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An Efficient Non-Line-of-Sight Error Mitigation Method for TOA measurement in Indoor Environments

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ABSTRACT

In this paper, we propose an efficient non-line-of-sight (NLOS) error mitigation method for TOA measurement in indoor environments. In order to meet era of ubiquitous computing, there is a developing need for an accurate real-time locating system (RTLS). In the presence of a NLOS error, the location estimation performance is likely to be degraded. For effective location estimation, NLOS errors should be recognized and mitigated before measurements are used in conventional location estimation method such as non-linear least squares (NLS), linear least squares (LLS), weighted-linear least squares (WLS), and least median squares (LMS). For improve location estimation, we assumed that measured distances using weighing mitigation factor are exploited for location estimation. Through simulation results, theoretical analysis of the performance is demonstrated.

Categories and Subject Descriptors

C.2.1 [**Sensor Neworks**]: Wireless positioning system – *wireless communication.*

General Terms

Algorithms

Keywords

Location Estimation, NLOS Error Mitigation, Time-of-Arrival (TOA), RTLS, Least squares (LS).

1. INTRODUCTION

As the era of information and computing, there is a growing need for an efficient location estimation system. Decision of the location of the wireless mobile device is requirement in wireless sensor systems. For example, in wireless location system such as the emergency 911 (E-911), cellular networks, hospitals, shopping malls, welfare facilities, accurate location estimation system of

unknown target can save time. Location estimation is obtaining more interest for use in wireless sensor network applications in ubiquitous age for location services in which positioning system such as global positioning system (GPS), local area system, and localization system in indoor environment are impractical. These location estimation methods have attracted a significant amount of attention in sensor networks. A variety of location estimation methods have been studied and investigated over the past decade [1]. Mobile device using location estimation methods usually involves time-of-arrival (TOA), time-difference-of-arrival (TDOA), angle-of-arrival (AOA), received-signal-strength (RSS) measurements. The time-of-arrival (TOA) is more popular in location estimation methods. TOA-based location estimation method measures the distance between the unknown target and three or more base station (BSs). The same point of intersections of TOA-circles with measured distance gives the unknown target's location. However, due to errors in TOA-based location estimation, the TOA-circles do not find a unique intersection point in [2].

In this paper, we assume that an efficient non-line-of-sight (NLOS) error mitigation method for TOA measurement in indoor environments. In the occurrence of a NLOS error, NLOS mitigation method is proposed for effective location estimation. For accurate location estimation, the measured distance affected NLOS error is likely to be degraded by the NLOS mitigation method. As a result, in order to induce this measured distance error, we proposed an effective NLOS error mitigation in order to improve location performance.

The paper is organized as follows: Section 2 is dedicated to account for problem definition of NLOS error. Section 3 briefly reviews ranging protocol for distance measurement, the system model of TOA-based location estimation scenario is outlined, and a variety method of location estimation is presented. We introduce that Section 4 is on effective NLOS error mitigation method. The performance evaluation of the proposed method is conducted in Section 5 via simulation results, and Section 6 draws conclusions.

2. Problem Definition in NLOS environments

Figure 1 illustrates typical signal propagation among BSs and an unknown target in absence obstacle environment. As illustrated in Figure 1, an NLOS bias error results from the obstacle of the signal direct path and the reflection signal of multipath environments. The NLOS bias is the error distance which has a nonnegative value, and signal propagation from BS to wireless device target. NLOS error can be described as a variety error such

as a deterministic error, a uniform distributed error, a Gaussian distributed error, or an exponentially distributed error. NLOS bias b_i is given by

$$b_i = \begin{cases} 0, & \text{if } i\text{-th BS is LOS} \\ \varPsi_i, & \text{if } i\text{-th BS is NLOS} \end{cases}. \qquad (1)$$
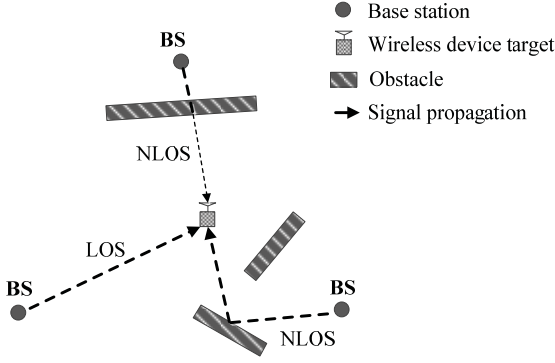

Figure 1. Illustration of LOS and NLOS signal propagation

3. SYSTEM MODEL

The NLOS error occurs from the obstacles of the direct path signal and the reflection signal affected multipath. It is difficult that accurate location estimation using measured distance influenced by NLOS error. In this section, we introduce mathematical modeling of the TOA-based location estimation in NLOS environments. Section 3.2 briefly facilitates the design of the TOA measurement. The conventional LS method for location estimation summarized in other Sections.

3.1 Ranging Protocol for Distance Measurement

The signal propagation time between two devices using ranging protocol such as two-way ranging (TWR) [3], and symmetric double-sided two-way ranging (SDS-TWR) [4] is able to calculate. TWR protocol in Figure 2 shows the system in a two-device scenario. As described in the Figure 2. The time of arrival of the signal at i-th device, t_i, is calculated by

$$t_{i,TWR} = \frac{1}{2}\left(T_{roundA} - T_{replyB}\right), \qquad (2)$$

where T_{round} denotes the round-trip time at i-th device and T_{reply} denotes the reply time of i-th device.
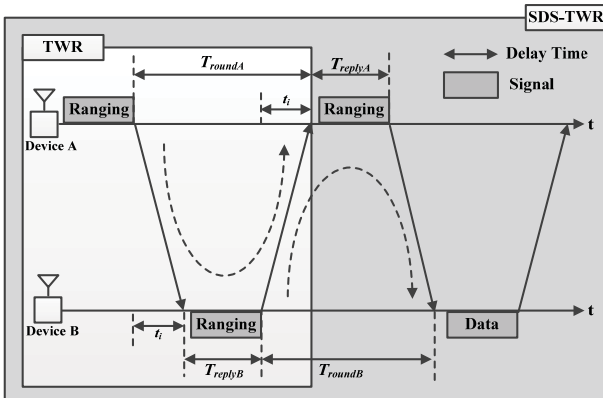

Figure 2. TWR and SDS-TWR protocols

The SDS-TWR protocol is proposed protocol method to induce the offset ranging error of TWR in [3] as described in the Figure 2. For effective TWR, SDS-TWR protocol is assumed that $T_{replyA}=T_{replyB}$ as determined in [4]. It can be seen that two round-trip times, denoted by T_{roundA} and T_{roundB}, are estimated using two-paths. Thus, the averaged of each path can be expressed

$$t_{i,SDS-TWR} = \frac{1}{4}\left\{\left(T_{roundA} - T_{replyB}\right) + \left(T_{roundB} - T_{replyA}\right)\right\}. \quad (3)$$

3.2 TOA Measurement in NLOS Environments

Consider a two-dimensional localization scenario as Figure 3 with one wireless device target and N fixed base stations (BSs), $\mathbf{x} = [x \; y]^T$ is the location of wireless device target, $\mathbf{x}_i = [x_i \; y_i]^T$ is the location of the i-th BS. The TOA measurement distance $\hat{d}_i$ from the i-th BS is modeled as

$$\begin{aligned} \hat{d}_i &= ct_i \\ &= d_i + b_i + n_i, \quad i = 1, 2, ..., N, \end{aligned} \qquad (4)$$

where d_i is the true distance between the target and i-th BS, c is the speed of light, and t_i is the time of arrival of the signal at i-th BS using ranging protocol in section 3.1, b_i is a positive NLOS bias error effected due to the obstacle of direct path, and $n_i \sim \mathcal{N}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) with variance σ^2. The noiseless true distance d_i is represented as

$$\begin{aligned} d_i &= \|\mathbf{x} - \mathbf{x}_i\| \\ &= \sqrt{(x-x_i)^2 + (y-y_i)^2} \end{aligned} \qquad (5)$$

where $\| \cdot \|$ represents the norm operation over a vector of distance between the target and i-th BS.
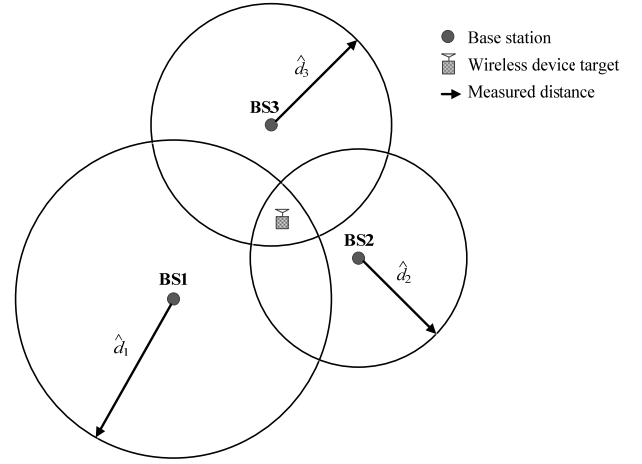

Figure 3. TOA-based localization in NLOS environments

3.3 Non-Linear Least Squares (NLS)

The NLS is a well-known estimation method for minimizing distance error between the unknown target and i-th BS. Taking the TOA-based location estimation, the performance deterioration due to NLOS bias errors can be used to find unknown target. The NLS is given by [5] followed as

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left\{ \sum_{i=1}^{N} \left(\hat{d}_i - \|\mathbf{x} - \mathbf{x}_i\| \right)^2 \right\}. \qquad (6)$$

3.4 Linear Least Squares (LLS)

Considering the absence of noise and NLOS bias, the TOA-circle around i-th BS corresponding to unknown target locations expressed as

$$\left(x - x_i \right)^2 + \left(y - y_i \right)^2 = d_i^2, \quad i = 1,...,N. \qquad (7)$$

However, in indoor environments absented the noise and NLOS bias error, the circle equations is defined by

$$\left(x - x_i \right)^2 + \left(y - y_i \right)^2 = \hat{d}_i^2, \quad i = 1,...,N. \qquad (8)$$

The intersection of TOA-circles using equation (8) do not intersect at the same point. For such reason, the LLS is represented as the linear equation in matrix for more compact and enumerated expression form. After some manipulation such as linearization, matrix representation, and differencing, we may write matrix as [6]

$$\mathbf{A}_1 \boldsymbol{\theta} = \frac{1}{2} \mathbf{p}_1, \qquad (9)$$

where

$$\mathbf{A}_1 = \begin{bmatrix} x_1 & y_1 & -0.5 \\ x_2 & y_2 & -0.5 \\ \vdots & \vdots & \vdots \\ x_N & y_N & -0.5 \end{bmatrix},$$

$$\boldsymbol{\theta} = \begin{bmatrix} x \\ y \\ x^2 + y^2 \end{bmatrix}, \quad \mathbf{p}_1 = \begin{bmatrix} x_1^2 + y_1^2 - d_1^2 \\ x_2^2 + y_2^2 - d_2^2 \\ \vdots \\ x_N^2 + y_N^2 - d_N^2 \end{bmatrix}. \qquad (10)$$

Obtaining a LS solution of unknown target location, we may solve matrix representation (9) as follows

$$\hat{\boldsymbol{\theta}} = \frac{1}{2} \left(\mathbf{A}_1^\mathsf{T} \mathbf{A}_1 \right)^{-1} \mathbf{A}_1^\mathsf{T} \mathbf{p}_1. \qquad (11)$$

The matrix solution such as equations (9)-(11) called LLS-1. In addition, LLS approach solution proposed a variety methods called LLS-2 [7] and LLS-3 [8].

3.5 Weighted-Linear Least Squares (WLS)

The WLS is method used weighting factor at conventional LS. Some weights w_i can be utilized to feature the remarkable characteristic of each measured distance in [9]. We may represent the weighting factor affected variance in (12) follow as

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left\{ \sum_{i=1}^{N} w_i \left(\hat{d}_i - \|\mathbf{x} - \mathbf{x}_i\| \right)^2 \right\}, \text{ where } w_i = \frac{1}{\mathrm{var}_i}, \quad (12)$$

where var_i is variance between the unknown target and i-th BS.

3.6 Least Median Squares (LMS)

In [8], the LMS is effective fitting algorithm, which is proposed for NLOS environments. It can apply as high speed used median result of distance error between measured distance and true distance. The location estimation of the unknown target using LMS method is given by

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left\{ \mathrm{med}_i \left(\hat{d}_i - \|\mathbf{x} - \mathbf{x}_i\| \right)^2 \right\}, \qquad (13)$$

where $\mathrm{med}_i (\cdot)$ is median expression. The computation of LMS method is computationally concentrated, and mathematical calculation of LMS method is lower complexity to gaining estimated location of the unknown target.

4. NLOS ERROR MITIGATION METHOD

In this section, we introduced various error sources in location estimation. Consequently, the intersections for the unknown target will shift away from the true location. As a result, overlapped area occurs according to location estimation error in Figure 4. It is difficult that accurate location of the unknown target finds insides overlapped area. In location estimation error, there are a variety of reasons: for example, different noise levels at different BSs due to multipath effects, different reliability of devices used by BSs, and different ranging accuracy of each BS due to line-of-sight (LOS)/non-line-of-sight (NLOS) conditions.
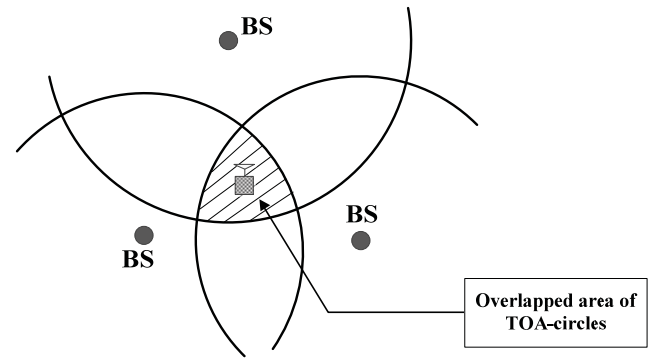

Figure 4. Overlapped area occurred NLOS environments

4.1 NLOS Error Mitigation

Measured distance has true distance added various errors such as NLOS bias error, and device difference error, is represented by

$$\begin{aligned} \hat{d}_i &= d_i + b_i + n_i \\ &= d_i + e_i, \qquad i = 1, 2,...,N. \end{aligned} \qquad (14)$$

The noise result of ranging estimation and NLOS bias is assumed to be a zero-mean Gaussian random variable. It can be lower if better signal propagation technology and ranging algorithm are applied.

As will be shown in the improved location estimation, a proper NLOS mitigation method is applied. In short, a following equation is expressed as

$$\begin{aligned} \tilde{d}_i &= \hat{d}_i - M_i \\ &= d_i + b_i + n_i - M_i \\ &= d_i + e_i - M_i, \qquad i = 1, 2,...,N, \end{aligned} \qquad (15)$$

where M_i is factor of NLOS error mitigation.

In figure 5, TOA-based location estimation using distance applied NLOS error mitigation shows smaller overlapped area in comparison with conventional location estimation in NLOS environments.
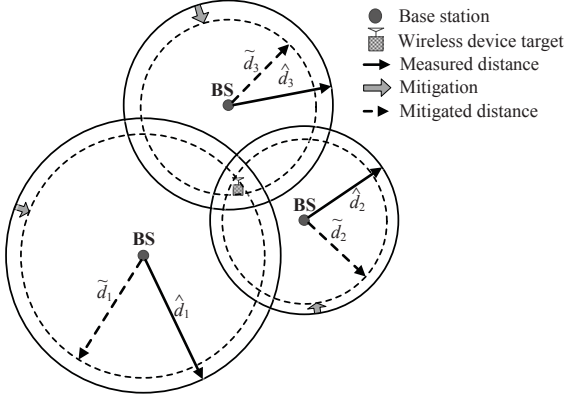

Figure 5. TOA-based localization of NLOS mitigation error

4.2 Proposed NLOS Error Mitigation Method

The proposed NLOS error mitigation method applies compensated distance using signal propagation of each different BS. Figure 6 shows ranging measurement using signal propagation of each BS. The r is true distance between locations of fixed BSs, and $\hat{r}$ is estimated by ranging estimation algorithm in accordance with signal propagation between BSs in Figure 6.
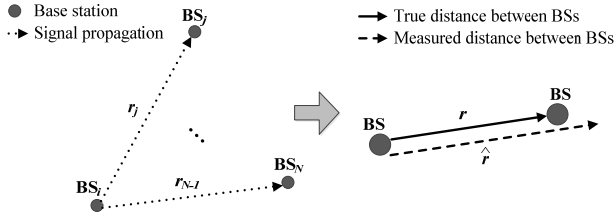

Figure 6. Signal propagation between BS and other BS

Compensated factor M_i is denoted by

$$M_i = \frac{\sum_{j=1}^{N-1}(\hat{r}_j - r_j)}{N-1}, \quad i, j = 1, 2, ..., N. \tag{16}$$

For all signal propagation for mitigation method, the averaged version of the NLOS error mitigation factor can be explained as follows:

Proposed NLOS ERROR Mitigation Algorithm

For the mitigated distance, NLOS error mitigation algorithm is performed and then, M_i is obtained.

    Set i = 1

      for j = 2 to N

        do : the calculation of r_j

        do : the ranging estimation of $\hat{r}_j$

        do : the estimation of error

      end for

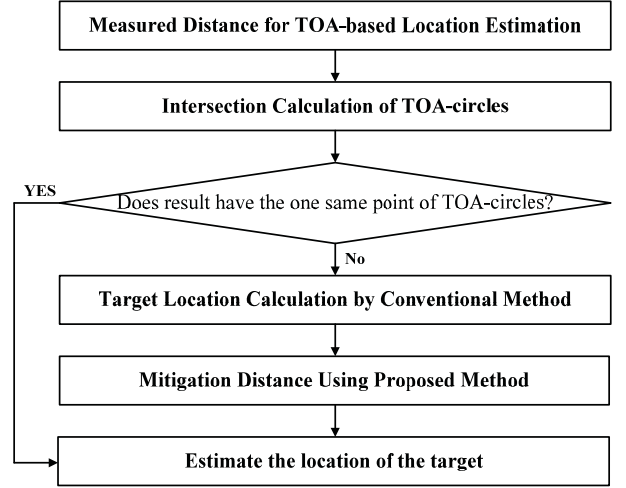   *do : the estimation of mitigation factor using averaging*

Figure 7. Structure step of the location estimation using proposed method

In figure 7, for estimation unknown target location, compensated distance using NLOS error mitigation method is applied by conventional methods: equation (6) in NLS, equation (9) in LLS, equation (12) in WLS, and equation (13) in LMS.

5. PERFORMANCE ANALYSIS

This section analyzes the location estimation performance for the NLS, LLS, WLS, LMS and conventional methods using the proposed method. Simulation results are provided to study the performance comparison of the proposed algorithm with NLS, LLS, WLS, and LMS in NLOS environments. To validate the proposed approach, NLOS error is positive bias error given uniform random distribution noise.
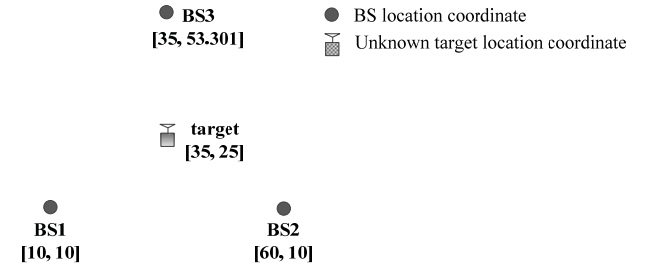

Figure 8. Location coordinates of devices for simulation results

In simulation environment, to verify the proposed mitigation approach, the unknown target is located at coordinate $[35, 25]^T$, and BSs are located at coordinates $[10, 10]^T$, $[60, 10]^T$, $[35, 10+25\sqrt{3}]^T$ in Figure 9. Simulations are implemented by Matlab.

In Figure 9, estimation error of various location estimation methods is compared. Conventional location estimation methods are the maximum estimation error over a 40m at low signal-to-ratio (SNR). In contrast, the proposed method is better performance analysis than conventional methods.
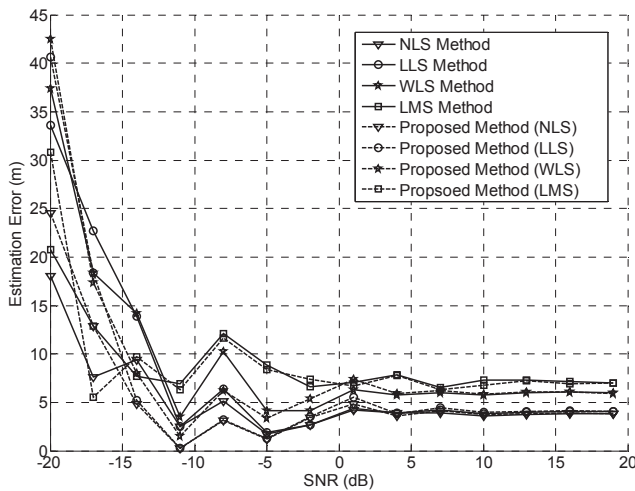
Figure 9. Comparison between conventional methods and proposed method

Figure 10 is comparison of estimation error in accordance with NLOS bias, and signal-to-noise power ratio (SNR) is set to 20 dB. NLOS power rate means greater NLOS bias error value had many obstacles. As a result, estimation error of conventional location estimation methods has results increased sharply. However, proposed mitigation method using compensated ranging distance has stable results. As shown in Figure 9 and 10, the performance of proposed mitigation method is more accurate estimation than conventional methods.
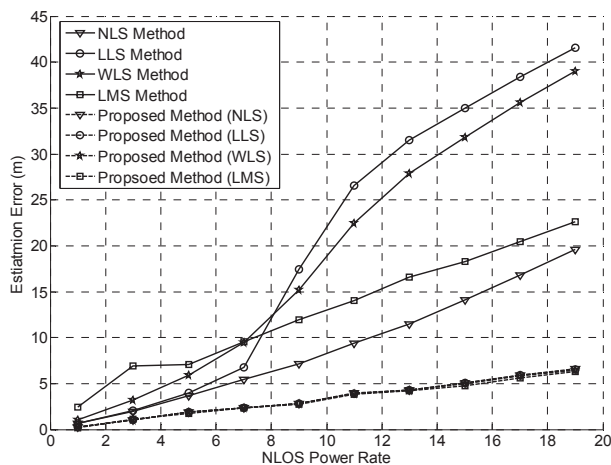

Figure 10. Comparison of estimation error (SNR: 20dB)

6. CONCLUSIONS

The presence of distance error in according with various errors is a serious issue in wireless sensor network, and degrades performance of location estimation. As a result, they must be mitigated or eliminated before estimation the unknown target. In this paper, we proposed an Efficient Non-Line-of-Sight Error Mitigation Method for TOA measurement in Indoor Environments. As we compensate distance error affected the NLOS bias error, the performance of location estimation is

improved. In indoor environments, NLOS bias error is occurred by obstacles, and measured distance is affected by multipath effects. Also, there is offset error in according with different reliability of devices. Utilizing proposed method, simulation results verified that wit NLOS error mitigation method, the location estimation error could be degraded.

7. ACKNOWLEDGMENTS

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