Proceedings of the 2009 IEEE 9th Malaysia International Conference on Communications
15 -17 December 2009 Kuala Lumpur Malaysia

Improved Weighting Algorithm for NLOS Radiolocation

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Abstract— **Non-Line-of-Sight (NLOS) propagation is a major problem facing accurate radiolocation using Time-of-Arrival (TOA) measurements in wireless communication systems. Weighting is among the important NLOS mitigation approaches whereby the system attempts to localize with both Line-of-Sight (LOS) and NLOS measurements, but provides scaling to minimize the effects of the NLOS contributions. In this paper, we present an improved weighting location algorithm that utilizes the geometrical feature of cell layout and TOA range measurements from three base stations (BSs). The MS location is estimated using weighted ranges that produce special points, called potential points. Simulations studying the performance of the proposed algorithm for different NLOS error models show that the proposed algorithm performance is notably better than traditional algorithms, even under highly NLOS conditions.**

***Index Terms*— Non-Line-of-sight (NLOS), mobile radiolocation, time-of-arrival (TOA), localization, NLOS weighting, scaling NLOS.**

I. INTRODUCTION

The need for radiolocation of mobile stations (MSs) is increasing rapidly in wireless cellular systems and sensor networks. In network-based radiolocation, MSs could be located by measuring the signal parameters (i.e. signal strength, angle of arrival (AOA), time of arrival (TOA) and time difference of arrival (TDOA)) traveling from the MS to a set of cellular BSs. Out of these approaches, TOA approach is found to be the most preferred and widely deployed technique for mobile radiolocation in wireless cellular networks (since it doesn't need any additional hardware equipment). Our focus in this paper will be centered on providing some enhancements for accurate MS location estimation using TOA measurements in the presence of non-line-of-sight (NLOS) propagation impairments.

Location error can be introduced to the TOA-based positioning process in different ways. The equipment that is used to measure signal parameters limits the accuracy that can be achieved by a given radiolocation algorithm. Even with perfect measurements, error could still result from the propagation channel over which signals must travel before being measured by the BS equipment. In this regard, the main sources of radiolocation error in wireless communication systems include multipath propagation, non-line-of-sight propagation (NLOS), and multiple access interference. Steps must be taken to mitigate these impairments to improve the location accuracy [1],[2].

Out of the three main sources of error, NLOS propagation in TOA-based radiolocation is found to be a critical issue [2]. NLOS propagation pertains to the scenario where the direct (or LOS) path between the MS and the BS is blocked by some structures like buildings. With NLOS propagation, the signal arriving at the BS from the MS is reflected or diffracted and takes a path that is longer than the direct path. As an indication of the impact of this problem, the typical ranging error introduced by NLOS propagation in practical GSM networks can average between 500-700 meters [3].

There are different approaches that have been proposed in the literature to mitigate NLOS error in TOA-Based radiolocation. Some of these approaches are similar to matched field processing for radiolocation [4]. By measuring the propagation characteristic of the channel, the location of MS can be estimated using predetermined scattering models of the location environment. However, because of the rapidly changing physical environments in urban areas, it is difficult to obtain accurate models, which constitutes a severe limitation for this technique.

The second approach is classification or LOS re-construction. Classification attempts to identify LOS measurements and locate the MS with only those measurements. Identification may be based on a time-history hypothesis test [5]; maximum likelihood detection [6]; or other probabilistic models [7], [8]. One limitation of this approach is that there is always the possibility of wrong identification.

The third approach uses all available measurements (i.e., both LOS and NLOS) to locate the MS. Minimizing the

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effects of the NLOS contributions is achieved by providing proper weighting or scaling of the available measurements. The weighting is derived either from the radiolocation geometry and cell layout, as the Range Scale Algorithm (RSA) presented in [9], or from the residuals of individual BS [10].

This paper considers the third approach. Particularly, we propose a weighting algorithm that only needs three range measurements, and does not identify NLOS from LOS BSs. The proposed algorithm analyses the geometrical features of the cell layout and TOA range measurements, from three base stations, and estimates the mobile location by searching over all weighted ranges that produce special points, called potential points. This approach can be applied to any system based on TOA range measurements or ranging techniques for which the measured range is greater than the true range. The simulation results demonstrate that the proposed algorithm is significantly more effective in radiolocation accuracy than the RSA [9] and the Linear Lines of Positions (LLOP) algorithm [11].

In the remaining part of the paper, we introduce the system model in Section II and review the localization algorithms and NLOS models in Section III. The proposed weighting algorithm is detailed in Section IV. The simulation results are presented in Section V, followed by conclusions in Section VI.

II. System Model

We consider a wireless network topology with a given mobile station (MS) of interest and several serving base stations (BSs). The MS is located at $\mathbf{\Theta}=(x, y)$, and its signal is received at three different BSs located at (x_i, y_i), where i=1,2,3. Signal propagation speed is assumed to be the speed of light, $c = 3\times10^8$ m/s. All BSs have the same time reference and full synchronization is assumed. The true distance between the MS and the i^{th} base station (BS_i) is given by

$$R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}\ , \quad i = 1,2,3 \tag{1}$$

and the measured distance is

$$l_i = c \times TOA_i \tag{2}$$

where TOA_i is the one way propagation time between the MS and the BS_i. The network layout consists of three BSs. This model is illustrated in Fig. 1. The coordinates for the given distribution of BSs and MS are summarized in Table 1.

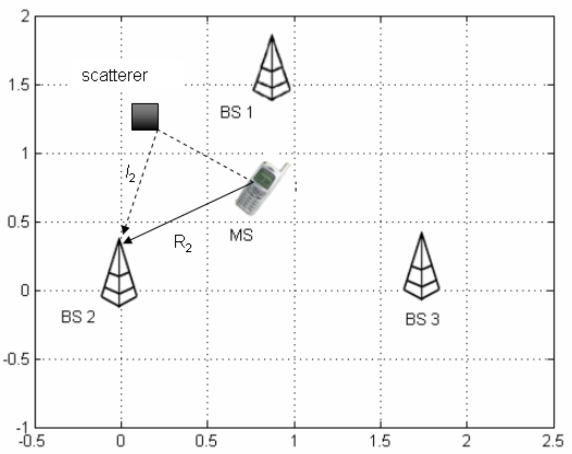

Fig. 1 NLOS Propagation and BSs Distribution

TABLE I
LOCATION OF MS AND BSS

BS #	x-coordinate (km)	y-coordinate (km)
1	0.866	1.5
2	0	0
3	1.732	0
MS	0.8	0.75

III. Localization Algorithms and NLOS models

Given the system model, there are different techniques to estimate the MS position. The maximum likelihood algorithm is optimal but it is complicated and requires statistical information about TOA measurements. Suboptimal localization techniques as linear line of position (LLOP) [11] and Least Squares (LS) [12] that do not need any probabilistic assumptions about the time measurements can be used. In the LLOP method, linear lines of positions are used to estimate the location of the MS, as shown in Fig. 2. The three circles are circular lines of positions. The intersections of two circles define two points through which the linear line of position is drawn, shown with dotted lines. The estimated MS location using LLOP algorithm is the intersection point of the two straight lines. The LS solution presented in [12] is the estimated MS location $\mathbf{\Theta}$ that minimizes J, where

$$J = \sum_{i=1}^{N} (l_i - R_i)^2 \tag{3}$$

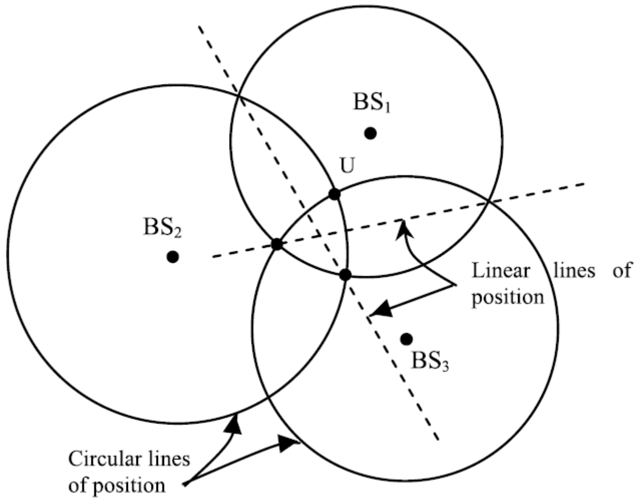

Fig. 2 The geometry of location showing circular and linear lines of position

The added NLOS error molded as a positive independent and identically distributed (i.i.d.) random variable. For simulation purposes, different scattering models that produce different NLOS error distributions can be used. Depending on the location environment used in the radiolocation system, one of these models is used to generate the NLOS error in performance evaluation simulations. NLOS error is usually modeled by assuming a certain distribution for the scatterers. In this paper, we have considered the most important and widely used ones, namely: the Disk of Scatterers (DOS), Reversed Disk of Scatterers (RDOS), and the uniformly distributed model [13].

In the next section, the proposed weighting algorithm is described.

IV. THE PROPOSED WEIGHTING ALGORITHM

Using the system model, the TOA measurements determine true ranges R_i which can be written in terms of the measured ranges l_i as

$$R_i = \alpha_i l_i \tag{4}$$

where, for NLOS propagation, $0 < \alpha_i \leq 1$. The values of α_i are restricted since the NLOS error is a large positive bias that causes the measured ranges to be greater than the true ranges. It is assumed that the BSs equipments measurements error is a zero-mean Gaussian random process with relatively small standard deviation and that its effect is negligible if the measured ranges are averaged over few seconds. It is also negligible as compared to the NLOS error. Squaring the range in (1) and substituting (4) results in

$$\alpha_i^2 l_i^2 = (x - x_i)^2 + (y - y_i)^2, \quad i = 1, 2, 3 \tag{5}$$

For simplification and development in the following derivations, we define

$$K_i = x_i^2 + y_i^2, \quad i = 1, 2, 3 \tag{6}$$

The proposed weighting algorithm utilizes the circle equations (5) and the boundaries of α_1, α_2, and α_3 to find all possible weighted ranges that produce special points, defined as potential points.

In the following subsections, the boundaries of α_1, α_2, and α_3 are presented. Then, calculations of potential points are presented. Finally, steps to estimate the MS location using the proposed algorithm are summarized.

A. Boundaries of α_1, α_2, and α_3

In order to decrease the computing time of potential points, we bound α_1, α_2, and α_3 to omit the non-significant calculations. Because the NLOS error is always positive, the measured ranges are greater than the true ranges and the MS location must lie in the region of overlap of the range circles (region enclosed by U, V, W) as shown in Fig. 3. The details of finding the boundaries of α_1, α_2, and α_3 are given in [9]. The bound on α_1 is given by

$$\begin{aligned} \alpha_{1,\min} &= \max\{1 - \frac{\overline{AB}}{l_1}, 1 - \frac{\overline{EF}}{l_1}\} \\ &= \max\{\frac{L_{12} - l_2}{l_1}, \frac{L_{13} - l_3}{l_1}\} \end{aligned} .$$

Similarly, the lower bounds on α_2 and α_3 are given by

$$\alpha_{2,\min} = \max\{\frac{L_{12} - l_1}{l_2}, \frac{L_{23} - l_3}{l_2}\}$$

and

$$\alpha_{3,\min} = \max\{\frac{L_{13} - l_1}{l_3}, \frac{L_{23} - l_2}{l_3}\}$$

where L_{12}, L_{13}, and L_{23} are defined as shown in Fig. 3.

B. Calculation of the potential points

The potential points can be computed using the weighted circles equations. These equations are written as follows:

$$(x - x_1)^2 + (y - y_1)^2 = \alpha_1^2 l_1^2 \tag{7}$$

$$(x - x_2)^2 + (y - y_2)^2 = \alpha_2^2 l_2^2 \tag{8}$$

$$(x - x_3)^2 + (y - y_3)^2 = \alpha_3^2 l_3^2 \tag{9}$$

Subtracting (8) and (9) from (7), we can respectively obtain the linear equations of S_{12} and S_{13}, as shown in Fig. 4 and Fig. 5.

$$S_{12}: \ 2(x_2 - x_1)x + 2(y_2 - y_1)y = \alpha_1^2 l_1^2 - \alpha_2^2 l_2^2 - K_1 + K_2$$

$$S_{13}: \ 2(x_3 - x_1)x + 2(y_3 - y_1)y = \alpha_1^2 l_1^2 - \alpha_3^2 l_3^2 - K_2 + K_3$$

Calculating the intersection point of those two lines using LLOP localization algorithm results in,

$$\mathbf{\Theta} = \mathbf{F}^{-1}\mathbf{q}$$

where

$$\mathbf{F} = \begin{bmatrix} 2(x_2 - x_1) & 2(y_2 - y_1) \\ 2(x_3 - x_1) & 2(y_3 - y_1) \end{bmatrix}$$

$$\mathbf{q} = \begin{bmatrix} \alpha_1^2 l_1^2 - \alpha_2^2 l_2^2 - K_1 + K_2 \\ \alpha_1^2 l_1^2 - \alpha_3^2 l_3^2 - K_1 + K_3 \end{bmatrix}$$

$$\mathbf{\Theta} = \begin{bmatrix} x \\ y \end{bmatrix}$$

If the intersection point of S_{12} and S_{13} linear equations is on the circles formed by BS_i and $\alpha_i l_i$ (i=1,2 and 3), this point is defined as potential point as shown in Fig. 5.

C. Estimation of the MS location

In the following, steps that summarize the estimation of the MS location using the proposed algorithm are listed.

1. Given the measured distances and the BSs positions, the lower boundaries of the weighting factors α_1, α_2, and α_3 are computed in order to define all allowable combinations of the weighting factors. Then, for all allowable combinations of the weighting factors, steps 2 to 3 are done.
2. Weighting factors are used to define the weighted circles equations (7)-(9) and the linear equations of S_{12} and S_{13}.
3. The intersection point of the two lines S_{12} and S_{13} is computed. If the intersection point lies on the weighted circles (i.e. satisfies circles equations (7)-(9)), that point is a potential point. If the intersection point is not on the weighted circles as shown in Fig. 4, discard these weighting factors and repeat step 2 after updating the weighting factors. Note that there should be a small numerical tolerance to assume that the circles interest in a point rather than a region.
4. The optimal MS location is the mean value of the MS locations estimated as all potential points.

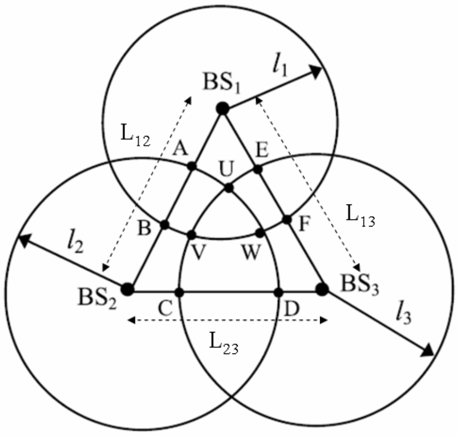

Fig. 3 Geometry of TOA-based location showing measured range circles and the region of overlap in which the MS lies

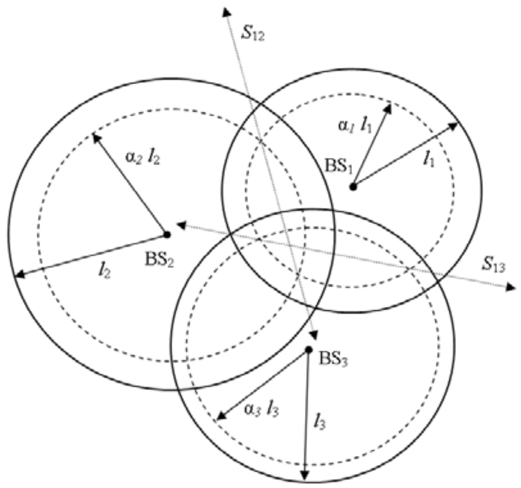

Fig. 4 The geometry of the three circular equations formed by BS_i and $\alpha_i l_i$ (i=1,2 and 3) with intersection which is not a potential point

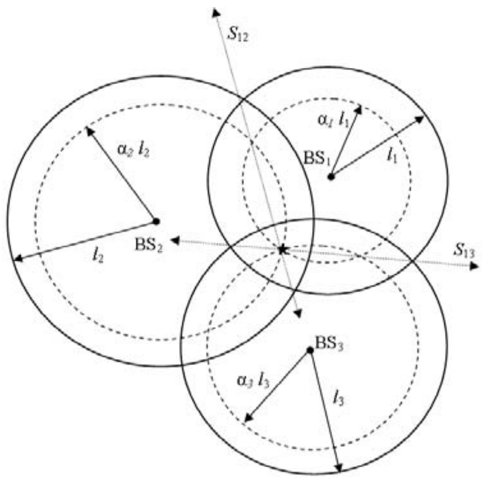

Fig. 5. The geometry of the three circular equations formed by BS_i and $\alpha_i l_i$ (i=1,2 and 3) with intersection forming a potential point

V. Simulations and Discussion of Results

In this section, simulation results based on the proposed weighting algorithm are shown and discussed. The performance of the proposed algorithm is examined and compared to the RSA and the un-weighted LLOP algorithm. The effect of varying different parameters (i.e. NLOS distribution, number of NLOS BSs and the magnitude of the NLOS error) on radiolocation performance using the proposed algorithm is investigated.

A. Performance under Different NLOS Environments

Using the cell layout shown in Fig.1, the performance of the proposed algorithm was examined and compared to the RSA and the un-weighted LLOP algorithm using different NLOS models (i.e. DOS, RDOS and Uniform models). The NLOS range errors in these simulations were modeled as positive random variables having support over $0 \leq \eta_i \leq 0.4$

km. For the DOS and RDOS models, the radius of scatterers R_d was considered 0.2 km and for the Uniform model, the lower bound, *LB,* was considered 0 while the upper bound, *UB,* equals to 0.4 km. It is assumed that the effect of the BSs equipments measurements error is negligible as compared to the NLOS error. By computing 1000 independent location trials, Fig. 6 shows the CDF plots of the average radiolocation error of the proposed weighting algorithm compared to the RSA and the un-weighted LLOP algorithm. It can be seen that the proposed algorithm is superior compared to both the RSA and the un-weighted one. Using RDOS NLOS error model, the radiolocation error of the proposed algorithm is less than 150 m for 80% of the time, while it is less than 58% and 35% of the time for the RSA and un-weighted LLOP algorithm, respectively. In addition, it is clear that the CDF plots of the proposed weighting algorithm are almost identical. This observation shows that the proposed weighting algorithm is applicable for all NLOS error models considered in the simulations.

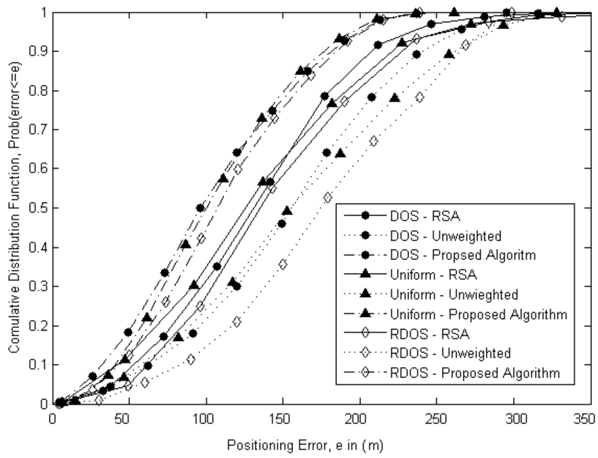

Fig. 6. CDF plots of the average radiolocation error for different NLOS models

B. Effect of Magnitude of NLOS on Radiolocation Accuracy

Another way to reflect the improved performance of the proposed weighting algorithm is to show its performance when the magnitude of the NLOS error is varied. Using Uniform NLOS model and by varying the upper bound of the NLOS error *UB* (where *LB*=0), it is evident from Fig. 7 that the proposed weighting algorithm shows its excellent performance compared to the other algorithms. This excellent performance becomes obvious with the small average radiolocation error compared to the RSA and the un-weighted algorithm. Moreover, it is clear from the same figure that the proposed algorithm is less sensitive to increases in maximum NLOS magnitude compared to the RSA and the un-weighted algorithm and that proves its excellent performance even in very harsh NLOS environments.

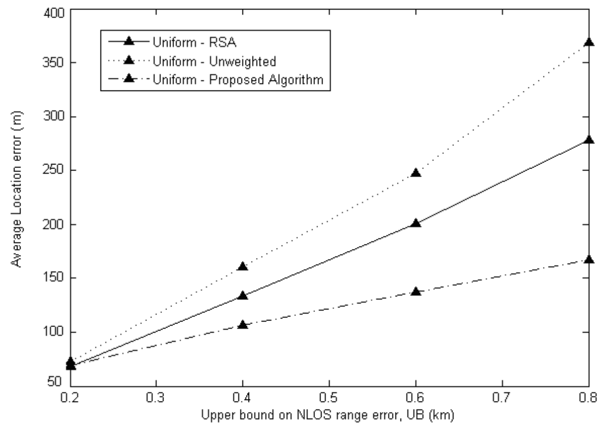

Fig. 7 Average radiolocation error vs. the upper bound on Uniform NLOS model

C. Effect of the Number of NLOS BSs

Simulations were performed to study how the average radiolocation error is affected by the number of NLOS BSs when the proposed algorithm is employed and compared to RSA and the un-weighted LLOP algorithm.

As expected, it is observed from Fig. 8 that the average radiolocation error increases with the number of NLOS BSs using all considered algorithms. It is also clear that the performance of the proposed algorithm is always better than the RSA and the un-weighted LLOP algorithm. For all considered algorithms, the average radiolocation error decreases slightly when all BSs are NLOS as compared to the case when two BSs are NLOS. This can be attributed to the geometric error cancellation, where the added NLOS bias is directional and can cancel out in some scenarios when the NLOS BSs surrounds the MS.

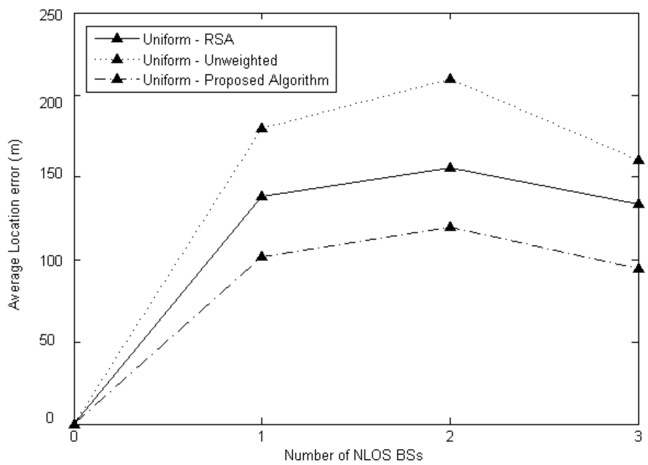

Fig. 8 Average radiolocation error vs. number of NLOS BSs

VI. CONCLUSION

The radiolocation of an MS can have significant errors when NLOS measurements are present. A new weighting algorithm was proposed and implemented. The proposed algorithm utilizes the geometrical feature of the cell layout and TOA range measurements when range measurements are available from three base stations BSs. The MS location is estimated using weighted ranges that produce special points, called potential points. Simulations studying the performance of the proposed algorithm for different NLOS error models showed that the performance is much better than the RSA and the un-weighted LLOP algorithm even under highly NLOS conditions.

ACKNOWLEDGMENT

The authors would like to thank King Fahd University of Petroleum & Minerals (KFUPM) for supporting this research.

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