SUMMARY To achieve more accurate measurements of the mobile station (MS) location, it is possible to integrate many kinds of measurements. In this paper, we propose several simpler methods that utilize time of arrival (TOA) at three base stations (BSs) and the angle of arrival (AOA) information at the serving BS to give location estimation of the MS in non-line-of-sight (NLOS) environments. From the viewpoint of geometric approach, for each a TOA value measured at any BS, one can generate a circle. Rather than applying the nonlinear circular lines of position (LOP), the proposed methods are much easier by using linear LOP to determine the MS. Numerical results demonstrate that the calculation time of using linear LOP is much less than employing circular LOP. Although the location precision of using linear LOP is only reduced slightly. However, the proposed efficient methods by using linear LOP can still provide precise solution of MS location and reduce the computational effort greatly. In addition, the proposed methods with less effort can mitigate the NLOS effect, simply by applying the weighted sum of the intersections between different linear LOP and the AOA line, without requiring priori knowledge of NLOS error statistics. Simulation results show that the proposed methods can always yield superior performance in comparison with Taylor series expansion linear LOP and the AOA line, without requiring priori knowledge of NLOS error statistics. Simulation results show that the proposed methods can always yield superior performance in comparison with Taylor series expansion linear LOP and the AOA line, without requiring priori knowledge of NLOS error statistics.

key words: time of arrival (TOA), angle of arrival (AOA), non-line-of-sight (NLOS)

1. Introduction

The need for determining the location of mobile station (MS) is becoming increasingly important in wireless cellular communication systems. It is always desirable to achieve the higher accuracy in location applications as possible. There are several fundamental approaches for determining MS location including signal strength, angle of arrival (AOA), time of arrival (TOA), and time difference of arrival (TDOA) techniques. The accuracy of MS location estimation highly depends on the propagation conditions of the wireless channels. The propagation signals in wireless location systems are usually corrupted by additive noise, multipath propagation, multiple access interference, and line-of-sight (LOS) blockage. Many procedures are necessary to reduce the effects of impairments. The dominant error for wireless location systems is usually due to the non-line-of-sight (NLOS) propagation effect. High accuracy can be achieved in location estimation if LOS propagation exists between the MS and each participating BS. However, in practice LOS paths are not always available, especially in urban or suburban areas. Due to the extra path length traveled by the reflection or refraction of the signal between the MS and the BSs, NLOS propagation can introduce a bias in time-based measurements, even when multipath is absent and when high-resolution techniques are used.

The NLOS propagation will heavily degrade the precision of MS location estimation. Therefore, it is very important to reduce and mitigate the effects of NLOS propagation. In the past few years, extensive research on NLOS-effect mitigation for location estimation has been carried out.

To enhance the precision of location estimation, it is reasonable to consider hybrid methods of integration two or more schemes. In [1] Sprito proposed the combination of TDOA and TOA, and showed that it is better than pure TDOA on the location estimation in GSM systems. If two BSs can provide both TOA and AOA measurements simultaneously, we have proposed the geometrical positioning methods utilizing the intersection of two circles and two lines to estimate MS location [2]. In addition, we expanded the methods in [2] to locate MS when three BSs are available for location purposes [3]. TOA measurements from three BSs and the AOA information at the serving BS can be used to give a location estimate of the MS. These methods can provide much better accuracy but with higher complexity, because the related circle equations are nonlinear.

To further reduce the computational complexity, the linear lines of position (LOP) formed by the intersection points of two circles is employed to replace the circular LOP for estimating the MS location in this paper. This technique is more simple than applying nonlinear circle LOP. Due to NLOS error, the MS may be located at various intersections of different LOP and AOA line. The proposed positioning methods have the advantage of simpler computation of MS location. These methods are based on the weighted sum of the feasible intersections of three LOP and the AOA line when three BSs are available. Simulation results show that the proposed methods always perform better than Taylor series algorithm (TSA) [4], [5] and the hybrid lines of position.
algorithm (HLOP) [6].

The rest of this paper is organized as follows. Section 2 describes the positioning methods by using TSA and HLOP. Section 3 introduces numerous approaches that use the intersections of various linear LOP and the AOA line to estimate the position of MS. Section 4 applies the simulations to evaluate the algorithms and analyze the results obtained. Finally, conclusions are drawn in Sect. 5.

2. Taylor Series Algorithm (TSA) and Hybrid Lines of Position Algorithm (HLOP)

If both the TOA and AOA measurements are accurate, only one BS is required to locate the MS [2]. In reality, TOA and AOA measurements contain errors due to NLOS propagation. Since the NLOS errors would seriously degrade location accuracy, so more than one BS is required for MS location of reasonable accuracy. Let \( t_i \) denote the propagation time from the MS to BS\( i \), the distances between BS\( i \) and the MS can be expressed as

\[
r_i = c \cdot t_i = \sqrt{(x - X_i)^2 + (y - Y_i)^2}
\]

where \( c \) is the propagation speed of the signals, \((x, y)\) is the MS location, and the coordinates of BS\( i \) are given by \((X_i, Y_i)\). We assume that BS\( 1 \) is the serving BS, and let \( \theta \) be the angle between MS and its serving BS, which is defined as:

\[
\theta = \tan^{-1}\left(\frac{y - Y_1}{x - X_1}\right)
\]

2.1 Taylor Series Algorithm (TSA)

TOA and AOA measurements are inputs to the Taylor series position estimator when three BSs are available. The Taylor series approach can achieve high accuracy, but requires an initial location guess. TSA may suffer from the convergence problem if the initial guess is not accurate enough [4], [5].

2.2 Hybrid Lines of Position Algorithm (HLOP)

The geometrical interpretation is presented in this section for which the linear LOP, rather than the circular LOP, are proposed to determine the position of the MS [7]. The hybrid linear LOP and AOA measurement (HLOP) algorithm is proposed in [6].

3. Proposed Hybrid TOA/AOA Methods

In the TOA approach, the distance between an MS and a BS is measured by finding the propagation time between an MS and a BS. Geometrically, TOA measurement generates a circle and the MS lie on a circle centered at the BS. Using the circles produced by TOA measurements at multiple BSs, the MS location can be found at the intersections of circles. The AOA method utilizes antenna arrays or directive antennas to estimate the direction of arrival of the signal. A single AOA measurement constrain the MS along a line. 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. The equations of the three TOA circles and the AOA line used in location estimation can be expressed as

\[
\text{Circle 1: } x^2 + y^2 = r_1^2
\]

\[
\text{Circle 2: } (x - X_2)^2 + y^2 = r_2^2
\]

\[
\text{Circle 3: } (x - X_3)^2 + (y - Y_3)^2 = r_3^2
\]

\[
\text{Line 1: } \tan \theta \cdot x - y = 0
\]

We have proposed the methods that employ the intersections of three TOA circles and the AOA line to estimate the MS location in [3]. These methods can achieve high accuracy of MS location, but the computational complexity is more intensive.

The complexity can be much reduced for solving the intersection of two linear lines rather than two nonlinear circles. Replacing conventional circular LOP, the linear LOP equation passes through the intersections of the two linear can be used in our proposed methods. The line which passes through the intersections of the two circular LOP, be found by squaring and subtracting the distances obtained by Eq. (1) for \( i = 1, 2, 3 \), can be expressed as

\[
L_{12}: X_2 x = \frac{1}{2}(r_1^2 - r_2^2 + X_2^2)
\]

\[
L_{13}: X_3 x + Y_3 y = \frac{1}{2}(r_1^2 - r_2^2 + X_3^2 + Y_3^2)
\]

\[
L_{23}: (X_3 - X_2) + Y_3 y = \frac{1}{2}(r_2^2 - r_3^2 + X_2^2 + Y_3^2 - X_2^2)
\]

Calculating the intersections of the three LOP and AOA line produced the MS location estimate. Under the assumption of LOS propagation and there exists no measurement error, the intersections of thee LOP and AOA line are at the same point. However, it is very often that the LOS does not exist for propagation of signals between an MS and some fixed BSs. Therefore, the NLOS effect could cause the three LOP and AOA line to intersect at various points, which will be offset from the true MS location. With NLOS propagation, the measured TOA values are always greater than the true TOA values due to the excess path length. The true MS location should be inside the region, enclosed by the overlap of the three circles. The intersections that are within this region are defined as feasible intersections. The feasible intersections must satisfy the following inequalities simultaneously:

\[
x^2 + y^2 \leq r_1^2
\]

\[
(x - X_2)^2 + y^2 \leq r_2^2
\]

\[
(x - X_3)^2 + (y - Y_3)^2 \leq r_3^2
\]

In order to enhance the performance of MS location estimation with less complexity, the hybrid TOA/AOA methods are proposed, which integrate three linear LOP and AOA line to find all the feasible intersections to determine the MS location. The weight of the feasible intersections can...
be determined by our proposed methods, such as distance-weighted method, sort-averaging, sort-weighted and threshold method. Please refer to [2] and [3] for details of these methods. These methods are much less difficult since there is no need to compute the intersections of circles. The complexity and computation load can be reduced to find the solution of two linear line equations rather than nonlinear circle ones.

4. Simulation Results

Assuming no knowledge of the NLOS errors in advance, computer simulations are performed to demonstrate the performance of the proposed location scheme. A number of 10,000 independent trials are performed for each simulation. The coordinates of the BSs are set to BS1: (0, 0), BS2: (1732 m, 0), and BS3: (866 m, 1500 m) [8]. The MS location is chosen randomly in accordance with a uniform distribution within the region formed by the points BS1, I, J, and K shown in Fig. 1. Regarding the NLOS effects in the simulations, three different propagation approaches were used to model the measured ranges and angle, the circular disk of scatterers model (CDSM) [8], [10], distance-dependent model [8] and the uniformly distributed noise model [8].

The first NLOS propagation model considers a CDSM [8], [10] and the radius of the scatterers for three BSs is considered to be 200 m. Figure 2 shows cumulative distribution function (CDF) of the location error for different methods applying circular LOP and linear LOP, respectively. The positioning precision of using circular LOP is only slightly better than that by applying linear LOP.

To compare the computational complexity, we have to measure the computing time of different methods with nonlinear circular LOP and linear LOP. Table 1 shows the average time for calculating 10,000 independent trials process. The computing time using circular LOP is more than three times than that by using linear LOP. Calculating the intersections of the circles brings large amount of computation. These results suggest that the linear LOP can be computationally efficient for MS location estimation.

Figure 3 provides the root mean square (RMS) error versus the radius of the CDSM. As the radius increases,
the NLOS error increase which leads to less accurate location estimation. To compare with TSA and HLOP, the performance degradation of the proposed methods is not pronounced for large NLOS errors. Thus the proposed methods help to obtain a more accurate MS location approximation.

The second NLOS propagation model is based on the distance-dependent NLOS error model [8]. The NLOS range error for the i-th range is taken to be $\xi_i = \chi_i \cdot R_i$, where $\chi_i$ is a proportional constant and $R_i$ is the true range between i-th BS and MS. The AOA measurement error is assumed to be $f_i = w \cdot \tau_1$, where $\tau_1 = 5^\circ$ and $w$ is a uniformly distributed variable over $[-1, 1]$ [9]. Figure 4 shows how the average location error is affected by the proportional constant. HLOP performs worse, but not as bad as the TSA under harsher NLOS error conditions. When the NLOS situation gets worse, both TSA and HLOP provide relatively poor estimation performance.

In addition, Fig. 5 shows the CDF of the average location error of different algorithms with distance-dependent NLOS error for $\chi_i = 0.13$. Because of the different operation principle, HLOP can cancel the part of the squared NLOS errors. One can see that HLOP gives better performance than TSA. But the proposed methods can give much better location estimation as compared with the other existing algorithms.

The third NLOS propagation model is based on the uniformly distributed noise model [8], in which the TOA measurement error is assumed to be uniformly distributed over $(0, U_i)$, where $U_i$ is the upper bound. The AOA measurement error is assumed to be $f_i = w \cdot \tau_1$, where $\tau_1 = 5^\circ$ [9]. Figure 6 illustrates the performance comparison of these location estimation methods. As expected, the location error increases with the upper bound of the uniform NLOS error. The superior MS location prediction for the proposed hybrid TOA/AOA method still can reduce the RMS errors.
effectively and estimate the MS location accurately.

The BS1 serving a particular MS is called the serving BS which can provides more accurate measurements. The variables of this model are chosen as follows: \( U_1 = 200 \) m, \( U_2 = 600 \) m, \( U_3 = 600 \) m, and \( \tau_1 = 5^\circ \). Figure 7 shows CDF of the average location error of different algorithms for the cases when the range errors were using the uniformly distributed noise model. The distance-weighted method provides the best results, followed by the threshold method. In the distance-weighted method, all of the feasible intersections will affect the location of MS. The sort averaging method and sort-weighted method do not consider the influence of these feasible intersections which are too far from the average MS location. Owing to the role of every feasible intersection is essential, hence distance-weighted method has the best performance. Furthermore, the performance of the proposed method is significantly better than TSA and HLOP.

5. Conclusions

In this paper we presented several hybrid location methods by using one AOA measurement together with the TOA measurements to get improved MS location estimation. The traditional geometrical approach for computing MS location is to solve for the intersections of the circular LOP. However, in this paper, the linear LOP is derived to reduce the complexity. Although the proposed methods may offer location accuracy slightly lesser than applying the circular LOP. However, calculating the intersections of the circles brings large amount of computation. Simulation results show the calculation time of using linear LOP is much less than employing circular LOP. Based on the NLOS situation and without the knowledge of NLOS error statistics in advance, the proposed hybrid methods utilize all the feasible intersections of three linear LOP and the AOA line to locate the MS accurately and efficiently. The proposed methods mitigate the NLOS effect simply by applying the weighted sum of the intersections between different linear LOP and the AOA line. The proposed methods consistently achieves the better performance than the conventional TSA and HLOP in the MS location estimation, regardless the NLOS propagation model. Simulation results demonstrate that the accurate MS location estimate of the proposed methods is possible even in severe NLOS conditions.

References