A Geometric Wireless Location System Utilizing Downlink Pilot Strength Measurement Messages

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***Abstract*—In this paper, the performance of the wireless-signal map-matching method under a code division multiple access network is demonstrated. The wirelss-signal map-matching method is the key step to implement the recentely introduced wireless location technology named as the localization exploring network measurement occurances. With respect to the downlink pilot strength measurement messages collected under a typical urban environment, the wireless-signal map-matching method is applied. By experiment result, it is shown that the accuracy improvement is possible by revealing the spatial structure of non-line-of-sight errors without any GPS information.**

I. INTRODUCTION

The wireless location technology (WLT) is attracting more and more attention since it is considered as the key technology for the development of various advanced location-based services (LBSs). Unfortunately, most of the wireless location technologies suffer from the non-line-of-sight (NLOS) error in dense urban area where the requests for the LBS would arise most frequently. Though there are many types of location measurements including the time of arrival (TOA), the time difference of arrival (TDOA), the angle of arrival (AOA), and signal strength (SS), the occurrence of NLOS error is unavoidable.

It is likely that NLOS error can cause considerable location errors in urban environments. For the reason, extensive investigations have been carried out during the past decades to mitigate NLOS error using probability density function models [1], NLOS detection and de-weighting methods [2-4], constrained optimization methods [5-7], NLOS extraction at known positions [8], and database correlation method [9-11]. However, NLOS error is still the single most critical issue for the advanced WLTs, having not yet been satisfactorily resolved.

By studying the previous research works, it can be found that, there are two choices that can be extended to the practical solution to mitigate the NLOS error effects. One is to utilize the characteristics of the NLOS errors and the other is to reveal and compensate the NLOS errors.

Currently, the most representative WLSs for the two cases are the database correlation method and the NLOS calibration method. In the database correlation method, during the preparation stage, the reference measurements (RMs) are accumulated into the location database with the corresponding reference locations (RLs). During the real-time location service stage, the location measurements of a mobile unit are compared to each entry of the location database. The mobile unit's location estimate is generated as the combination of the several RLs which show maximum similarities in terms of the measurement characteristics.

In the NLOS calibration method, the NLOS errors are directed extracted by subtracting the ideal RM from the actually measured RM. The extracted NLOS error vector is added to the calibration database with the associated RL during the preparation phase. If a mobile unit requests location, the location measurements sampled by the mobile unit is corrected based on the calibration database resulting in an improved location estimate.

As explained, both of the two most representative WLSs utilize the RMs sampled at known RLs. Thus, the exact coordinates of the RLs need to be surveyed during the preparation stage. In general, the WLSs' accuracy increases as the number of the surveyed RLs increases. Thus, to achieve a good accuracy, the distribution of the surveyed RLs needs to be dense to reveal the spatial variation of the NLOS error.

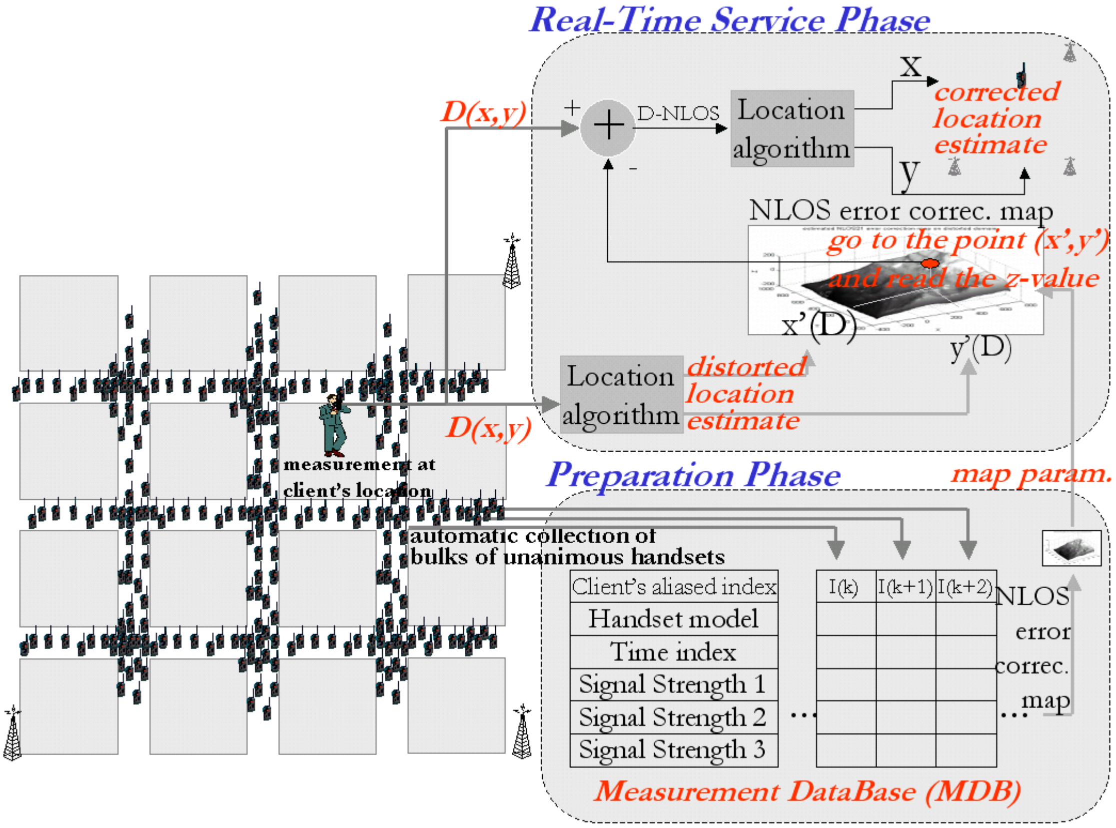

Fig. 1. Implementation concept of LENMO

(Localization Exploring Network Measurement Occurrences)

On the other hand, the RM surveying is, in general, not an easy problem. Even by the most recently developed surveying procedure, which is called as the war driving, a surveyor needs to spend considerable time running both the diagnostic monitoring software and the GPS receiver [12-14]. A more discouraging fact is that the RM surveying needs to be repeated periodically to consider environmental changes like building constructions.

To eliminate the tedious human labour for the outdoor RM surveying, an automatic RM collection and exploring procedure was proposed recently [15-18]. The proposed LENMO (Localization Exploring Network Measurement Occurrences) collects location measurements by intercepting the location measurements interchanged between the mobile units and the core network infrastructure. The system configuration to implement the LENMO is depicted in Fig. 1. As shown in Fig. 1, no location tag and no privacy information are required during the location measurement collection. The collected measurements are analyzed to extract as many RMs and possible. For the implementation of the LENMO, a procedure to identify RMs among the collected location measurements without utilizing any GPS information is required. This procedure is based on the wireless-signal map-matching (WSMM) principle and is performed by checking signal features (SFs) corresponding to the proximity to the signal transmitters and geometric features (GFs) corresponding to the appearances of road segment combinations. The configuration of the WSMM is illustrated in Fig. 2.

To demonstrate the benefit of the WSMM in location accuracy improvement, this paper presents an experiment result by processing the real pilot strength measurement messages (PSMM) collected in a code division multiple access (CDMA) network. The PSMM is originally designed for handover in mobile communication and can be supplied by any legacy handset.

II. LOCALIZATION EXPLORING NETWORK MEASUREMENT OCCURRENCES

To mitigate the NLOS error effects, the proposed LENMO extracts the RMs by investigating two features. One is SF and the other is GF. The utilization of SF is relatively simple. For this purpose, SS values of each measurement are checked. According to Hata–Okumura model [19] or COST 231 Walfisch-Ikegami model [20], SS value describes the distance between a transmitter and a receiver with good accuracy if they are sufficiently adjacent so that there is no obstruction for the line-of-sight condition. Thus, the measurement set which includes the maximum SS with respect to some BTS means that they are sampled near that BTS. In these proxi-measurement sets, the effects of NLOS error would be small and their sampled position would approximately equals that of the corresponding BTS.

Usually, the amount of RMs by SF would be too small to eliminate the distortion sufficiently. To provide sufficient amount of reference measurements, GF should be utilized.

Dense urban area is mostly composed of road junctions, road segments, and buildings, where road junctions are stored as node, road segments are stored as links. 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 [21]. Among the various combinations of nodes and links, a road junction which appears as a simple node, is the easiest feature to identify. The identification of the reference measurements by GF is illustrated in Fig. 2.

After the RMs are extracted either by SF or GF, the NLOS error correction maps are generated. Since each RM is related to a point on ideal (undistorted) domain $\{X=[x\,y]^T\}$ and a point on distorted domain $\{\bar{X}=[\bar{x}\,\bar{y}]^T\}$, the NLOS errors can be as follows [15-18].

$$\tilde{y}(X)-f(X)=NLOS(X)+\tilde{v} \qquad (1)$$

where

$\tilde{y}(X)=[\tilde{y}_1\,\tilde{y}_2\cdots\tilde{y}_{Nb}]^T$: measured distance vector derived from the SS measurements

$f(X)=[f_1\,f_2\cdots f_{Nb}]^T$: ideal distance vector for the SS measurements

$NLOS(X)=[NLOS_1\,NLOS_2\cdots NLOS_{Nb}]^T$: NLOS error vector contained in the measured distance vector

$\tilde{v}(X)=[\tilde{v}_1\,\tilde{v}_2\cdots\tilde{v}_{Nb}]^T$: measured error vector

N_b : number of base stations

If the signal strength values are utilized as the location measurements, each entry of the ideal distance vector can be modelled as follows [24,25].

$$f_j(X)=r_0\exp\left(-\frac{S_j(X)-S_0}{10\alpha}\right) \qquad (2)$$

where

$S_j(X)$: ideal SS of the mobile unit at the location X to the j -th base station

S_0 : ideal SS of the mobile unit located at the distance r_0 from the j -th base station

α : distance decaying factor

As widely known, the magnitude of NLOS error is largely dependent on the geometry of the signal transmitter (base station) and receiver (mobile unit). This, in other words, means that, if two mobile units are located nearby, the two mobile units experience similar NLOS errors. Utilizing the spatial characteristic, the NLOS error on the distorted position domain can be modelled as follows.

$$NLOS(\bar{X})=h(\bar{X})\beta \qquad (3)$$

where β indicate the spatial structure of the NLOS error and $h(\bar{X})$ is the observation matrix on distorted position domain $\{\bar{X}=[\bar{x}\,\bar{y}]^T\}$ whose distortion originates from the NLOS error. Depending on the complexity of the surrounding environments between the base station and mobile units, the NLOS spatial structure β can be modelled as a linear trend or a quadratic trend. In this case, $h(\bar{X})$ and β can be expressed as follows.

linear trend:

$h(X):=[1\,\bar{x}\,\bar{y}\,]$,

$\beta:=[\beta_0\ \ \beta_1\ \ \beta_2\,]^T$

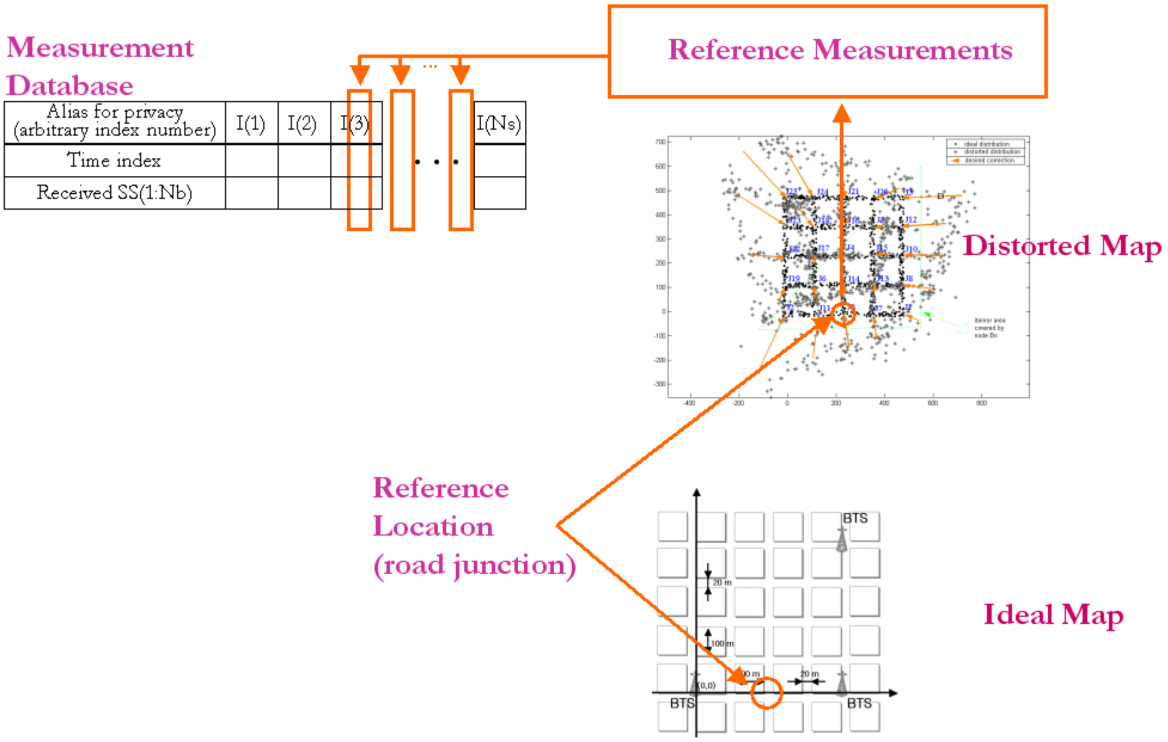

Fig. 2. Configuration of wireless-signal map-matching to identify reference measurements to extract and compensate non-line-of-sight errors

quadratic trend:

$$h(X) := [1 \;\; x \;\; y \;\; x^2 \;\; y^2 \;\; xy],$$
$$\beta := [\beta_0 \;\; \beta_1 \;\; \beta_2 \;\; \beta_3 \;\; \beta_4 \;\; \beta_5]^T \tag{4}$$

In both cases, β_0 indicates the bias term in the spatial structure of NLOS error.

At several RLs, the NLOS error can be directly extracted from the corresponding RMs as follows.

$$\begin{aligned}\tilde{n}(\bar{X}) &:= z(X) - \|X - X_{B1}\| + \|X - X_{B2}\| \\ &= h(\bar{X})\beta + v(\bar{X})\end{aligned} \tag{5}$$

where $\tilde{n}(\bar{X})$ indicates the newly defined NLOS measurement.

No matter how densely the RLs are distributed, they cannot cover the entire area where any mobile unit can be placed. To extract NLOS errors at arbitrary non-reference locations, the following Kriging equation can be utilized with the RMs $\{\tilde{n}(\hat{X}_j)\}_{j=1,2,\cdots,J}$ sampled at the reference locations [22,23].

$$\begin{aligned}\hat{\beta} &= \left(H^T C_1^{-1} H\right)^{-1} H^T C_1^{-1} \tilde{N} \\ \hat{n}(\bar{X}_0) &= c_0^T C_1^{-1}\left[\tilde{N} - H\hat{\beta}\right] + h(\bar{X}_0)\hat{\beta}\end{aligned} \tag{6}$$

where

$$H := \begin{bmatrix} h(\bar{X}_1) \\ h(\bar{X}_2) \\ \vdots \\ h(\bar{X}_J) \end{bmatrix}, \quad \tilde{N} := \begin{bmatrix} \tilde{n}(\bar{X}_1) \\ \tilde{n}(\bar{X}_2) \\ \vdots \\ \tilde{n}(\bar{X}_J) \end{bmatrix}, \quad c_0 := \begin{bmatrix} \gamma(\bar{X}_0, \bar{X}_1) \\ \gamma(\bar{X}_0, \bar{X}_2) \\ \vdots \\ \gamma(\bar{X}_0, \bar{X}_J) \end{bmatrix}$$

$$C_1 := \begin{bmatrix} \gamma(\bar{X}_1,\bar{X}_1) & \gamma(\bar{X}_1,\bar{X}_2) & \cdots & \gamma(\bar{X}_1,\bar{X}_J) \\ \gamma(\bar{X}_2,\bar{X}_1) & \gamma(\bar{X}_2,\bar{X}_2) & \cdots & \gamma(\bar{X}_2,\bar{X}_J) \\ \vdots & \vdots & \ddots & \vdots \\ \gamma(\bar{X}_J,\bar{X}_1) & \gamma(\bar{X}_J,\bar{X}_2) & \cdots & \gamma(\bar{X}_J,\bar{X}_J) \end{bmatrix}$$

$$\gamma(\bar{X}_i,\bar{X}_j) = \frac{1}{2} Var\left[v(\bar{X}_i) - v(\bar{X}_j) \right] \text{: variogram} \qquad (7)$$

III. EXPERIMENT

To verify the capability of the accuracy improvement by the proposed method, an experiment was performed. For the experiment, the PSMMs are collected in a typical urban environment from a CDMA network. According to the CDMA standard, any mobile unit need to measure and report the PSMM for handover and mobility management. The PSMM contains a searcher and multiple finger information describing the downlink pilot signal strength and time offset for each neighbouring base station observed by the mobile unit. The searcher continuously checks the strong pilot signal from each neighbouring base station. Based on the searcher's measurement, each finger is assigned a short PN offset corresponding to a specific base station. The PSMM is one of the basic messages that a mobile unit with simplest hardware can provide.

To capture the PSMMs, a diagnostic monitoring (DM) software is utilized. By walking with the handset and a laptop computer which runs the DM software, the PSMMs are collected in the downtown area of Ilsan-city, Korea during 2 hours. For the accuracy analysis purpose, all the PSMMs are logged with the GPS location tags. The GPS location tags are utilized only in the location accuracy analysis and are not utilized to estimate the location of the mobile unit. The configuration of the experiment area is depicted in Fig. 3.

By the collected PSMMs, it is revealed that signals from more than 10 base stations are usually available for each location. Utilizing the five strongest signals from different base stations, the location estimates are generated by the proposed methodology.

To estimate location, the total sum of four signal strength values contained in the PSMM finger information are smoothed and converted to the range values. The conversion is based on Eq. (2) with the following parameters.

$$\alpha = 3,\ r_0 = 900,\ S_0 = -90 \qquad (8)$$

For comparison purpose, two types of processing scenarios are applied. One is the iterated least-mean-square algorithm without considering the NLOS error and the other is the iterated least-mean-square algorithm with the NLOS error identification and correction as explained.

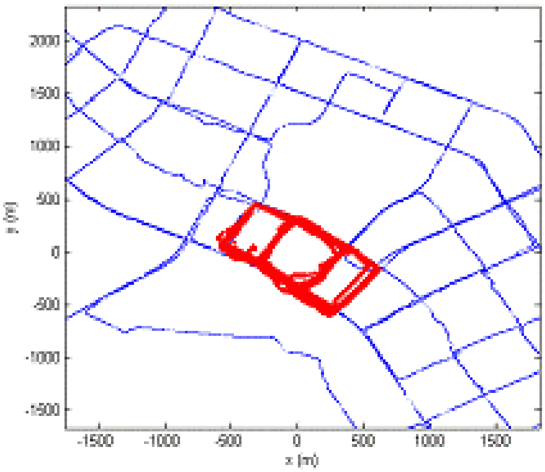

Fig. 3. Road segment profile around the experiment area

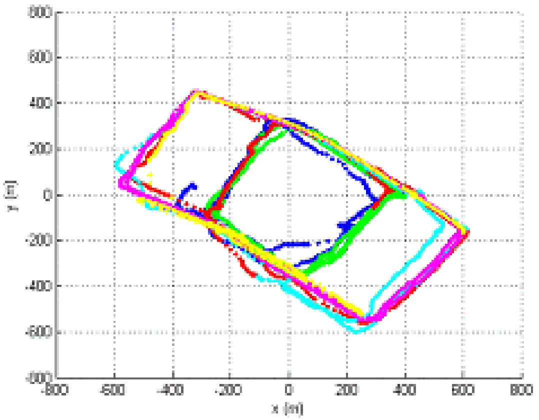

Fig. 4. Actual distribution of mobile unit during the experiment

Fig. 4 depicts the actual distribution of the mobile unit which is based GPS location tags and Fig. 5 depicts the distribution of the mobile unit by applying the iterated least-mean-square algorithm without considering the NLOS error. By comparing Fig. 4 and Fig. 5, it can be seen that the mobile distribution without considering the NLOS error is distorted quite considerably. Next, the same PSMM data sets are applied to the WSMM algorithm. By identifying and correcting the NLOS error effects, the WSMM algorithm generates less distorted distribution as shown in Fig. 6 implying the improvement of location accuracy. For the explicit comparison of location accuracy, a cumulative distance error plot is constructed as shown in Fig. 7. In Fig. 7, it can be seen about 60 % and 95 % of the location estimates are within the error distance of 300 m with and without the NLOS error correction, respectively. This result means that the WSMM is quite effective in improving the location accuracy even if the low-resolution PSMMs are utilized as the location measurements.

IV. CONCLUSION

This paper demonstrated the performance of the wireless-signal map-matching method to obtain improved location estimates in a typical urban environment where the non-line-of-sight errors occur frequently. With respect to the downlink pilot strength measurement messages collected under a code division multiple access network, the proposed method was applied. By experiment result, it was shown that the accuracy improvement is possible by revealing the spatial structure of non-line-of-sight errors without any GPS information.

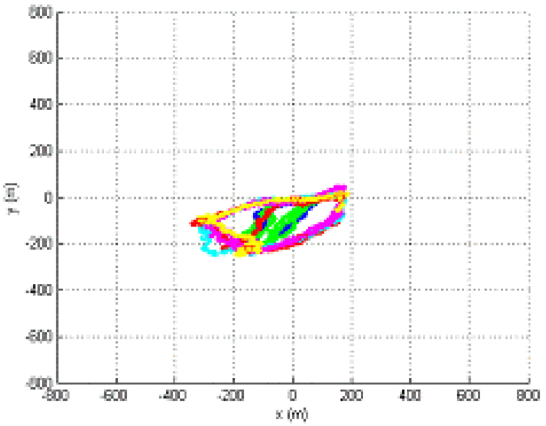

Fig. 5. Distribution of mobile unit without non-line-of-sight error compensation

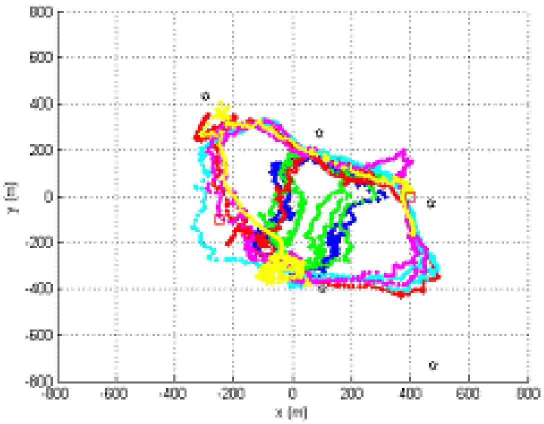

Fig. 6. Distribution of mobile unit with non-line-of-sight error compensation

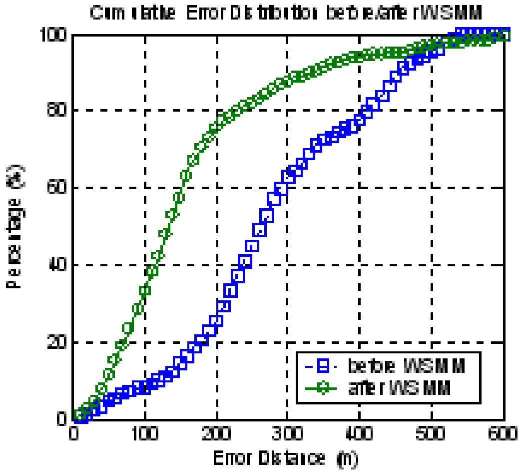

Fig. 7. Cumulative error distribution

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