An Integration Method for Wireless Location Using Mobile Phone Built-in Sensors and TDOA Landmarks

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ABSTRACT

Non-line-of-sight (NLOS) signal propagation is the major source of error in wireless Time Difference of Arrival (TDOA) indoor system. Even if enough LMs can be deployed by service providers or system designers, existing methods encounter the problem for location estimation when less line-of-sight (LOS) measurements are detected. In this paper, we propose a new method to solve the problem. The proposed method integrates the user's step length into location estimation in wireless TDOA indoor location systems. The proposed method utilizes the user's step size and counts from mobile phone built-in sensors as reference to detect LOS/NLOS measurements. When less LOS measurements are detected, the previous location and step length are added to the least square (LS) method as a supplementary reference landmark (LM) and distance. Simulations results show that, when less number of hearable LOS measurements is not enough, the user's location is estimated with the supplementary reference LM and distance. Simulation results show that location error over time is reduced in a wireless TDOA location system, compared with the related works, in which NLOS measurement detections are overestimated or underestimated.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication

General Terms

Methods, Performance

Keywords

Mobile Phone Built-in sensors, Wireless Location System, Time Difference of Arrival (TDOA)

1. INTRODUCTION

Recently, mobile devices are widely spreading. The location information of mobile devices is expected to be used in many new services, such as friend finding, shopping guide, etc. Many mobile phones have GPS receivers, but some service should be provided in the situations where the function of GPS receivers is not available, such as indoor areas, underground areas and complicated urban districts with a lot of buildings.

Many studies have investigated wireless location technologies and some services are available today [1-10]. TDOA wireless location system is one of indoor location systems. The location system estimates the user's location that relies on the time propagation between a mobile device and landmarks. When the moving mobile device users meet the obstacles, encounter the multipath effects, NLOS errors happen to make the tracking accuracy worse. The presence of NLOS measurements is a serious issue in wireless location, because these errors tend to be very large and, hence, dramatically degrade location accuracy [11, 12].

Mitigating NLOS measurements has attracted a lot of attention and several optimization algorithms have been proposed [11-19]. Broadly speaking, the literature on the NLOS problem falls in two categories: NLOS identification [13-14] and NLOS mitigation [15-19]. The former deals with the problem of distinguishing between LOS and NLOS range information, whereas the latter typically deals with the reduction of the adverse impact of NLOS range errors on the accuracy of location estimates, assuming that the NLOS range estimates have been identified. To mitigate the NLOS errors, a biased kalman filter algorithm is proposed in [11]. The existence of NLOS component is identified first. The range measurements are smoothed for calculating standard deviation in a hypothesis testing. This biased kalman filter algorithm avoids inaccurate estimation of the range rate from the NLOS mitigation. However, it may result in large error to interpret NLOS condition into LOS condition. The noise covariance generated by NLOS error is compensated only when the measured range data is smaller than the estimated range data. Several statistical NLOS-identification techniques [12-19] for TDOA/ time of arrival (TOA) systems have been discussed previously, which exploit prior knowledge of NLOS delays and a series

Table 1: Comparison of Wireless Indoor Location Systems

	Location Accuracy	Hardware Cost
Wireless TDOA location system	High (100m^2 with 10～12 LMs) Low (100m^2 with 6,7 LMs)	RF/acoustic sensors
Dead-reckoning (using mobile phone built-in sensors	Becomes low (more than (10m^2), with time flying	Built-in sensors mobile phone, e.g. Xperia-X10, iphone

of measurements to reduce the bias in NLOS range estimates. NLOS detection measurements results indicate that when the square residual between the estimated distance and the measured distance cannot be updated on time, usually overestimate or underestimate a measurement happen. Mobile phone with built-in sensors is well-suited to solve the problem due to its support of diverse sensors which enable localization (e.g.3-axis, magnetic, gyro.etc). In this sense, recent research works [14-19] present location-based services running on carried sensors or mobile phone built-in sensors based largely on outdoor GPS use, but precise indoor localization would require complicit computation cost on a mobile phone.

In this paper, we propose a new method. It integrates step length and counts from mobile phone built-in sensors into location estimation procedure as the reference to detect LOS/NLOS measurements; then the previous location (initial location is assumed to be obtained with high accuracy) and step length are added to the least square (LS) method as a supplementary reference LM and distance, when the number of hearable LOS measurements are not enough.

The paper is organized as follows. Section 2 briefly describes the wireless TDOA location system. Section 3 presents the motivation of using mobile phone built-in sensors. Section 4 illustrates the details of the proposed method. Section 5 gives the simulation results of the proposed method and the existing method. Finally, section 6 concludes the paper.

2. Wireless TDOA location system

2.1 System Architecture

Fig. 1 illustrates a wireless TDOA location system with several LMs and a MP user. The true distance r_i between i_{th} LM with the coordinate of (x_i, y_i) and the MP with the coordinate of (x, y) can be described as,

$$r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad (1)$$

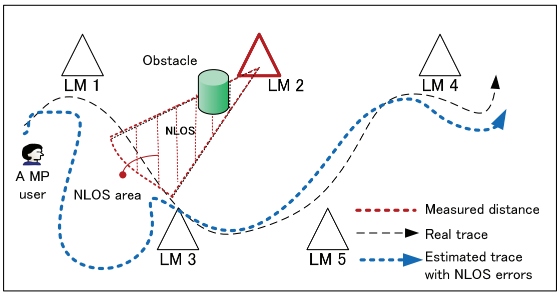


Figure 1: NLOS problem in Wireless TDOA indoor location system

2.2 NLOS problems in System

As shown in Fig. 1, an NLOS error results from the blockage of the direct measurement and the reflection of multipath measurements between LM2 and the MP. With receiver noise and NLOS errors, the measured distance r_i can be expressed as

$$d_i = r_i + n_i + NLOS_i \quad (2)$$

where n_i represents the receiver noise, and $NLOS_i$ represents NLOS error from the i_{th} LM. The receiver noise n_i is assumed to be a zero-mean Gaussian random variable. An NLOS error can be described as a deterministic error, a Gaussian error, or an exponentially distributed error [5-6]. The measured distance in a TDOA location system is much larger than the receiver noise, therefore location errors result mainly from the NLOS errors.

2.3 TDOA LMs

The TDOA LMs operate as follow; the sender broadcasts a radio message followed by an acoustic signal (chirp) with a known frequency signature. The mobile phone receives the radio message by starting to listen the chip. Once the mobile detects the radio message, they estimate the distance by computing the difference in arrival time of the radio and acoustic signals. As an example, modified MICA2 motes with MTS310 sensor boards can be used as these TDOA reference LMs [1]. The MTS310 sensor board is equipped with a hardware phase-locked loop tone detector, whose output is a binary value to let the user know whether the 4.0 and 4.5 kHz frequency band is available.

3. Data Integration

3.1 Sensor Data from Mobile Phone

Manual configuration of locations is not feasible for large-scale networks or networks. Providing many sensors with localization hardware (e.g., GPS) is expensive in terms of cost and energy consumption [3]. A more reasonable solution to the localization problem is to allow mobile phones to have their step information at all times, and allow users to infer this information from these sensors. Recently, mobile phones with built-in sensors (e.g., 3-axis, magnetic, gyro sensors, etc) have been widely spreading. These sensors help providing a lot of user's information that can be used in a location system: arm swing detection, step count estimation, direction estimation and step length estimation. swing detection, step count estimation, direction estimation and step length estimation. We use step count estimation (90%~102%) and step length estimation is about 0.5~0.8m, computation time is 0.1s, estimation distance is about 90%~109%.

3.2 Measurement Combination

For measurement combinations, TDOA measurements are obtained from LMs to estimate the position of a mobile phone. At least, four TDOA distance measurements from LMs are required to estimate the position of a mobile phone. If the number of TDOA measurements is less than four, mobile phone built-in sensor data is combined with TDOA measurements. In the next section, we propose a new method to yield satisfied location estimation when less LMs are deployed. The basic idea is to integrate step size and counts from mobile phone built-in sensors into wireless TDOA location system.

4. The Proposed Location Method

For wireless TDOA location, in mixed LOS/NLOS environments, as multiple TDOA measurements are collected, may some of them are biased by NLOS error at a certain time step. If we could effectively detect those LOS measurements and make use of them to locate the MP, the performance of the classical location algorithms will be better than using all mixed LOS/NLOS measurements. Therefore, the proposed method falls in two steps: LOS/NLOS measurements detection and location estimation.

The detail steps of the LOS/NLOS measurement detection method and location estimation method are illustrated in subsections 4.1 and 4.2 separately.

4.1 LOS/NLOS Measurements Detection

In the following, we focus on LOS/NLOS measurements detection. In the LOS/NLOS detection method, since the physical statistical properties of a user's movement at the current status can be treated continuous in a short time interval. Once the residual between the predicated and the measured distance value is larger than a threshold, the measured distance is detected as a NLOS measurement. However, the residual between the estimated distance and the measured distance is usually determined by using a prior knowledge of LOS measurement distribution. But this method is usually experimentally cost. The proposed method utilizes the user's step size and counts from mobile phone built-in sensors as the reference distribution to detect LOS/NLOS measurements.

In the proposed method, at each time step, we firstly get an estimated position of the MP using LS algorithm, using last

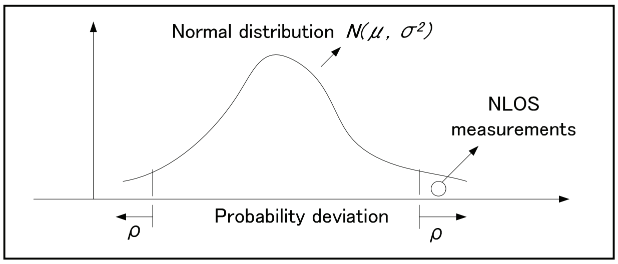


Figure 2: Chauvenet's criterion test

position, step length and all TDOA measurements. Then we substitute the estimated position of the moving MP to the measurement equation (1) to obtain estimated distances for each hearable LM. And then, we form a normal distribution for the estimation differences. Finally, we use Chauvenet's criteria to separate LOS and NLOS measurements from this normal distribution. In statistical theory, Chauvenet's criterion is a mean of assessing whether one piece of experimental data from a set of observations, is likely to be spurious [20], as shown in Figure 3.

Notice that, at the begging of the method or when the MP is standing still, the measurements of distances can be repeatedly received from hearable LMs several times. The flowchart is shown in Figure 3. The detail steps are described below.

[Step 1] Estimate the initial location of a MP.

We make use of the WLS (weighted least square estimation) method [11], to estimate the initial location of a MP, where each weight is equal to the inverse of the corresponding sample variance. To reduce the computation cost, we basically use LS method to estimate the location of MP, the details will be discussed in the location estimation method (section 4.2),

[Step 2] Integrate step size and count from mobile phone built-in sensors. It can be achieved by [14-15].

[Step 3] Generate an estimated location using last location of the MP, step size, and all hearable TDOA measurements with LS method; if the current location is not an initial location.

[Step 4] Generate the estimated distance by substituting the estimated position (step 3) of the moving MP to the measurement equation (1) to obtain estimated distances for each hearable LM.

[Step 5] Generate estimation differences for the distance measurements from all hearable LMs.

$$\gamma_i(k) = d_i(k) - H_i(k) \tag{3}$$

$\gamma_i(k)$ is the estimation difference, $d_i(k)$ is the measured distance and $H_i(k)$ is the estimated distance from the i_{th} LM at the time slot k, computed from step 4.

$\gamma(k) = (\gamma_1(k), \gamma_2(k), \ldots, \gamma_N(k))$

[Step 6] Generate a normal distribution for $\gamma(k)$; and calculate the probability deviation for $\gamma_i(k)$.

[Step 7] Calculates Chauvenet's criterion test [20] for the generated distribution;

$$C(\gamma_i(k)) = P(\gamma_i(k)), \sim N(\bar{\gamma}(k), \sigma^2(k))) * (n * p) \qquad (4)$$

where $C(\gamma_i(k))$ represents the Chauvenet's criterion test result for the estimation set $\gamma(k)$. p is the number of LOS measurements in $\gamma(k)$.

[Step 8] Determines the current measurement is a LOS or a NLOS one. Equations (5-6) illustrate the determination rules,

$$\text{LOS measurement} \qquad C(\gamma_i(k)) < 0.5 \qquad (5)$$

$$\text{NLOS measurement} \qquad C(\gamma_i(k)) \geq 0.5 \qquad (6)$$

If the test results show that the current measurement a LOS measured distance, we add it to the LOS measurements to form a new estimation distribution.

Figure 4 shows an example for the proposed LOS/NLOS detection method. Assume that the measured distance from LM1 to LM4 is (18.1, 6.3, 12.6, 14.6) ; step length is 7.6m in five seconds, then the estimated distance from LM1 to LM4 is calculated as (9, 8.4, 10.2, 15.8). The estimation difference is (9.1, -2.1, 2.4, -1.2). The normal distribution of a user's step length can be obtained as $\mathrm{N}(2, 3.5^2)$. Finally, the result for Chauvenet's criterion test is that, the measured distance from LM1 (18.1) is regarded as a NLOS measurement.

4.2 Location Estimation

In mixed LOS/NLOS environments, the estimated location of the MP from all measurements may be far away from the true location due to the NLOS problem. As multiple TDOA measurements are collected, may some of them are biased by NLOS error at a certain time step. If we could effectively detect those LOS measurements and make use of them to locate the MP, the performance of the classical location algorithms will be better than using all mixed LOS/NLOS measurements. However, if the number of hearable LOS measurements is less than three, it will be a problem to estimate the location of MP.

In this subsection, the idea of the proposed method is summarized as follows: if the number of hearable LOS measurements is bigger than four, we discard the hearable NLOS measurements and use LOS measurements with LS algorithm to estimate the location of a MP directly; if the number of hearable LOS measurements is less than four, we combine the last location of MP, the step length, and hearable NLOS measurements into LS algorithm to estimate the location. The flowchart is shown in Figure 5.

The detail steps are shown below.

[Step 1] Receive TDOA measurements from hearable LMs.

[Step 2] Check the number of LOS measurements. It can be achieved by the method in 4.1

[Step 3] Integrate step size and count from mobile phone built-in sensors. Assume the estimation error to be ∓α%. The step length for the user is estimated as follows,

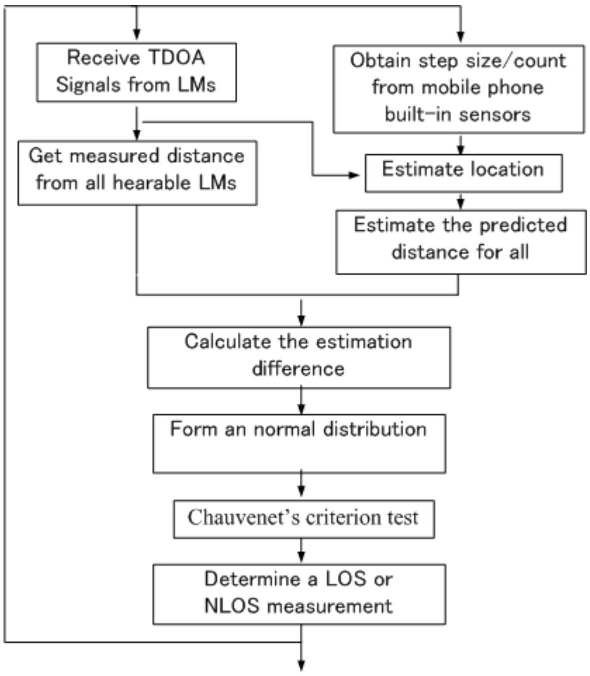


Figure 3: The flowchart of LOS/NLOS detection method

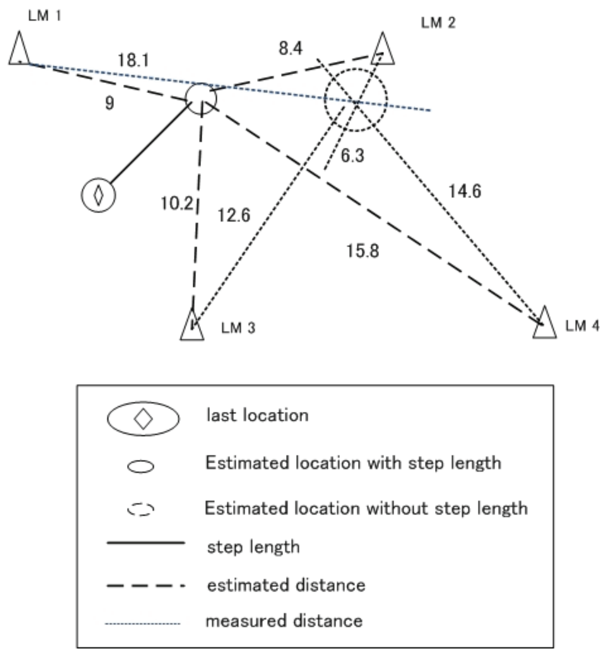


Figure 4: An example of LOS/NLOS detection method

$$s_{length}(k) = s_{size}(k) * s_{count}(k) * (1 + \alpha\%) \qquad (7)$$

[Step 4] Get all the combinations which contain N-1 TDOA location measurements and built-in sensor measurements. Form two combinations,

$$N_1 = \sum_{i \in LMs}^{N_1} \binom{N_1}{i};$$

$N_2 = \sum_{j\in LMs,sensors}^{N_2} \binom{N_2}{j}$;

N_1 is the set that only combines the measurements from the LMs;

N_2 is the set that combines the measurements from the LMs and built-in sensors.

[Step 5] Estimate the user's location by using LOS measurement in combination N_1 with LS algorithm, if the hearable LOS measurements are bigger than four.

[Step 6] Estimate the location by using last location, step length, LOS and NLOS measurements, if hearable LOS measurements are less than four. The last position of the mobile phone is considered as a new LM, denoted as $\mathrm{LM}_{\mathrm{past}}$. $s_{length}(k)$ is treated as distance measurements from $\mathrm{LM}_{\mathrm{past}}$.

Figure 6(a,b) show an example for the proposed location estimation method. Figure 6(a) is the scenario, where the three TDOA measurements are received, the signals from LM2 is detected as a NLOS measurement. Therefore the current location is estimated by using the two LOS measurements (13m and 14.8m) from LM1 (0,0), LM3(43.25,0) and the last location(12,-14.3); and the step length with 7.5m. Then using LS method, the estimated location is (24.3, -4,7). Figure 6(b) is the scenario, where three TDOA signals are received; all these signals are detected as LOS measurements. Therefore, the location is estimated by using these three LOS measurements with LS algorithm directly. The estimated location is (25.1, -3.8).

5. Simulations

In this section, simulations are performed to evaluate the performance of the proposed method.

5.1 Simulation Setup

We consider a simulation area, where 7 LMs are placed in the simulation area, as shown in Figure 8. The transmission distance (R) of a LM is assumed to be 25m. The coordinates of each LM are as: (0, 0), ($-\sqrt{3}$R, 0), ($\sqrt{3}$R, 0), ($-\sqrt{3}\mathrm{R}/2$, 3R/2), ($\sqrt{3}\mathrm{R}/2$, 3R/2), ($-\sqrt{3}\mathrm{R}/2$,-3R/2), ($\sqrt{3}$R,-3R/2). Hearable LMs are varied from four to six. Considering the impact of the wireless irregular radio distance, we assume that the radio distance of LM follows the Gaussian distribution $N(0, 0.5^2)$.

To evaluate the localization performance, the user is simulated to walk in the pre-determined route in the simulation area. As shown in Figure 8, A is the start point and B is the end point of the user's walking trajectory. C is a place where some TDOA measurements are biased by NLOS errors. When the TDOA measurement from the i_{th} LM is simulated to be biased by NLOS error, we added a NLOS error distribution to the true distance. For the purpose of simulation, we assume that NLOS errors are also Gaussian distribution $N(0, 5^2)$. The number of NLOS measurements is varied for performance evaluation. We simulate a user's step length using built-in sensor data in a

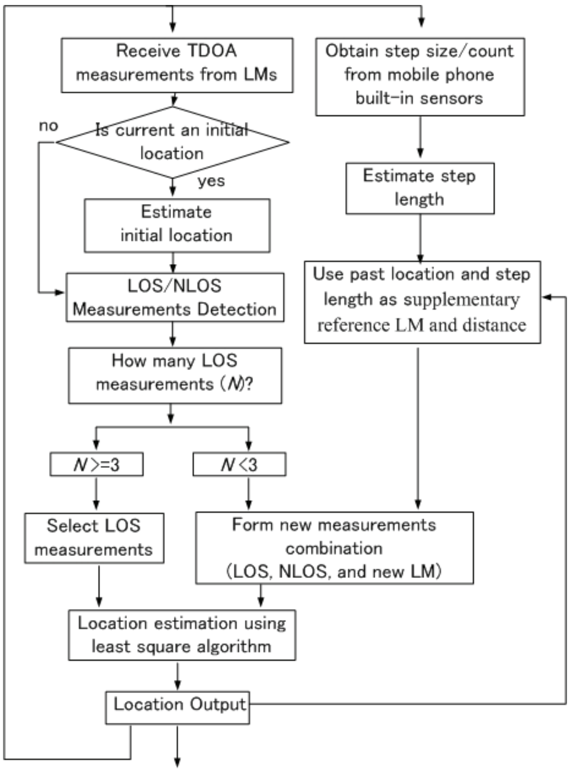


Figure 5: The flowchart of location estimation method

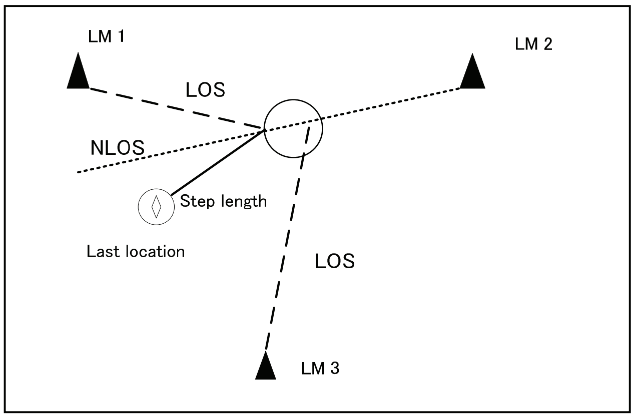


Figure 6(a): An example of location estimation method (two LOS and one NLOS measurements)

mobile phone from reference [14-15]. A random walking speed is selected between 0.8m/s~1.4m/s for an adult user [17]. The user's walking distance is obtained at each second. The user's step size at each second is sampled from this walking distance with $\pm 10\%$ error. All the simulation results are the average of 50 runs.

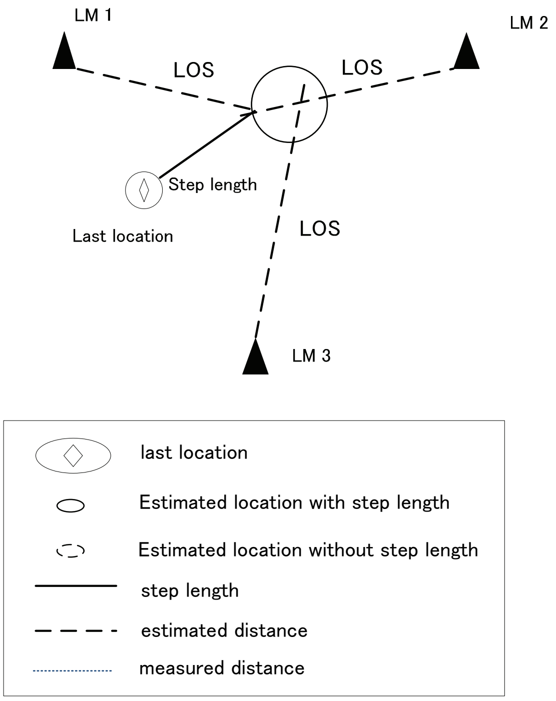


Figure 6(b): An example of location estimation method (three LOS measurements)

5.2 Comparison Algorithms

The following methods are used for comparison:

For part I: LOS/NLOS measurements detection, the user encounter NLOS at 30s, 90s and 150s, the following methods are used for comparisons,

- KF: a kalman filter-based mitigation algorithm [7]. The existence of NLOS component is identified first. Then the distance measurements are smoothed for calculating standard deviation in a hypothesis testing.
- RV: a distance variance-based estimation method introduced in reference [11]. It estimates the relevant parameters to certain thresholds, and then distinguishes NLOS measurements from LOS ones.

For part II, location estimation, the following methods are used for comparisons,

- LS: the method introduced in reference [6]. It uses range measurements to produce location estimation.
- WLS: the method introduced in reference [18]. The residual weight of each intermediate estimate is calculated first, then to generate location estimation.
- LOS measurement only: the first evaluation way of the proposed method. Detect LOS measurements by part I then use them with LS methods to estimate the location.
- Combination: the second evaluation way of the proposed method. Use detected LOS measurements, last location and step length information with LS methods to estimate the location.

5.3 LOS/NLOS Measurements Detection Ratio

In this subsection, we want to make detailed observations and comparisons for the proposed LOS/NLOS measurements detection method. LOS/NLOS measurement detection ratio is used as an evaluation metric. In the evaluations, two conditions are considered to be wrong detection results: NLOS measurements are detected as LOS measurements; and LOS measurements are detected as NLOS measurements. Therefore, LOS/NLOS measurement detection ratio is defined as,

$$(Measured_{\mathrm{t}} - Measured_{\mathrm{w}})/Measured_{\mathrm{t}} * 100\% \qquad (8)$$

where $Measured_{\mathrm{w}}$ is the number of TDOA measurements that are wrong detections; $Measured_{\mathrm{t}}$ is the number of TDOA measurements that are totally detected. Larger detection ratio means better result.

Simulation results were summarized in Fig.8 (a-c) for different combination of LOS/NLOS measurements. Obviously, KF method performs worst in all scenarios, about 50%-75% detection ratio. This is because using bias kalman filter method, NLOS errors will not be detected when the measured distance is bigger than the predicated distance. The bias adjusting rule makes the detection less effective since some NLOS measurements are easily to be identified as LOS measurements. RV method performs well when four or five TDOA measurements are heard, as LOS/NLOS detection ratio is about 85%- 90%. This is because that, RV method does not need to perform MP location before NLOS identification can be carried out. However, its performance reduces when the number of hearable measurements is increased. The proposed method performs best and stable in all scenarios. This is because the last location information and step length is introduced to estimate the location of MP before the LOS/NLOS measurement detection. This step makes the detection method more reliable, therefore it achieves better performance.

5.4 Location accuracy

The goal of a wireless location system is to accurately localize a user. In this subsection, we evaluate the location estimation by using location error. Location error is defined as the difference between the user's pre-determined location route and the estimated location route.

Figure 9(a) shows the simulation results for location errors evaluated by different methods when the number of detected LOS measurements is more than three. From the figure, we see that the proposed method that only uses LOS measurements with LS method performs best, and also outperforms the proposed method that uses the combination of measurements. LS performs worst, WLS performs stable, as the number of TDOA measurement increases. For instance, when there are six TDOA measurements, four are detected as LOS measurements. The location error using the proposed method in the first evaluation way is about 4.2 m and 6.9m in the second evaluation way. One reason for

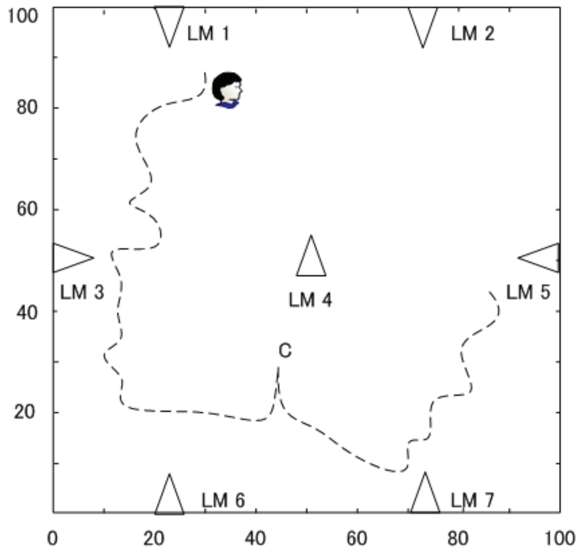


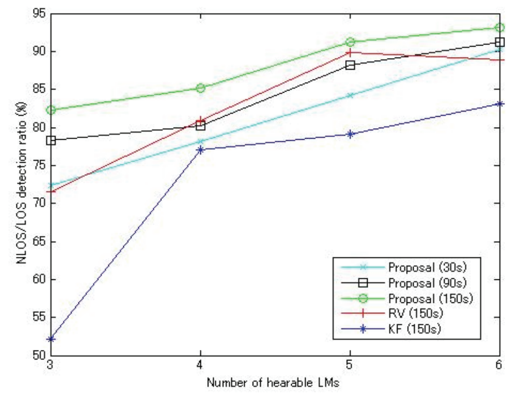
Figure 7: Simulation scenario

combination way perform worse than only LOS measurements is that even if the last position and step length can used as a supplementary LM and measurements in location estimation, actually the initial location is based on the average results of several WLS steps. I.e. the accuracy of the initial location has impact on the location accuracy. Therefore, the result that only uses LOS measurements performs better.

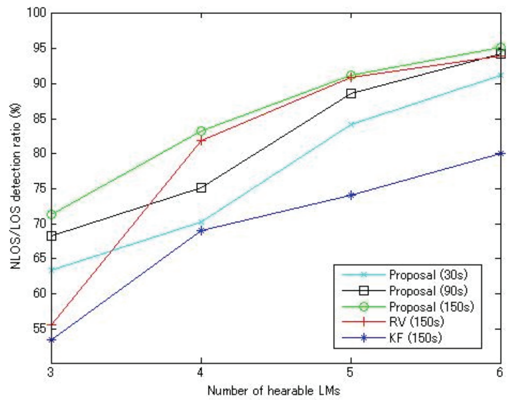
Figure 9(b) shows simulation results for location errors evaluated by different methods when the number of detected LOS measurements is less than three. We see that location estimation using LS method performs worst, and the proposed method with the combination measurements performs best. The result is clear when the number of NLOS measurements increases. The combination provides more measurements when the hearable LOS measurements are less than three. WLS methods perform less than combination but steadily, this is because that the NLOS/LOS detection also performs worse while steadily as shown in section 5.2, if the same initial location is provided

6. Conclusions

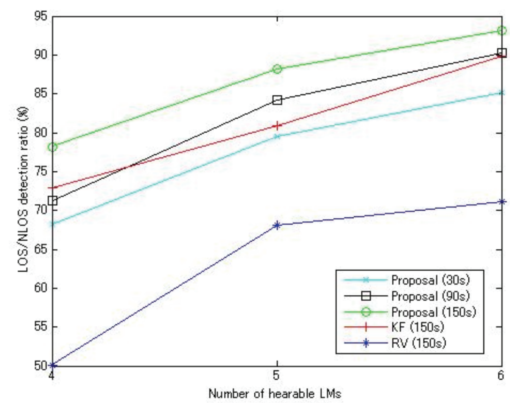
In this paper, we proposed a new integration location method to solve the NLOS problem in wireless TDOA location system. Simulation results show that in typical indoor wireless networks, it is likely to compute a node's location using a mixture of LOS and NLOS distance estimates. Step length information from mobile phone built-in sensors could be used to improve LOS/NLOS measurements detection ratio without incurring location accuracy degradation. Also, simulation results show that using the proposed method, location estimation error is reduced, when less LOS measurements are detected in a wireless TDOA location system.



(a). One NLOS measurements

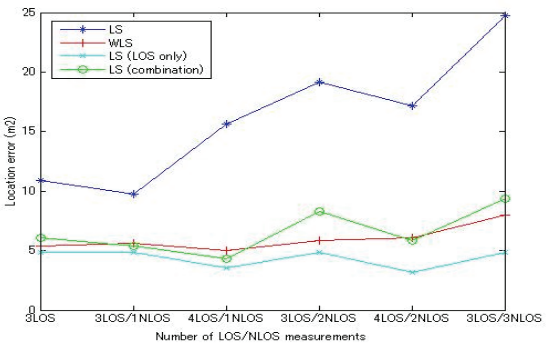


(b). Two NLOS measurements

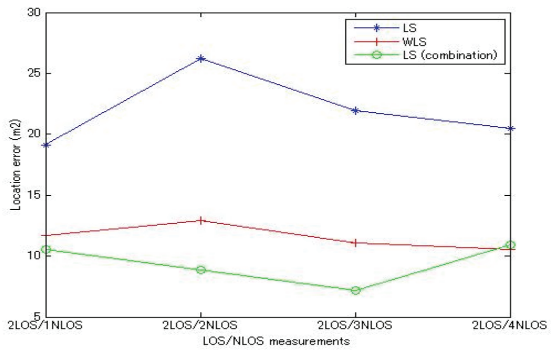


(c). Three NLOS measurements

Figure 8: LOS/NLOS Measurement detection ratio



(a). LOS measurements are larger than three



(b). LOS measurements are smaller than three

Figure 9: Location error

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