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A TDOA location algorithm based on data fusion

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Abstract A new positioning method in mobile networks is presented. Based on the data fusion technology, it processes multi-layer information fusion for the location estimates achieved by the Chan algorithm, which increases mobile positioning accuracy effectively by only using measured difference of arriving (TDOA) signals. The method is simple and practical, especially when the location estimates are corrupted by the non-line-of-sight (NLOS) error. It not only has high positioning accuracy, but also reduces the location failure probability. Results from computer simulation show that the proposed method is effective in various environments.

Keywords mobile location, TDOA, data fusion, NLOS

1 Introduction

With the high growth of the wireless communication services industry, mobile station location has become a hot topic in the research area of wireless communication technology. It could be used for not only emergency service, but also other services based on location, such as location-based billing system, fleet management or intelligent transportation system in wireless networks. According to the E-911 location requirement announced by the U. S. Federal Communication Committee in 1996, there was a requirement for businessmen on time-limit and accuracy of using the location techniques in wireless communication networks [1].

In cellular networks, the main mobile station location techniques are:

- 1) Based on the intensity of arrival.
- 2) Based on the incidence angle of arrival (AOA).
- 3) Based on the time of arrival (TOA) or the time difference of arrival (TDOA). There are two methods in practice, which are based on network location and based on mobile station location. Since the network location technique doesn't require the modification of the existing mobile station and can make full use of the terminal equipment in being, it has got high attention.

The location technique based on the TDOA measurements is easy to implement in the practical system (such as IS-95 CDMA) because the synchronization between base station (BS) and mobile station (MS) is not required and synchronization among the base stations involved in the measurement has been accomplished. The key factor of this kind of position location method is to find the solution of nonlinear hyperbolic equations created by the TDOA measurements. The general algorithm to solve hyperbolic equations is the Chan [2] method. It can achieve good performance for Gauss noise circumstance, but the performance will decrease when the radio measurements are corrupted by the NLOS error.

This paper presents a new location method base on the Chan algorithm and data fusion technology. Simulation results show that positioning accuracy of the proposed approach is better than the Chan algorithm when the location estimates are corrupted by the NLOS error and different measurement errors.

2 TDOA location algorithm based on data fusion

2.1 Chan algorithm

The Chan algorithm is a widely used method in solving the hyperbolic position equations, since it can achieve optimum performance under various conditions [3]. When there are more than four base stations involved in location measurement, the main idea of the Chan algorithm is: transforming the original set of nonlinear TDOA equations into another set of equations that are linear, then using the

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weighted linear LS to acquire an initial solution. Finally a second weighted LS achieved utilizing the initial solution and other known constraints between source coordinates and the extra variable is used to get the improved final position estimate. The processes shown in detail are:

1) Acquiring the initial approximate solution

$$\mathbf{z}_a \approx (\mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{h} \quad (1)$$

where

$$\mathbf{G}_a = - \begin{bmatrix} X_{2,1} & Y_{2,1} & R_{2,1} \\ X_{3,1} & Y_{3,1} & R_{3,1} \\ \vdots & \vdots & \vdots \\ X_{M,1} & Y_{M,1} & R_{M,1} \end{bmatrix}$$

$$\mathbf{h} = \frac{1}{2} \begin{bmatrix} R_{2,1}^2 - X_2^2 - Y_2^2 + X_1^2 + Y_1^2 \\ R_{3,1}^2 - X_3^2 - Y_3^2 + X_1^2 + Y_1^2 \\ \vdots \\ R_{M,1}^2 - X_M^2 - Y_M^2 + X_1^2 + Y_1^2 \end{bmatrix}$$

\mathbf{Q} is the TDOA covariance matrix, X_i and Y_i are coordinates of the i th metrical BS, $X_{i,1}$ and $Y_{i,1}$ are the differences of coordinates between the i th BS and the serving BS, $R_{i,1}$ is the difference of the distance from the MS to the i th BS and the distance from the MS to the serving BS.

2) Calculating the WLS estimates

a) If the MS is near the BS, calculate the first and second WLS solutions separately by using these two equations below:

$$\mathbf{z}_a = (\mathbf{G}_a^T \mathbf{\Psi}^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \mathbf{\Psi}^{-1} \mathbf{h} \quad (2)$$

$$\mathbf{z}'_a = (\mathbf{G}'_a{}^T \mathbf{\Psi}'^{-1} \mathbf{G}'_a)^{-1} \mathbf{G}'_a{}^T \mathbf{\Psi}'^{-1} \mathbf{h}' \quad (3)$$

where $\mathbf{\Psi} = c^2 \mathbf{B} \mathbf{Q} \mathbf{B}$ is the error vector, $\mathbf{B} = \text{diag} \{R_2^0, R_3^0, \dots, R_M^0\}$, and

$$\mathbf{G}'_a = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}, \quad \mathbf{h}' = \begin{bmatrix} (z_{a,1} - X_1)^2 \\ (z_{a,2} - Y_1)^2 \\ z_{a,3}^2 \end{bmatrix}$$

b) If the MS is far from the BS, calculate the first WLS estimate through Eq. (1) and obtain the second VLS estimate using the equation below:

$$\mathbf{z}'_a \approx (\mathbf{G}'_a{}^T \mathbf{B}'^{-1} \mathbf{G}'_a{}^T \mathbf{Q}^{-1} \mathbf{G}'_a \mathbf{B}'^{-1} \mathbf{G}'_a)^{-1} (\mathbf{G}'_a{}^T \mathbf{B}'^{-1} \mathbf{G}'_a{}^T \mathbf{Q}^{-1} \mathbf{G}'_a \mathbf{B}'^{-1}) \mathbf{h}' \quad (4)$$

At last, gain the final location estimate of the mobile station utilizing Eq. (5).

$$\mathbf{z}_p = \pm \sqrt{\mathbf{z}'_a} + \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix} \quad (5)$$

2.2 TDOA algorithm based on data fusion

The idea of data fusion is to combine the data based on different estimating methods logically to achieve a new computing approach that is more precise than that achieved using any single method. The fusion objects can be the initial or processed estimated data.

General models of mobile position location data fusion are based on either different algorithms (Taylor series and Chan) [3] or different measurements (TDOA, TOA, AOA) [4]. Targeted at TDOA measurement, this paper proposes a simple and practical position location model based on data fusion. The main idea is only committing the data fusion to different stage's results calculated by the Chan algorithm. The steps are:

1) From the TDOA measurement, obtain three location estimates using the Chan algorithm: initial estimates, near estimates and far estimates.

2) Use the accessible information such as the radius of the cell and the sector information of the mobile station to filter the bad estimates.

3) The first level data fusion: the first level data fusion estimate is the linear combination of the three dealt initial estimates (\bar{x}_1, \bar{y}_1) , (\bar{x}_2, \bar{y}_2) , (\bar{x}_3, \bar{y}_3) with equal weight.

$$\hat{x}_{l1} = \frac{\bar{x}_1 + \bar{x}_2 + \bar{x}_3}{3} \quad (6a)$$

$$\hat{y}_{l1} = \frac{\bar{y}_1 + \bar{y}_2 + \bar{y}_3}{3} \quad (6b)$$

4) The second level data fusion: this fusion process is based on Bayesian inference. Suppose three position estimates with different means and variances are $(\bar{x}_1, \bar{y}_1, \sigma_{x1}, \sigma_{y1})$, $(\bar{x}_2, \bar{y}_2, \sigma_{x2}, \sigma_{y2})$ and $(\bar{x}_3, \bar{y}_3, \sigma_{x3}, \sigma_{y3})$, then the position estimate is:

$$\hat{x}_{l2} = \frac{\bar{x}_1 / \sigma_{x1}^2 + \bar{x}_2 / \sigma_{x2}^2 + \bar{x}_3 / \sigma_{x3}^2}{1 / \sigma_{x1}^2 + 1 / \sigma_{x2}^2 + 1 / \sigma_{x3}^2} \quad (7a)$$

$$\hat{y}_{l2} = \frac{\bar{y}_1 / \sigma_{y1}^2 + \bar{y}_2 / \sigma_{y2}^2 + \hat{y}_3 / \sigma_{y3}^2}{1 / \sigma_{y1}^2 + 1 / \sigma_{y2}^2 + 1 / \sigma_{y3}^2} \quad (7b)$$

At the same time, another estimate will be provided in this level by selecting an estimate with the smallest variance from the three initial estimates.

5) The third level data fusion: choose the appropriate position estimate as the final optimal estimate based on the information calculated previously. This process uses the variance information of distances between MS and BS and the probability of obtaining the least location error of the different level estimate output.

3 Simulation and results

3.1 Simulation conditions

The location measurement system is shown in Fig. 1. It is a seven-base station cellular network, and wireless cells adopt a 120 degree sector structure. BS1 is the serving BS. The test conditions are bad urban, urban, suburb and rural. To verify the applicability of the proposed algorithm, 4200 test locations are selected in the serving BS cell. These points locate on the twenty circles that distribute in the area uniformly around the BS1. For each location, the simulation will repeat ten times to obtain the mean result.

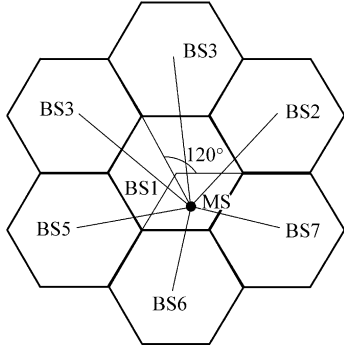


Fig. 1 Structure of cellular network

Consider two types of errors: measurement error and NLOS error. The measurement error is modeled as a Gaussian random variable [5], with zero mean and standard deviation of 25 m, 50 m and 100 m in our simulation. NLOS error l adopts the exponential distribution error model [6], and its probability density function (PDF) is :

$$D(l) = \begin{cases} \frac{1}{c\tau_{\text{rms}}} \exp\left(-\frac{l}{c\tau_{\text{rms}}}\right) & d > 0 \\ 0 & d \leq 0 \end{cases} \quad (8)$$

where c is the speed of light, $\tau_{\text{rms}} = T_1 d^\epsilon \xi$ is the delay spread which depends on the propagation environment. T_1 is the median value of τ_{rms} at $d = 1$ km, d is the distance between the transmitter and receiver. ϵ is an exponent that lies between 0.5–1, ξ is a lognormal variate, which makes $10 \log \xi$ be a Gaussian random variable having zero mean

and a standard deviation σ_ξ that lies between 2–6 dB. Table 1 shows the different values of the parameters T_1, ϵ and σ_ξ in four typical environments.

Table 1 Parameters in typical mobile environment

| Environment | $T_1 / \mu\text{s}$ | ϵ | σ_ξ / dB |
|-------------|---------------------|------------|--------------------------|
| Bad urban | 1.0 | 0.5 | 4 |
| Urban | 0.4 | 0.5 | 4 |
| Suburb | 0.3 | 0.5 | 4 |
| Rural | 0.1 | 0.5 | 4 |

In fact, not all the signals that propagated between the base stations and MS are corrupted by the NLOS error, so we consider two types of NLOS existing in the simulation: One is for the real circumstance. We set the P_{NLOS} of the serving BS to be 0.4, and those of the other surrounding base stations are 0.7 in the simulation. The other is setting all the P_{NLOS} of base stations involved in the measurement to be 1. This hypothesis doesn't fit the real station, so it is only to test the validity of our algorithm under the worst condition. Mean location error is chosen as the performance criteria.

3.2 Simulation results

Figure 2 shows the mean location error P_{av} when the standard deviation of measurement error is 25 m under four

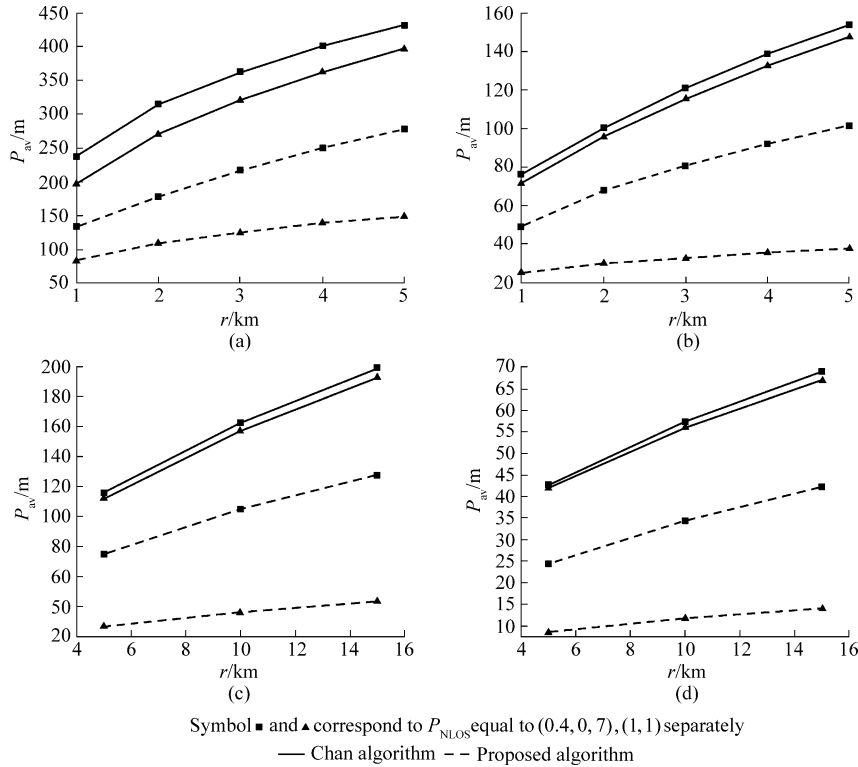


Fig. 2 Results of average positioning error in typical environment. (a) Bad urban; (b) Urban; (c) Suburb; (d) Rural

typical environments. In the case of Bad urban and Urban, the radius of the cell is 1–5 km, and for Suburb and Rural, the radius is 5, 10 or 15 km. The results of P_{av} when P_{NLOS} is (0.4, 0.7) with different measured mean variances P_t (25, 50, and 100 m) are provided in Fig. 3.

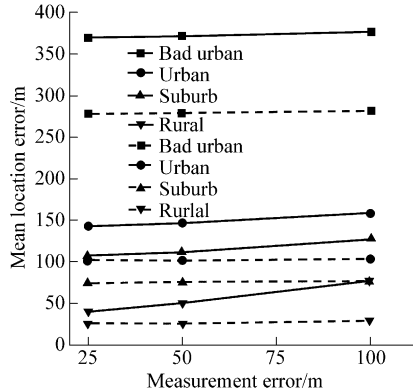


Fig. 3 Simulate results of different mean-square error in measurement ($P_{NLOS} = (0.4, 0.7)$)

Table 2 Improvement of positioning accuracy in different environment %

| r/km | Bad UrBan * | Bad Urban | Urban * | Urban |
|--------|-------------|-----------|---------|-------|
| 1 | 44.0 | 57.9 | 35.6 | 64.9 |
| 2 | 43.7 | 60.2 | 32.2 | 69.1 |
| 3 | 40.3 | 61.4 | 32.2 | 71.8 |
| 4 | 37.8 | 62.1 | 33.9 | 73.2 |
| 5 | 35.9 | 62.8 | 34.0 | 74.2 |
| r/km | Suburb * | Suburb | Rural * | Rural |
| 5 | 35.2 | 76.1 | 42.6 | 79.8 |
| 10 | 35.5 | 77.0 | 39.7 | 79.2 |
| 15 | 35.9 | 77.4 | 38.8 | 79.0 |

Note: Symble* correspond to $P_{NLOS} = (0.4, 0.7)$, others correspond to $P_{NLOS} = (1, 1)$

From Figs. 2 and 3, we can observe that, when the measured mean variance is from 25 m to 100 m, using the proposed algorithm we can achieve higher positioning accuracy than using the Chan algorithm in the four typical mobile communication environments. In addition, the worse

the mobile environment is, namely the larger the probability of NLOS occurring, the more obvious the improvement in location accuracy would be, and the effect is not sensitive to the measurement error. The improvement of positioning accuracy is shown in Table 2.

4 Conclusions

The proposed model in this paper has the following characteristic: it is based on only one kind of measurement (TDOA) and one algorithm (Chan), which makes its computation less than that of the TOA/TDOA, TDOA/AOA data fusion model. If there is NLOS error, the positioning accuracy of this model is higher than that of the Chan algorithm in various mobile communication environments.

Another characteristic is that it can reduce the location failure probability caused by estimates that hardly satisfy the requirement. Since three estimates are used simultaneously, even if one estimate is discarded due to error, there are still other estimates that can be used. The simulation result has proved that compared to that of the Chan algorithm, the location failure probability of this proposed algorithm will decrease by 88 %.

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