A Regional Positioning Algorithm for Non-line-of-sight (NOLS) Propagation

Huiming Wu, Jiankang Yang and Cheng Chang

The PLA Army Armored Forces Academy

2535288375@qq.com

Abstract. This paper presents a Regional Positioning Algorithm based on NOLS propagation, which is a Positioning Algorithm based on measured value of arrival time, using geometric constraints to estimate the position of the mobile station. One of its remarkable features is that, compared with other algorithms, this algorithm greatly simplified the calculation amount while ensuring the positioning accuracy.

Keywords: Non-line-of-sight (NOLS) propagation, regional positioning, geometric position, probability density.

1. Introduction

With the development of the integrated electronic system of Army equipment, in order to improve the ability of superior commanders to control the situation of armored units, achieve the interconnection between various types of sensor on vehicles and information sharing, and form the capacity of timely detection, rapid response, joint strike and regional coordinated operations, it's necessary to achieve the precise positioning of the vehicles of the armored units and the monitoring of the regional situation of the armored units.

Line-of-sight (LOS) propagation is a necessary condition for accurate measurement of positioning parameters. However, in the coverage area of the positioning network, especially in the modern battlefield, the vehicle density and the information traffic are heavy, meanwhile, for the battlefield positioning that requires high positioning accuracy, the direct path is often blocked due to the complex terrain, therefore the existence of LOS propagation is very rare, and the NLOS propagation pollution is serious. Since the propagation path of NLOS is longer than that of LOS, the radio wave propagation time of NLOS is longer than LOS, which brings a large error to the time-based positioning. Besides, the receiver will receive a superposed signal from series of uncertain reflection and diffraction paths due to the lack of direct path, which will result in a great uncertainty of the TOA (Time of Arrival)/TDOA (Time Difference of Arrival) measurement result, shown by measured value's random distribution within a wide range from the actual value. Therefore, how to improve the accuracy of the regional positioning algorithm under NLOS conditions and to simplify the algorithm is the essential object of regional positioning research.

2. Effect of NLOS Propagation on Positioning

To determine the position of mobile station within the region, there are usually two steps: the first step is to estimate the corresponding positioning parameters according to different positioning types; the second step is to estimate the position of mobile station by using the corresponding positioning algorithm and the estimated positioning parameters.

The wireless positioning algorithm is divided into geometric structure method and statistical positioning method, according to their different processing of positioning parameters. It is divided into LOS positioning and NLOS positioning algorithms, according to the different application scenarios. The early wireless positioning is mainly used in the navigation field, where there are usually LOS propagations between the transceiver devices of navigation system. Therefore, the early positioning algorithms are all LOS positioning algorithms. The typical LOS positioning algorithms include Chan algorithm of system TDOA proposed by Chan, and Taylor series positioning algorithm proposed by Taylor.

Since the propagation path of NLOS is longer than that of LOS, the radio wave propagation time of NLOS is longer than LOS, which brings a large error to the time-based positioning. Besides, the receiver will receive a superposed signal from series of uncertain reflection and diffraction paths due to the lack of direct path, which will result in a great uncertainty of the measurement result TOA and TDOA, shown by measured value's random distribution within a wide range from the actual value. Therefore, how to identify and suppress NLOS errors is the essential object of military area autonomous positioning research.

The effect of NLOS propagation on measurement value TOA is shown in the fact that: there is no direct path between the base station and the mobile station due to the blockage caused by buildings or mountains. Therefore, the electromagnetic waves can only be reflected between the base station and the mobile station, that is, the electromagnetic waves can only be propagated in NLOS condition. Since the NLOS propagation path is longer than the LOS propagation path, the measured TOA will have an excessive delay, that is, the NLOS error, and this error is a random error with a positive mean value. The existence of this error will inevitably affect the positioning accuracy. In different channel environments, it could be exponential, uniform, Gaussian or Delta distribution, and it is impossible to eliminate the NLOS error by improving the TOA and TDOA measurement accuracy of the system receiver. It is only related to the propagation environment of the radio wave.

3. Geometric Constraint Algorithm that Overcomes NLOS

When using TOA/TDOA technology for position estimation, the main factor that affects the positioning accuracy is the NLOS error. The NLOS error is defined as the excessive propagation distance compared to the direct path, and its variation is from 0 to 1300 meters. During position, after processing the NLOS error, it's necessary to solve the nonlinear equations obtained by these methods. In solving nonlinear equations, the most common method is to use the linear ML function for iterative calculation (Taylor algorithm). The disadvantage of this method is that the calculation is complicated and the initial value is difficult to determine. Another method is to use the algorithms which solution has analytical expression in it (such as the Chan algorithm). These algorithms do not need iterative calculations or initial values, but are not optimal ML methods.

In this paper it's proposed an algorithm of ML estimation based on geometric position constraints. This algorithm is a positioning algorithm based on TOA measurement. Firstly, using any three TOA values, considering the geometric relationship between the TOA value, the position of the mobile station and the position of the base station, estimate all possible positions of the mobile station. Then, using the ML algorithm, select an estimated value that is most likely to be the real position of the mobile station from all possible positions, as the final positioning result. The algorithm can always obtain the best estimated value by small calculation amount and high calculation precision to effectively suppress the NLOS error.

In order to facilitate the derivation of the algorithm, a mathematical model of the TOA measured value is first given below.

$$r_k = \int_k (X) + n_{los,k} + n_{nlos,k} \quad k=1,2.....N \tag{1}$$

Where r_k represents the TOA measured value corresponding to measured distance from the k^{th} base station to the mobile station, $n_{los,k}$ represents the measurement error, $n_{nlos,k}$ represents the NLOS error, and $\int_k (X)$ represents the true distance from mobile station to the k^{th} base station, that is, $\int_k (X)=\sqrt{(x-x_k)^2+(y-y_k)^2}$, where (x, y) is the real position of the mobile station, x_k, y_k is the coordinate position of the k^{th} base station. Normally, $n_{los,k}$ is of Gaussian distribution with zero mean, and $n_{nlos,k}$ is a positive NLOS error whose distribution is usually unknown.

Under this assumption, the Probability Density Function (PDF) of the TOA measured in the kth base station in the LOS and NLOS environments can be expressed as:

$$P_{LOS}\left(r_k/(x,y)\right) = \frac{1}{\sqrt{2\pi}\sigma_k} e^{-\frac{1}{2}\left(\frac{r_k - f_k(x)}{\sigma_k}\right)^2} \quad (2)$$

$$P_{NLOS}\left(r_k/(x,y), n_{los,k}\right) = \frac{1}{\sqrt{2\pi}\sigma_k} e^{-\frac{1}{2}\left(\frac{r_k - f_k(x) - n_{los,k}}{\sigma_k}\right)^2} \quad (3)$$

Therefore, the maximum likelihood estimation (MLE) of mobile station location can be expressed as:

$$\hat{X} = \text{argmax}_x \prod_{k \in s^{Los}} P_{LOS}(r_k/(x,y)) \quad \prod_{k \in s^{Los}} P_{NLOS}\left(r_k/(x,y), n_{nlos,k}\right) \quad (4)$$

Where SLOS represents a set of BS in a LOS environment; and SNLOS represents a set of base stations in a NLOS environment.

Take the natural logarithm of the above formula, there is

$$\hat{X} = \text{argmax}_x \sum_{k \in s^{Los}} \frac{(r_k - f_k(X))^2}{\sigma_k^2} \sum_{k \in s^{Los}} \frac{(r_k - f_k(X) - n_{nlos,k})^2}{\sigma_k^2} \quad (5)$$

When all base stations are in LOS environment, or when NLOS recognition techniques can be used to separate LOS from NLOS, the ML position estimation using only LOS measurement value is expressed as:

$$\hat{X} = \text{argmax}_x \sum_{k \in s^{Los}} \frac{(r_k - f_k(X))^2}{\sigma_k^2} \quad (6)$$

For the ML algorithm, the most difficult part is the maximization process in (5) or the minimization process in (6) to make X best match the PDF of TOA.

The TOA system determines the MS position by the intersection of the distance circles. For Fig. 2, two circles provide a fuzzy solution and three circles determine a unique solution. Since the NLOS error is a large non-negative value, the measured distance is much larger than the real distance, so the position of the mobile station is located in the overlapping area of the distance circle (as defined by the three points A, B, and C in Fig. 1). In this region, the point which sum of distances to the three points ABC is the smallest, will be determined as the position of the mobile station. That is, (x , y) = min F(x , y), where F(x, y) is defined as:

$$F(x,y) = (x - x_A)^2 + (y - y_A)^2 + (x - x_B)^2 + (y - y_B)^2 + (x - x_C)^2 (y - y_C)^2 \quad (7)$$

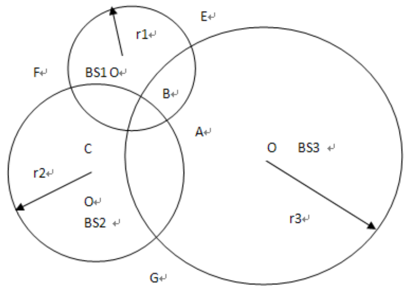


Fig. 1 Schematic diagram of the geometric relationship constraint algorithm based on TOA

In the GLE algorithm of this paper, the principle in determination of intersections A, B and C is:

(1) Select any two circles (such as r1 and r2) and calculate the intersection of these two circles (i.e. A and F);

(2) From the two intersection points, select on point that is closest to the third circle (r3) and located within the third circle (i.e. A) as a boundary point of the overlap region;

(3) If both intersection points are in the third circle, both points are selected;

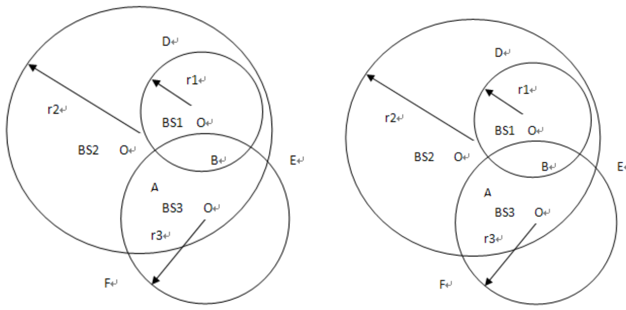
(4) If both intersection points are not in the third circle, none of these two points is selected;

But some special circumstances must be considered. Due to measurement errors, the two circles may not have intersections, as shown in Fig. 2. In Fig. 2 (a), there is no intersection between the circles r1 and r2. The non-existence of intersection is due to the large NLOS measurement error in the TOA value measured in BS2. To deal with this situation, we will modify r2 to r2', =d12+ri, where d12 represents the distance between base stations BS1 and BS2. As shown in Fig. 2 (a), the corrected circle with radius r2' intersects with the circle determined by BS1 at one point (i.e. point D). Thus, according to the above principle of determination of the boundary point of the coverage area, only points A and B of the 5 points satisfy the condition, therefore, F(x, y) is corrected to

$$F(x, y) = (x - x_A)^2 + (y - y_A)^2 + (x - x_B)^2 + (y - y_B)^2 \quad (8)$$

The position of the MS is still determined by (x, y) = min F(x, y).

In Fig. 2(b), there is no intersection between the circles r1 and r3. This case of non-existence of intersection is mainly due to the large measurement error in the TOA measured in the two base stations. In order to deal with this non-existence of intersection, the midpoint of the BS1-BS3 connection (i.e. point A) will be considered as the intersection of the two circles. According to the principle in determining the boundary point of the coverage area, the point A is the estimated position of the mobile station.



(a) (b)

Fig. 2 Circles with no intersection

The ML algorithm based on geometric restriction proposed in this paper is based on the hypothesis test of the characteristics set of base stations. If the base stations of the set are all in the LOS environment, the location of the mobile station can be estimated by equation (8). Conversely, if a point $\hat{X}$ is the best estimated value of MS in LOS environment, then it must satisfy the equation (8), and $\sum_{k\in s^{Los}} \frac{(r_k - f_k(\hat{X}))^2}{\sigma_k^2}$ will take the minimum value. If a point $\hat{X}$ is the estimated value of MS in NLOS environment, then the equation (8) will not be satisfied, and $\sum_{k\in s^{Los}} \frac{(r_k - f_k(\hat{X}))^2}{\sigma_k^2}$ will not be the minimum value. Therefore, when we have a set containing all possible locations of the mobile station, the point in the set which is most likely to be the real position of the mobile station should be the point in the set that makes $\sum_{k\in s^{Los}} \frac{(r_k - f_k(\hat{X}))^2}{\sigma_k^2}$ the minimum value. Obviously, the estimated position of the mobile station obtained in this way is the best.

Therefore,

1. Suppose there are N measured values (values measured from N different base stations), and select any 3 measured values from N measured values, there are totally $M=C_n^3$ combinations and each combination is represented by code of BS, that is $\{S_k | k = 1,2 \ldots M\}$

2. Each combination uses the GLE algorithm to estimate the position of the mobile station, and its estimated value is recorded as $\hat{x}^k, \hat{y}^k$, and calculate the PDF value of the corresponding set using the estimated value $\hat{x}^k, \hat{y}^k$ according to the following formula

$$P_k\left[(\hat{x}^k, \hat{y}^k), S_k\right] = \prod_{k\in S_k{}^{Los}} P_{Los}\left(r_l / (\hat{x}^k, \hat{y}^k)\right)$$

$$\text{Or } P_k^1 = \sum_{k\in S_k} \frac{(r_1 - f_1(X))^2}{\sigma_1^2}$$

3. The estimated value $\hat{x}^k, \hat{y}^k$ corresponding to the maximum value Pn (or the minimum value Pn' in Pk') (k=l, 2...M) in Pk is the final estimated value of the mobile station.

4. Conclusion

The proposed improved algorithm is simulated under different conditions. The simulated network topology is a typical regional structure, with one serving base station and six neighboring base stations.

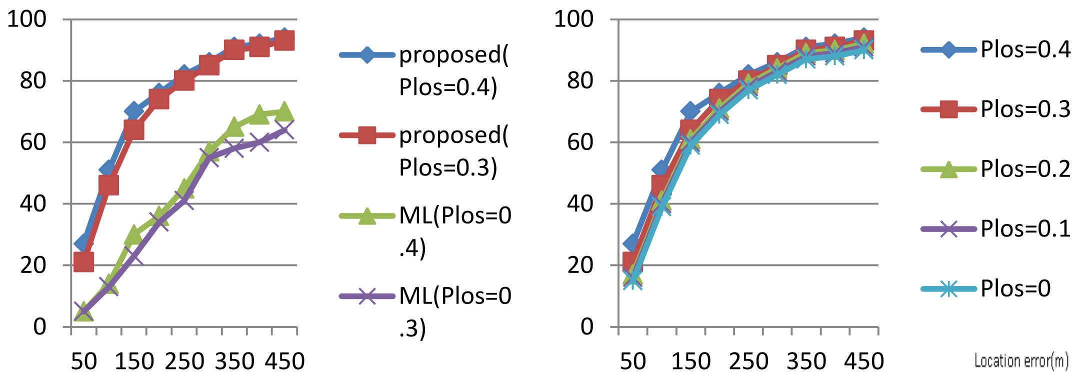


Fig. 3 Simulation evaluation

The figure on the left shows the performance comparison between the improved algorithm and the standard ML algorithm under the same conditions (7 base stations, Badurban environment, radius of 1000 meters). In this figure, Plos represents the probability that each of the seven base stations is in the LOS environment, and 1-Plos is the probability of the corresponding NLOS environment. The simulation results show that the proposed algorithm in this paper is far better than the ML algorithm.

The picture on the right shows the performance simulation of the improved algorithm under different NLOS probabilities (7 base stations, Badurban environment, radius of 1000 meters). The simulation results show that when Plos falls, the performance of the improved algorithm declines slowly. This means that the proposed improved algorithm can suppress the NLOS error very well, and its performance is not sensitive to the variation of NLOS error. Even when all base stations are in NLOS environment (Plos = 0), the cumulative distribution probability of positioning error less than 200 meters can still reach 71.11% (CDF (200) = 71, 11%).

References

[1]. Raythecn Systems Company. Enhanced Position Location Reporting System. 2003. 10.

[2]. Director, (Operational Test & Evaluation FY99 Annual Report. 2002.

[3]. Liu Junhua et al. Virtual Instrument Graphic Programming Language. Xidian University. 2001.4.