLUSIONS

To eliminate the poor geometry influence and improve the positioning accuracy, the minimum GDOP subset can be used to estimate the location of MS in cellular communication networks. In this paper and the simulation results, only four or five BSs with best geometry among seven BSs are chosen to determine MS

location. It can be seen that the subset with minimum GDOP for predicting MS location can provide better degree of accuracy.

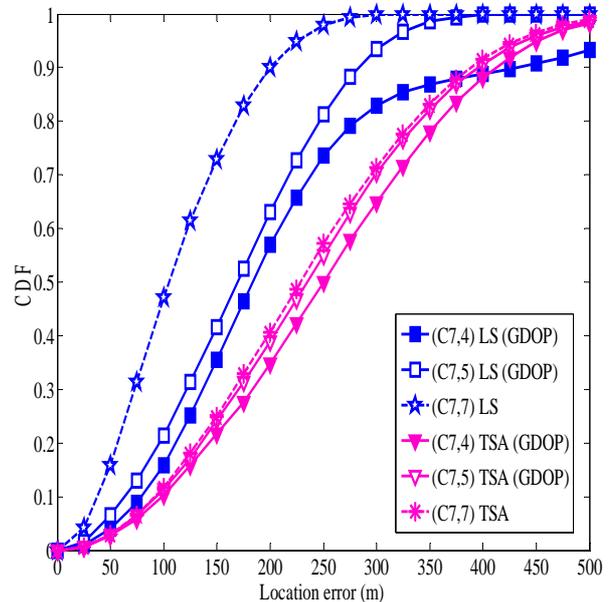


Figure 7. Comparison of error CDFs between the subset with minimum GDOP and using all seven BSs.

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