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Wireless Signal Map Matching for NLOS error mitigation in mobile phone positioning

Binghao Li, Andrew G. Dempster, Chris Rizos, Joel Barnes
School of surveying and spatial information system, UNSW, Australia
Tel: 61-02-93854190 Fax: 61-02-93137493 Email: binghao.li@student.unsw.edu.au

Hyung Keun Lee
School of Electronics, Telecommunication & Computer Engineering, Hankuk Aviation University, Korea

Presenter
Andrew G. Dempster

ABSTRACT

Angle of arrival (AOA), time of arrival (TOA) and time difference of arrival (TDOA) are widely used for mobile phone positioning. However, these measurements experience degradation of location accuracy due to localised non-line-of-sight (NLOS) signal propagation, especially in urban or suburban area. NLOS error is well known to be a major source of error in mobile phone positioning and is simply caused by buildings blocking the line-of-sight propagation of the RF signal. Hence mobile station (MS) appears further away from the base transceiver station than it actually is. This significantly increases the positioning error. To mitigate the effects of NLOS error in terrestrial wireless location systems, a wireless signal map-matching (WSMM) concept was recently introduced. WSMM is based on using a database method to generate the NLOS error correction map, and then use the correction map to correct the measurements. Therefore, a more accurate MS location can be estimated. Furthermore, WSMM can automatically extract the relationship between an electronic map representing the ideal world and the fully-populated anonymous user distribution representing distorted world. After the concept was verified by simulation, an experiment was carried out in a typical suburban area. The test result shows the proposed database method based on universal kriging can improve the accuracy of position estimate using the TDOA technique if the reference points can be identified.

KEYWORDS: mobile phone positioning, TDOA, NLOS error, database

1. INTRODUCTION

Utilizing mobile phone networks for positioning has been a hot research topic since the end of 1990's. It is well known that the basic Cell ID technique has been deployed around the world, but the method does not meet most of the requirements for applications in location-based services (LBS). Much attention has been focused on the signal time delay and angle of arrival measurements. Generally, approaches based on signal time delay (time-of-arrival (TOA) or time-difference-of-arrival (TDOA) etc.) and angle-of-arrival (AOA) measurement can greatly improve the accuracy of position determination. Unfortunately the main shortcoming of these methods is that they require line-of-sight (LOS) propagation for accurate location estimates. However, non-line-of-sight (NLOS) error is the dominant error in location estimation (Caffery and Stüber, 1998) in urban or suburban area where people are more interested in the mobile user's (MU) location. Figure 1 shows how the NLOS error problem occurs. When direct signal paths between handset and base transceiver station (BTS) are mostly obstructed by buildings and other structures, alternate, reflected paths dominate. These paths are longer, affecting TDOA and TOA methods, and arrive from a different direction, affecting AOA. TDOA and TOA NLOS errors are always positive, i.e. the path is longer, but range from a small number to thousands of meters (Silventoinen and Rantalainen, 1996; Woo et al., 2000), depending on the propagation environment. Li (1998) studied the effect of NLOS error on the performance of AOA technique in position estimation. The study shows when a NLOS condition is presented for only one BTS, the estimation error of AOA technique increases 10 times or so.

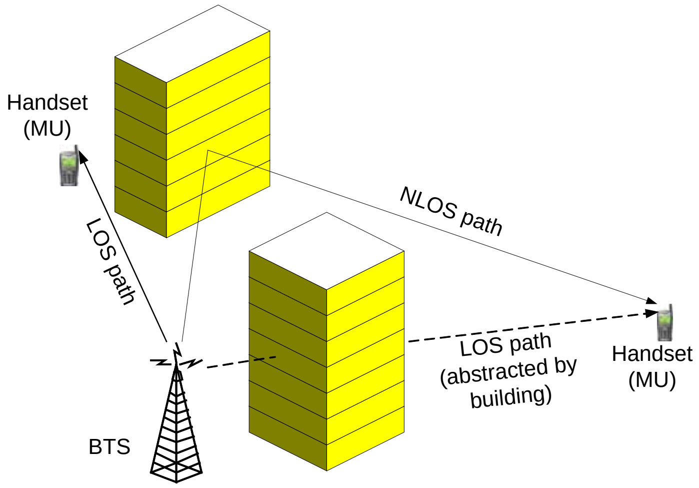


Figure 1 LOS path and NLOS path, how NLOS error occurs

To mitigate position estimates from NLOS error corruption, different approaches have been investigated. In (Morley and Grover, 1995), the authors used an algorithm based on the probability density function (pdf) model to reduce the NLOS error. However, it is difficult to formulate the pdf, and this function should vary with the changing environment. A general method use to mitigate the NLOS error is error identification and reconstruction. Wylie and Holtzman (1996) explained, by using the time history of the range measurements in a simple hypothesis test, and exploiting the knowledge of the standard deviation of the standard measurement noise, one can determine if the measurements correspond to a LOS or NLOS environment. A two-step LOS reconstruction was proposed. First the data was smoothed by N^{th} order polynomial fit, then the knowledge of the standard measurement noise was utilized to correct the NLOS error. Similarly, Woo et al. (2000) identify the NLOS from the range characteristic and reconstruct the LOS ranging using a Kalman filter. While in (Cong and Zhuang, 2001), the NLOS BTS detection was based on an assumption that if a large NLOS error exists for a particular BTS, on the average the residual will be large in magnitude. This requires redundant measurements. Furthermore, in (Cong and Zhuang, 2004), two approaches were proposed to detect the NLOS error depending on how much a priori information is available. An NLOS State Estimation algorithm could be used with some prior information on NLOS errors available from an empirical database. In the case with no knowledge of NLOS, an improved residual algorithm could be applied to detect a small number of NLOS BSs (treating NLOS corrupted measurements as outliers and rely solely on the knowledge of Gaussian measurement noise). Another approach consists of exploiting the redundant information present in the measurements to detect and reject the NLOS errors. The main contribution in this direction was presented in (Chen, 1999) where the problem was formulated in terms of hypotheses, where each hypothesis corresponded to a set of BS considered under NLOS scenarios. The algorithm presented there was based on a weighted combination of the partial position estimates associated to each hypothesis. A well-known category of NLOS error mitigation method is constrained optimization method. This method is to exploit the property that the NLOS errors are always positive errors, then to search the true position by adding some constraints such as penalty function in (Caffery and Stuber, 1998). In (Wang et al., 2003), mathematical programming is used to find the ML (maximum-likelihood) estimate of the source position in the restricted domain defined by the inequalities induced due to NLOS propagation.

Unfortunately, none of these methods can solve the NLOS problem adequately, since too many elements affect the signal propagation, and the propagation environment varies from place to place. Especially in urban or suburban areas, NLOS propagation is common for radio frequency (RF) signal. Often, only 1 or 2, even none of the signals from BTSs (or MS) can propagate in LOS scenario. The NLOS error mitigation is a classic problem, which could be solved using a basic database method. In this method, the NLOS error can be directly extracted from the reference measurements at the reference points, and logged in a database for further usage. Jayaraman et al. (2000) describe methods for collecting data to create the database. But the data collection and database maintenance is quite a costly and laborious process. To solve this problem and effectively mitigate the NLOS error, a wireless signal map-matching (WSMM) concept was recently introduced. WSMM can automatically extract the relationship between an electronic map representing the ideal world and the fully populated anonymous user distribution representing distorted world. Then a NLOS error correction map can be generated based on the spatial correlation. The correction map can be used to correct the measurements. Therefore, a more accurate MS location can be estimated. As using TDOA measurement for positioning has many advantages, the WSMM will be discussed here base on it.

2. HYPERBOLIC POSITIONING ALGORITHMS

TDOA measurement multiplying speed of light gives the range difference measurement. The range difference measurement determines a hyperbola with the two BTSs as foci. Generally, two TDOA measurements, which need at least three BTSs, can determine the transmitter's location, that is, the intersection of the two hyperbolas.

Assume that there are M BTSs distributed arbitrarily in a 2-D plane. Consider the TDOAs with respect to the first BTS which is the one communicating with the handset and normally (but not necessarily) is the closest one to the handset.

$$\tau_{i1} = \tau_i - \tau_1, i = 2,3,\ldots,M \tag{1}$$

Let $\tau = [\tau_{21}, \tau_{31}, \ldots, \tau_{M1}]^T$ be the estimated TDOA vector. TDOA between receivers *i* and *j* are computed from

$$\tau_{ij} = \tau_{i1} - \tau_{j1}, i = 2,3,\ldots,M \tag{2}$$

Let the source (handset) be at unknown position (*x*, *y*). The BTSs' locations (x_i, y_i) are known. The distance between source and BTS_i is

$$\begin{aligned} r_i &= \sqrt{(x_i - x)^2 + (y_i - y)^2} \\ &= \sqrt{x_i^2 + y_i^2 - 2x_i x - 2y_i y + x^2 + y^2} \ , i = 2,3,\ldots,M \end{aligned} \tag{3}$$

if c is the speed of light, then,

$$\begin{aligned} r_{i1} &= c\tau_{i1} = r_i - r_1 \\ &= \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \ , i = 2,3,\ldots,M \end{aligned} \tag{4}$$

define a set of nonlinear equations whose solution gives the location of the source (*x*, *y*).

However, solving the nonlinear equations (4) is not trivial. A substantial amount of work has been done in solving this problem. The widely used algorithms are the Taylor-series method, Fang's method and Chan's method. Taylor-series method was introduced in (Foy, 1976). It is an iterative method, starts with an initial guess, and improves the estimate at each step using least-squares (LS). This method can provide a precise position estimate at reasonable noise levels and has been commonly employed. The disadvantage of this method is the risk of divergence during the processing, and the computation burden. Fang's method (Fang, 1990) gives an exact solution when the number of TDOA measurements is equal to the number of unknowns, but it cannot use redundant measurements. Chan's method (Chan and Ho, 1994) provides the exact solution and also takes advantage of redundant measurements. Furthermore it approaches the CRLB (Cramer-Rao lower bound). However, both Fang's method and Chan's method occasionally suffer from the ambiguities' problem (there are 2 results, but only one is the reasonable estimate, discussed in detail later), and if the TDOA measurements are contaminated by noise or other errors (say NLOS error), these methods have some difficulties to provide the location. It has been evidenced by our simulation and experiment that the Taylor-series method can work well when TDOA measurements are seriously contaminated by NLOS error and noise. Further more, Taylor-series method is more flexible comparing with other methods. As the PC is becoming more and more powerful, the computation burden is no longer a serious problem. Hence, Taylor-series method was chosen to estimate the MS's position in our research.

3. WIRELESS SIGNAL MAP MATCHING

Since terrestrial wireless location systems enables a large amount of sampling with respect to multiple users at different locations, fully populated user distribution, though distorted by the NLOS error, has become practically possible. The key idea of WSMM is to extract NLOS-induced position error and each measurement's NLOS error by comparing the geometric features of the distorted user distribution with those of the ideal map. As a result, the proposed WSMM has two attractive advantages in mitigating NLOS error. One is that it does not require additional network element installation and the other is that it eliminates human effort for surveying field data with special instruments.

The purpose of WSMM is to create a correction map (CMAP) which can be used to correct the NLOS error. The whole procedure of WSMM is shown in Figure 2.

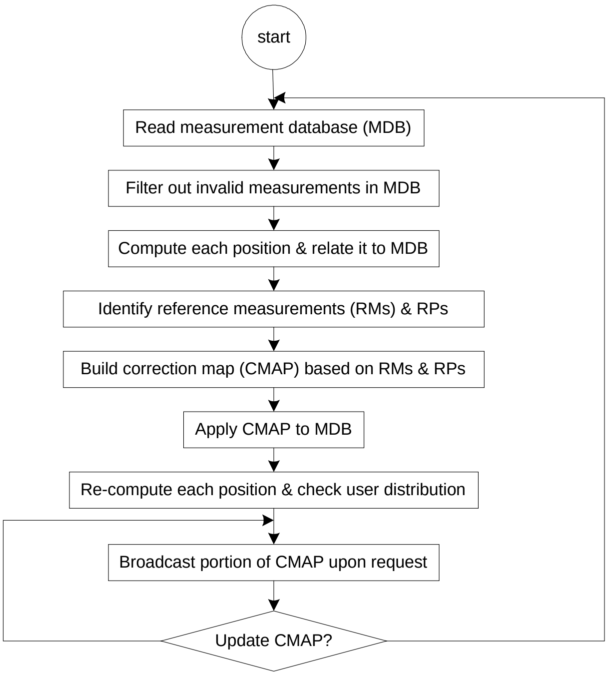


Figure 2 Block diagram for the whole procedure of WSMM

3.1 Measurement Database

The most important prerequisite for the proposed WSMM is the construction of measurement database (MDB). The MDB can be constructed by sampling the measurements from a handset within the area of interest by core network infrastructure shown in Figure 3. The function of WSMM server could be also accomplished by GMLC (Gateway Mobile Location Centre). The sampled measurements are filled into a data structure that is designed for efficient MDB management. Figure 4 shows a typical data structure for MDB construction. The data fields are categorized into user index, handset model, time index, location-related network measurements, and any LBS-related variables for which a spatial-temporal or a statistical surface map is desired. The location-related network measurements may comprise one or more of TDOA, TOA, AOA, transmitted signal strength (TSS), frequency-of-arrival (FOA), received signal strength (RSS), and signal-to-noise ratio (SNR) etc.

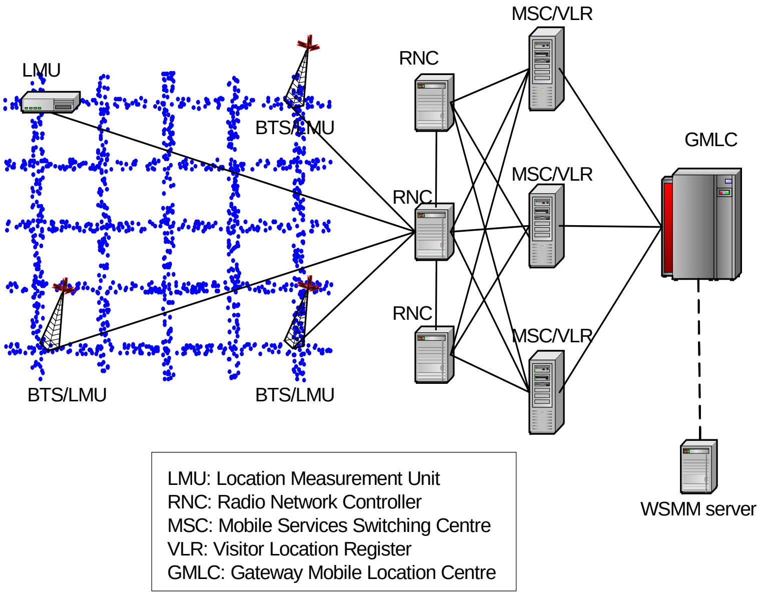


Figure 3 Core network infrastructure for terrestrial wireless location systems

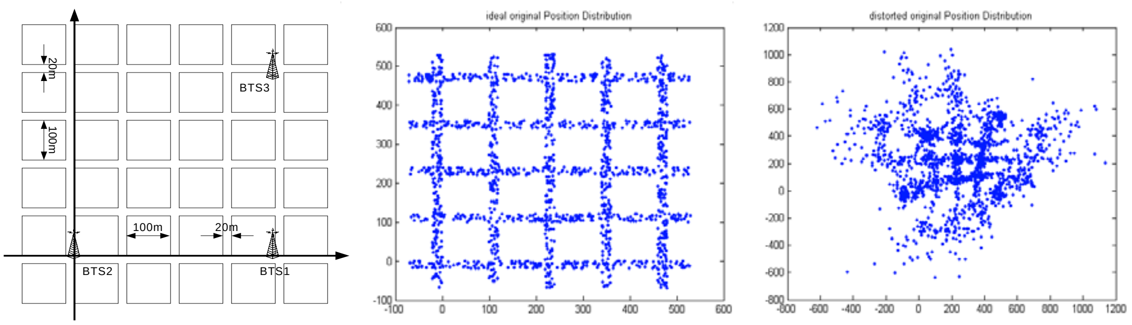
Alias for privacy (arbitrary index number)	I(1)	I(2)	…	I(Nb)
Handset model				
Time index				
TDOA(1:Nb-1)				
TOA(1:Nb)				
AOA(1:Nb)				
TSS(1:Nb)				
RSS(1:Nb)				
SNR(1:Nb)				
Variables to be analyzed on either distorted or corrected spatial-temporal domain				
Temporary Results				

Figure 4 Data structure for measurement database

3.2 Reference Measurement Extraction

Reference measurement extraction is obviously the key aspect of WSMM. Acquiring the references automatically can greatly support the database method (Li et al., 2005).

The uncompensated NLOS errors in sampled measurements generate biased position estimates which constitute distorted user distribution. Figure 5 shows an example in typical Manhattan-like urban environment. To recover the distorted distribution to the ideal distribution, some form of reference information is required. In WSMM, the reference information is formed by two techniques. One is measurement characteristic classification and the other is map feature extraction. The utilization of measurement characteristic classification is relatively simple. For this purpose, signal strength (SS) value of each MDB element is checked compared to a pre-defined threshold value. According to the Hata-Okumura model (Hata, 1980), SS value describes the distance between any transmitter and receiver with good accuracy if they are sufficiently adjacent so that there is no obstruction for the LOS condition. Thus, the measurement set which has the maximum SS with respect to one BTS means that they are sampled near that BTS. In these measurement sets, the effects of NLOS error would be small and their sampled position would approximately equal that of the corresponding BTS.



a *b* *c*

Figure 5 (a) Manhattan-like urban environment, (b) Ideal MU position distribution and (c) distorted MU position distribution

Usually, the amount of reference information provided by the measurement characteristic classification would be not sufficient for NLOS error mitigation. To provide a sufficient amount of reference information, map features should be extracted. If we consider a simple map that consists of nodes and links, any feasible map-matching techniques can be applied with respect to nodes, links, and node-link combined geometry (White, 2000). Dense urban areas are mostly composed of road junctions, road segments, and buildings, where road junctions are stored as nodes and road segments are stored as links. Though any map feature is useful as reference information, a road junction is the easiest feature for map matching.

To extract reference measurements by map features, two maps are utilized, an ideal map (IMAP) and a feature map (FMAP). The IMAP is used as the reference information for WSMM. Thus, it should accurately represent the real world and usually includes the coordinates of BTSs, buildings, and geometric features such as road junctions and links (refer to Figure 5). The FMAP is a 3-dimensional surface map based on distorted user distribution computed by the MDB. The z-values (e.g. the height) of FMAP represent the degree of confidence of their corresponding xy-positions as feature areas. For example, the higher the z-value is, the more possible its xy-position corresponds to a map feature (Lee et al, 2005).

Many candidates may be utilized as the FMAP, including a population surface (refer to Figure 6), a DOP surface utilizing user points within a specific radius, and any possible measure surface that expresses the similarity between local user distributions with feature area patterns. In Figure 6, a typical FMAP representing a smoothed population surface is illustrated where the z-values corresponding to the distorted road junction locations show local maxima. By comparing the xy-positions of road junctions stored in the IMAP and the xy-positions with local maximum z-values in the FMAP, the distorted positions of road junctions are identified. For each identified xy-position of the FMAP, several measurement sets in the MDB can be found that corresponds to its neighbourhood.

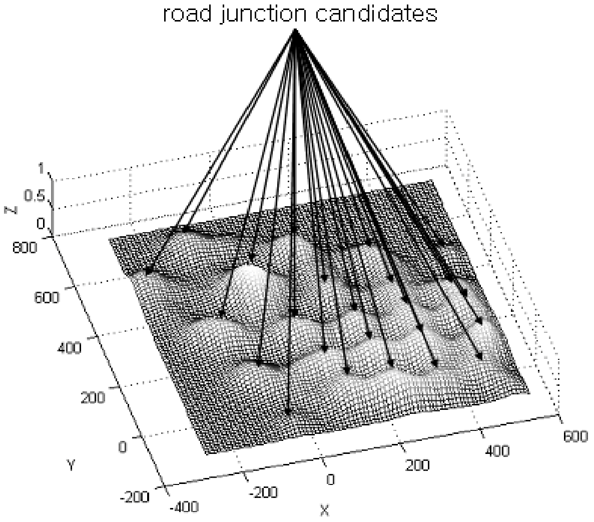


Figure 6 A typical FMAP representing smoothed population surface

In this way, the reference points can be found automatically and the NLOS errors of the reference points can be extracted (Lee et al, 2005). All the reference points are used to generate the correction map. In order to generate the correction map efficiently, universal kriging is utilized. Kriging is an estimation procedure which was first used by the mining industry. The basic tool in kriging, the variogram, is used to quantify spatial correlations between observations. As there are many advantages of kriging (Clark, 1979), its application can be found in very different disciplines.

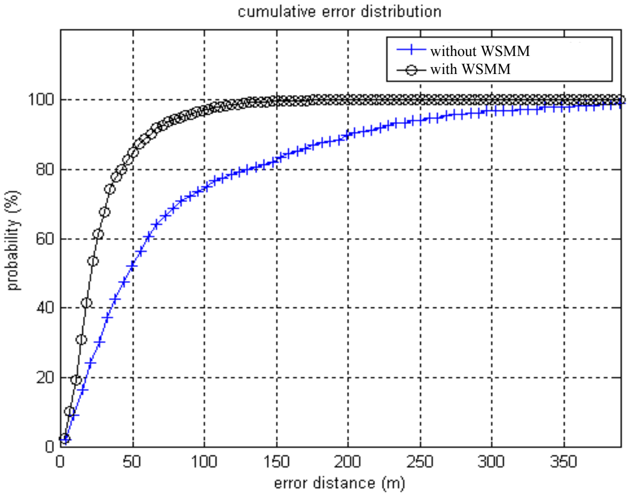


Figure 7 Cumulative error distribution with and without WSMM (simulation of the typical Manhattan-like area)

Based on our simulated data error distances between estimates and true user positions were computed. As a result, the cumulative error distribution diagram of Figure 7 was obtained. Two lines in the figure with the symbols ‘o’ and ‘+’ correspond to the cumulative error distribution with and without the WSMM respectively. One can see 85 percent of users are within 50 m error distance with the WSMM while 52 percent of users are within the same error distance without the WSMM.

4. EXPERIMENTS AND RESULTS

To verify the proposed WSMM, an experiment was carried out using a CDMA (Code Division Multiple Access) network in a typical suburban environment in Beijing, China. In such an environment, NLOS propagation can be expected. The test area is about 1km by 2km and in total there are 4 BTSs. At least 8 BTSs are located in the adjacent areas. To simplify the experiment, the test area is further divided into 2 small areas (partly overlapped), named area A and area B. Figure 8 shows the map of test area A. In each small area, 3 BTSs are distributed evenly. As we know, a typical BTS has 3 sectors and each sector has a unique ID. Hence each sector (antenna) can provide a TDOA measurement. However, the 3 sectors are part of one BTS, so they have the same or very similar location. From the trilateration positioning point of view, the 3 sectors can be only used as one base station because the measurements must come from spatially diverse locations. The coordinates of these BTS are prerequisite. A standard CDMA2000 1x handset was used to collect data. A normal GPS receiver was used to provide the 'true' location of MU.

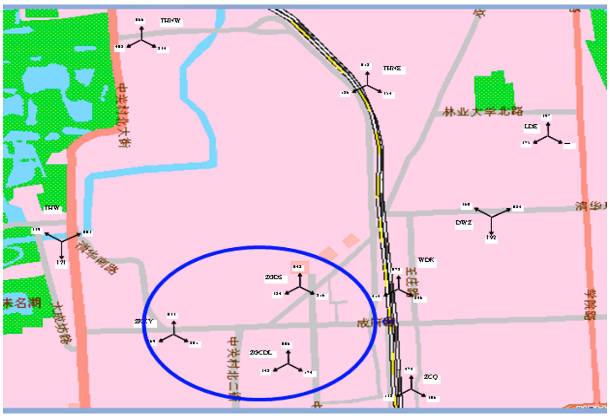


Figure 8 The map of test area A

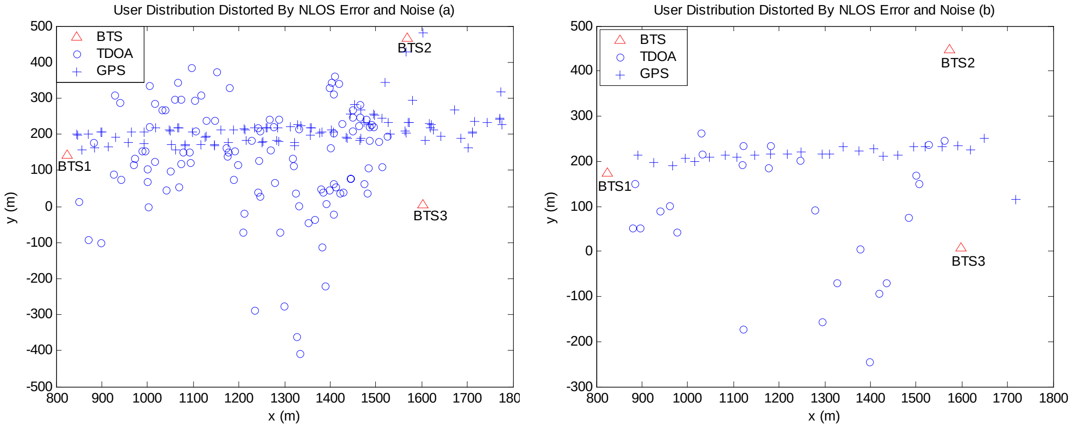


Figure 9 User position distribution along a suburbans street in the presence of distorted by NLOS error and noise; (a) using dense test points but less measurements at each point and (b) using less test points but around 30 measurements at each point

We walked along the nearby streets, and several thousands of measurements were taken. The position provided by GPS was used as the 'truth' reference (because of the blockage of satellite's signal by the buildings, sometimes map matching was used to correct the offset). Figure 9 depicts the test results along a main street in test area A. Part (a) is based on data collected at densely distributed test points (the average interval of the test points is about 15 m), and at each point, only 2 measurements were taken (the average of the measurements were utilized). Part (b) is based on data collected at less densely distributed test points (average interval is about 40 m), but around 30 measurements were acquired at each point. The results were distorted seriously because of the NLOS error. Part (a) also shows the effect of the noise. However, both of the two diagrams have a similar pattern. It indicates that the NLOS error has a fixed pattern along this street.

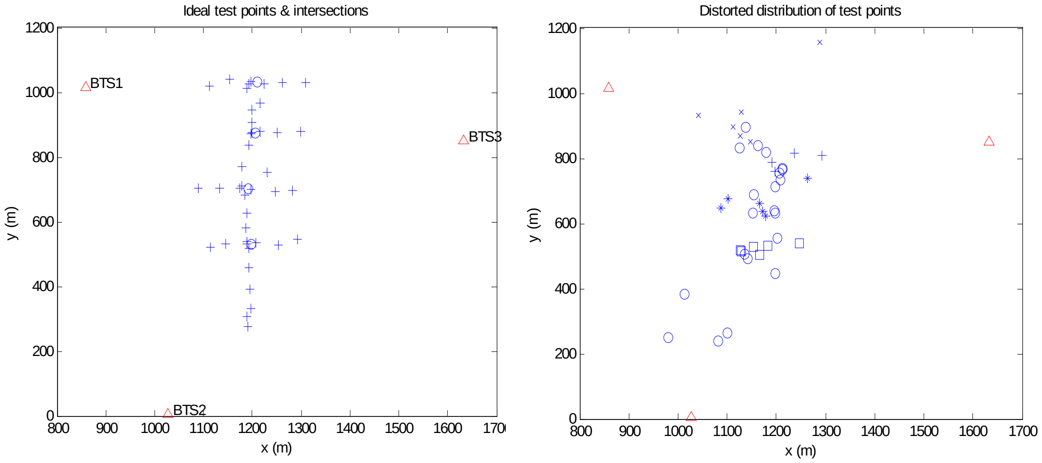


Figure 10 The ideal map (left) and distorted map (right) of test area B. The circles in ideal map indicate the intersections; the different symbols indicate the test points from different streets.

After the data along the street in the test area had been collected, a distorted map was generated. Figure 10 shows the ideal map which was based on GPS data, and the distorted map of area B as an example. The ideal map was generated using GPS data. The different symbols in the distorted map indicate the different streets. Since the map has been deformed seriously, without those symbols, it is hard to find the streets. The noise and the rarity of test points made it almost impossible to find the intersections using the distorted map only. This is one of the difficulties in deploying WSMM in a real application. Assuming the intersections showing in the ideal map (indicated by circles) can be found, the proposed method can be utilized. The NLOS error can be mitigated more or less in that case. Figure 11 compares the cumulative distance error distribution before and after using the correction map. The improvement is considerable. Before applying the correction, only 23% of the test points within 50m-distance error and close to 60% of the test points within 100m-distance error while after correction, those percentages increase to 49 and 86 respectively. One thing that must be emphasized is that only 4 reference points (the intersections) were utilized to generate the correction map. Intuitively, if more reference points were used, the result would be better. Similar improvements were also found in area A.

5. CONCLUSIONS

In this paper, a new approach for mitigating NLOS error, the WSMM technique is introduced. The main advantage of WSMM is that it can automatically extract the reference points and employ a small number of reference points to generate a NLOS error correction map efficiently (based on kriging). From the simulation and experiment results, it has been shown that this approach can improve the accuracy of TDOA positioning considerably.

From the experiment, it is observed that the noise level is much higher than what anticipated; and it gets serious in the NLOS scenario. This makes the detection of the reference points extremely complex and difficult. Apparently, this is the major problem for WSMM. Future work will focus on noise reduction and reference point detection.

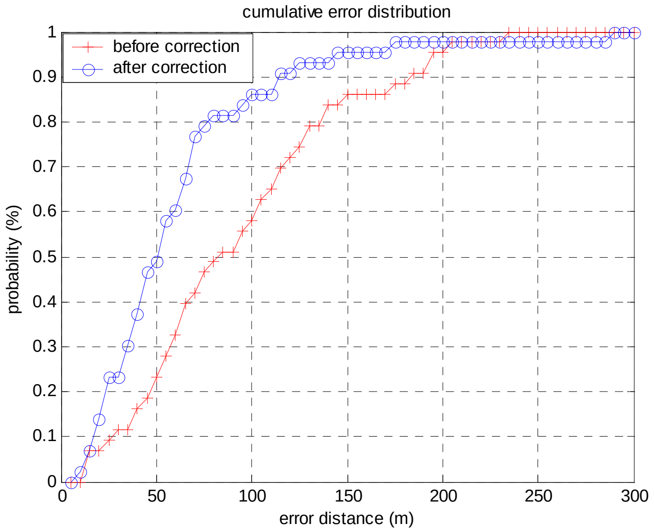


Figure 11 Cumulative error distribution before and after applying the correction

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