Exploring and Evaluating the Key Technologies in TDOA-Based Indoor Positioning

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Abstract. As the communication field continues to evolve, positioning technology has emerged as a crucial and valuable research avenue. Particularly, indoor positioning presents an innovative and trending direction in this technology. During the research process of indoor positioning, it is essential to consider the impact of various environmental disturbances on positioning accuracy. Additionally, efforts should be geared towards minimizing these environmental influences on the positioning system's performance and reducing the complexity of the positioning algorithm. The ideal scenario for indoor positioning involves using a relatively straightforward positioning algorithm to obtain results with high positioning accuracy. That said, it is a challenging balance to strike, given the intricate factors that influence the effectiveness of indoor positioning. This paper focuses on the Time Difference of Arrival (TDOA) localization method. We explore the TDOA-based triangle centroid algorithm, Fang's algorithm, and Chan's algorithm, all prominent methods in this field. Each of these approaches presents unique strengths and challenges, offering diverse solutions to address the complexity of indoor positioning. Their comparative analysis will provide insights into the development of efficient, accurate, and straightforward indoor positioning techniques.

Keywords: Positioning technology, TDOA, Chan algorithm, Indoor positioning.

1. Introduction

Theoretically, modern indoor positioning technology has proposed location-based services in many fields. There are bigger challenges.

In view of the above situation and characteristics, researchers have conducted a lot of in-depth research work and proposed many positioning methods suitable for different indoor environments. The positioning principles of these positioning technologies are different, so the related positioning technologies and algorithms are also different, and the positioning models and ranging technologies are also different, thus showing different positioning performances. The positioning principles of these positioning technologies are different, so the related positioning technologies and algorithms are also different, and the positioning models and ranging technologies are also different, thus showing different positioning performances. Differences in positioning models, data acquisition, and data processing algorithms also make the system have different performances [1].

Since the working principles of various indoor positioning technologies have different characteristics in various aspects, it is necessary to analyze from the perspective of positioning requirements, select and optimize from various indoor positioning technologies, so as to design indoor positioning systems according to actual scene requirements [2].

With the continuous in-depth research on indoor positioning technology, the current indoor positioning technology solutions have included multiple positioning technologies such as Bluetooth, WiFi, ultrasonic and UWB. In different indoor scenes and the interference of various obstacles on the signal will cause a large error in the final position. For example, infrared ranging technology, indoor positioning will be interfered by various lights in different environments; WiFi positioning is limited by the coverage and strength of the signal; and Bluetooth technology essentially uses the signal strength value for positioning, so its positioning coverage The range is relatively small. In comparison, wireless positioning technology can obtain better anti-interference ability through modulation and demodulation, so TDOA technology is now the research focus of indoor positioning.

In indoor positioning, the system model of TDOA positioning algorithm is: By measuring the signal acceptance time difference between the target point and two known base stations, Multiplying the difference by the speed of signal propagation, thus, the distance difference between the target point and the two base stations is obtained, combining the difference with the positions of the two base stations creates a hyperbolic coordinate model. The hyperbola takes the location coordinate points of the two base stations as the focus, the target point is located on a branch curve of the hyperbola, the intersection point of this hyperbola and the hyperbola formed by other base stations is the location of the tag. The TDOA positioning model diagram is shown in Figure 1. In order to solve the problem of base station clock synchronization, this paper uses a two-way ranging method to measure the distance between the tag and each base station, and subtract them to obtain the distance difference. The standard TDOA positioning algorithm can be divided into the following steps:

Measure the time difference between the target point and the signal reception between two known base stations; Multiply the time difference by the speed of signal propagation to convert it into a distance difference, and substitute it into a system of equations composed of multiple hyperbolas [3]; Solve the system of equations with a suitable positioning method, and the solution obtained is the estimated coordinate value of the label.

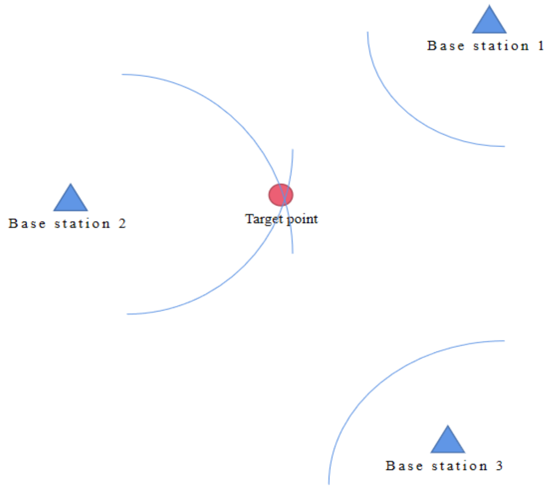

Fig. 1 Schematic Diagram of the TDOA Positioning Model

When establishing a hyperbolic equation system, assuming that the label coordinates are (x,y),the coordinates of the base station are (x_i,y_i),i = 1, 2, 3....The distances from the tag to base station 1 and base station 2 are R_1 and R_2.Then the distance difference is expressed as $R_{2,1}$=R_2-R_1.Similarly, the distance difference between the target point and base station 1 and base station 3 is $R_{3,1}$=$R_3 -$ R_1,Then according to the geometric relationship of the two hyperbolas, the equation system shown in formula 1 is obtained:

$$\begin{cases}\sqrt{(x_2-x)^2+(y_2-y)^2}-\sqrt{(x_1-x)^2+(y_1-y)^2} = R_{2,1} \\ \sqrt{(x_3-x)^2+(y_3-y)^2}-\sqrt{(x_1-x)^2+(y_1-y)^2} = R_{3,1}\end{cases} \quad (1)$$

(x_i,y_i) and $R_{3,1}$. $R_{2,1}$ in equation (2.1) are known values,so the result obtained after solving the equation system is the coordinate estimate of the label.

2. Several positioning algorithms based on TDOA

2.1. Triangle Centroid Algorithm

It is known that there are three non-collinear base stations.Its coordinates are A(x_1,y_1). B (x_2,y_2). C(x_3,y_3), the target point is the position to be requested,Let its coordinates be S(x_S,y_S),Using the TOA ranging method, the distance lengths from the terminal target point to each base station are,

d_1, d_2, d_3。 Taking the position of the base station as the center point, and taking the distance between the target point and each base station as the radius, three circles can be obtained. The three circles are at one point, and the coordinates of this point are the coordinates of the target point to be solved, as shown in Figure 2.

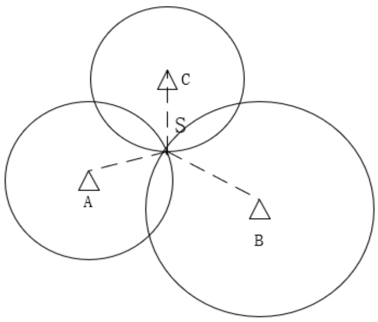

Fig. 2 Intersection of Three Circles: Identifying the Target Coordinates

According to the geometric relationship, we can get:

$$\begin{cases} (x_1 - x_s)^2 + (y_1 - y_s)^2 = {d_1}^2 \\ (x_2 - x_s)^2 + (y_2 - y_s)^2 = {d_2}^2 \\ (x_3 - x_s)^2 + (y_3 - y_s)^2 = {d_3}^2 \end{cases} \tag{2}$$

After tidying up:

$$\begin{cases} {x_1}^2 - 2x_1x_s + {x_s}^2 + {y_1}^2 - 2y_1y_s + {y_s}^2 = {d_1}^2 \\ {x_2}^2 - 2x_2x_s + {x_s}^2 + {y_2}^2 - 2y_2y_s + {y_s}^2 = {d_2}^2 \\ {x_3}^2 - 2x_3x_s + {x_s}^2 + {y_3}^2 - 2y_3y_s + {y_s}^2 = {d_3}^2 \end{cases} \tag{3}$$

Solve to get the coordinates of the target point S (x_S,y_S)

$$\begin{bmatrix} x_s \\ y_s \end{bmatrix} = \frac{1}{2}\ \mathrm{AB} \tag{4}$$

Among them, the matrix

$$\mathrm{A} = \begin{bmatrix} (x_1 - x_3) & (y_1 - y_3) \\ (x_2 - x_3) & (y_2 - y_3) \end{bmatrix} \tag{5}$$

$$\mathrm{B} = \begin{bmatrix} {x_1}^2 - {x_3}^2 + {y_1}^2 - {y_3}^2 + {d_3}^2 - {d_1}^2 \\ {x_2}^2 - {x_3}^2 + {y_2}^2 - {y_3}^2 + {d_3}^2 - {d_2}^2 \end{bmatrix} \tag{6}$$

2.2. Fang Positioning Algorithm

The Fang algorithm is a method to achieve localization using TDOA. This method uses a linearized hyperbolic equation, and And the calculation results can be optimized and solved. The locations of the three indoor base stations are known, as followed A(x_1,y_1), B(x_2,y_2), C(x_3,y_3), The distance between the target point and all base stations is recorded as d_1, d_2, d_3.The position of the target point is to be solved, set as S(x_S,y_S [4].

It can be drawn as follows:

$${d_i}^2 = (x_{1i} - x_s)^2 + (y_{1i} - y_s)^2 \tag{7}$$

set up ${k_i}^2 = {x_i}^2 + {y_i}^2$,the above formula is equivalent to:

$${d_i}^2 = {k_i}^2 - 2x_ix_s - 2y_iy_s + {x_s}^2 + {y_s}^2 \tag{8}$$

set up $d_{i1} = d_i - d_1$, after rearranging equation 5, get:

$$d_{i1}{}^2 + 2d_{i1}d_1 + d_1{}^2 = k_i{}^2 - 2x_i x_s - 2y_i y_s + x_s{}^2 + y_s{}^2 \tag{9}$$

Let i = 1 in equation 6, it can be deduced:

$$d_1{}^2 = k_1{}^2 - 2x_1 x_s - 2y_1 y_s + x_s{}^2 + y_s{}^2 \tag{10}$$

Subtracting 8 from equation 7 yields:

$$d_{i1}{}^2 + 2d_{i1}d_1 = k_i{}^2 - k_1{}^2 - 2(x_i - x_1)x_s - 2(y_i - y_1)y_s \tag{11}$$

For the convenience of calculation, the coordinates of the base station are set as A (0,0), B(x_2,0) , C(x_3,0), Let i = 2, 3, the following equation can be obtained:

$$\begin{cases} d_{21}{}^2 + 2d_{21}d_1 = x_2{}^2 - 2x_2 x_s \\ d_{31}{}^2 + 2d_{31}d_1 = x_3{}^2 - 2x_3 x_s \end{cases} \tag{12}$$

Simplify to get:

$$y_s = \frac{x_2 d_{31}}{y_2 d_{21}} x_s + \frac{1}{2} y_3 - \frac{x_2{}^2 d_{31}}{2y_3 d_{21}} + \frac{d_{31} d_{21}}{2y_3} - \frac{d_{31}{}^2}{2y_3} \tag{13}$$

Among them, x_S and y_S are linearly related,set up

$$\mathrm{n} = \frac{1}{2} y_3 - \frac{x_2{}^2 d_{31}}{2y_3 d_{21}} + \frac{d_{31} d_{21}}{2y_3} - \frac{d_{31}{}^2}{2y_3}, \mathrm{m} = \frac{x_2 d_{31}}{y_2 d_{21}}, \tag{14}$$

The equation can be obtained:

$$y_s = m x_s + n \tag{15}$$

Substituting equation 12 into equation 8, set up $d_1 = \sqrt{x_s{}^2 + y_s{}^2}$ can launch:

$$\mathrm{a} x_s{}^2 + b x_s + c = 0 \tag{16}$$

Among them,

$$\mathrm{a} = (1 + \mathrm{m}^2) - \frac{x_2{}^2}{d_{21}{}^2}, \ \mathrm{b} = 2\mathrm{mn} + x_2 \left(\frac{x_2{}^2}{d_{21}{}^2} - 1 \right),$$

$$\mathrm{c} = \mathrm{n}^2 - \frac{x_2{}^2 - d_{21}{}^2}{4d_{21}{}^2} \tag{17}$$

Equation 13 can get two results, judge the correct solution according to the information, and substitute this value into equation 13 to obtain y_s .Thus, the position of the target point can be derived S (x_S,y_S)。

2.3. Chan Positioning Algorithm

In the TDOA positioning scene, the application of the Chan algorithm is more common. The Chan algorithm is a scheme that uses the method of maximum likelihood estimation to achieve positioning. If the distance error of the signal measurement presents a Gaussian distribution, the calculation amount of the Chan algorithm is smaller than other algorithms, and the positioning accuracy is relatively higher [5]. The research scope of the Chan algorithm usually involves scenarios with three or more base stations. This section will solve the positioning scenario in the case of three base stations.

There are three non-collinear base station locations are known, and their respective coordinates are A(x_1,y_1), B(x_2,y_2), C(x_3,y_3), The position of the target point is to be requested, set as S(x_S,y_S)。The distances between the target point and all base stations are recorded as d_1, d_2, d_3 .set up $d_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2}$, i=1,2,3.

Solving the system of hyperbolic equations yields the system of equations 14:

$$\begin{cases} d_2 - d_1 = \sqrt{(x_2 - x_s)^2 + (y_2 - y_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2} \\ d_3 - d_1 = \sqrt{(x_3 - x_s)^2 + (y_3 - y_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2} \end{cases} \tag{18}$$

After sorting out, we get Equation 15:

$$\begin{cases} d_{21} + d_1 = d_2 \\ d_{31} + d_1 = d_3 \end{cases} \tag{19}$$

After squaring Equation 14 and subtracting both sides of the equation $d_1{}^2$, equation 16 can be obtained :

$$\begin{cases} d_2{}^2 - d_1{}^2 = (d_{21} + d_1)^2 - d_1{}^2 \\ d_3{}^2 - d_1{}^2 = (d_{31} + d_1)^2 - d_1{}^2 \end{cases} \tag{20}$$

After expanding the equation 15 we get 17:

$$\begin{cases} (x_2 - x_1)x_s + (y_2 - y_1)y_s = -d_1 d_{21} + \frac{(k_2{}^2 - k_1{}^2 - d_{21}{}^2)}{2} \\ (x_3 - x_1)x_s + (y_3 - y_1)y_s = -d_1 d_{31} + \frac{(k_3{}^2 - k_1{}^2 - d_{31}{}^2)}{2} \end{cases} \tag{21}$$

Among them,$k_i{}^2 = x_i{}^2 + y_i{}^2$, i=1,2,3

order matrix A = $\begin{bmatrix} x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \end{bmatrix}$, $X_s = \begin{bmatrix} x_S \\ y_S \end{bmatrix}$, B = -$\begin{bmatrix} d_{21} \\ d_{31} \end{bmatrix}$, C= -$\begin{bmatrix} k_2{}^2 - k_1{}^2 - d_{21}{}^2 \\ k_3{}^2 - k_1{}^2 - d_{31}{}^2 \end{bmatrix}$, get:

The coordinates of the target point are S (x_S,y_S), It can be solved by equation 18:

$$X_s = A^{-1} d_1 B + A^{-1} C \tag{22}$$

TDOA positioning requires all base station nodes to maintain time synchronization, while the terminal node and all base station nodes can be out of time synchronization. The distance d_1 between the target point and the base station A is unknown, So the position of the target point S(x_S,y_S) calculated by equation 18.Included are the unknowns d_1, which can be calculated by equation 19.

$$d_1 = \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2} \tag{23}$$

3. Simulation and Performance Analysis of Chan Positioning Algorithm

The derivation of Chan algorithm is based on a Gaussian random variable with zero mean measurement error.When the number of base stations is greater than 3, the number of nonlinear equations is less than the number of unknown variables [6,7], The weighted least squares method can be used to obtain the initial solution, and the second weighted least squares method is used to estimate the obtained initial solution and constraint variables, and finally an improved position estimate is obtained [8,9]. The positioning simulation is shown in Figure 3 and Figure 4.

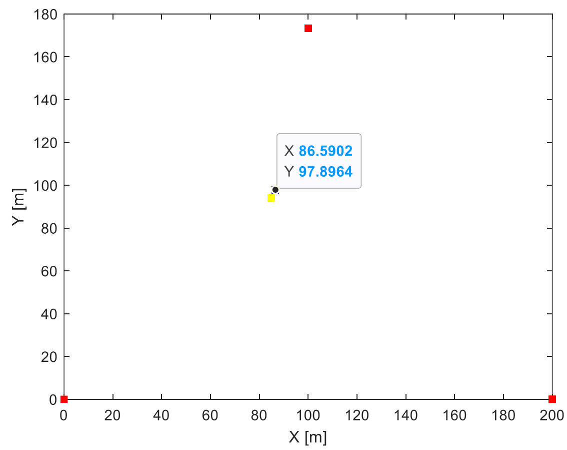

Fig. 3 Indoor Positioning System Simulation 1

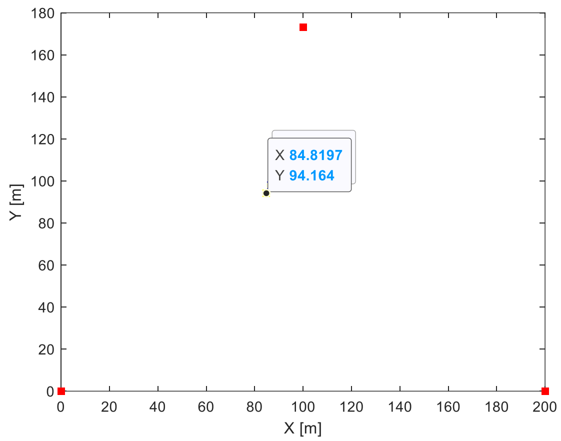

Fig. 4 Indoor Positioning System Simulation 2

The simulation performance analysis is shown in Figure 5

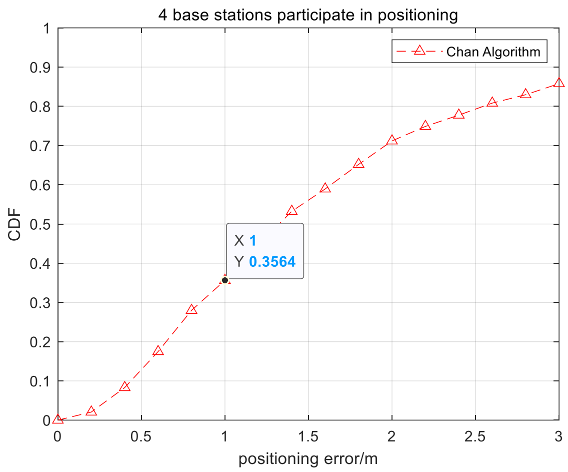

Fig. 5 Performance Analysis of the Simulation

It can be seen from the figure that the abscissa is the positioning error, and the ordinate is the cumulative distribution function CDF [10].

4. Conclusion

This paper focuses on a wireless positioning technology that relies on measuring signal time differences. It delves into the underlying positioning principles of this technology and introduces a method based on analyzing the time differences in signal transmission from multiple base stations. Building upon these principles, the paper presents the design of an indoor positioning system.

The indoor positioning system described in the paper utilizes the time differences in signal transmission from multiple base stations to accurately determine the location of a target. To validate the proposed principles and design methods, the researchers conducted comprehensive system simulations and performance analyses. Based on the results obtained from the simulations and performance analysis, the paper affirms the feasibility and accuracy of the positioning principles and design methods proposed. The system successfully achieves accurate target positioning by leveraging multiple base stations.

Future work outlined in the paper includes further optimization of the positioning algorithm and conducting additional analyses to understand and mitigate positioning errors. The primary objective is to enhance the accuracy of the positioning system and minimize the impact of environmental interferences on its performance. By expanding the paper to 500 words, additional details can be provided. For instance, the positioning technology discussed in the paper may utilize a method such as Time Difference of Arrival (TDOA) or Time of Arrival (TOA) to measure the time differences in signal transmission. These techniques rely on precise timing synchronization between the base stations and the target device. The paper may elaborate on the specific measurement methods employed in the system, such as the use of reference signals or pilot signals transmitted by the base stations. These signals aid in accurately calculating the time differences and subsequently determining the position of the target device.

To validate the performance of the proposed system, the researchers likely conducted extensive simulations. The simulations may have involved various scenarios and environments, taking into account factors such as multipath propagation, signal attenuation, and interference. The paper may provide details on the simulation setup, including the parameters and assumptions considered.

The performance analysis discussed in the paper may involve evaluating metrics such as positioning accuracy, precision, and robustness. It may also address issues related to system stability, scalability, and the computational complexity of the positioning algorithm. The paper may highlight the potential applications of the wireless positioning system, such as indoor navigation, asset tracking, and location-based services. It may discuss the advantages of this technology over alternative positioning methods, such as Global Navigation Satellite Systems (GNSS) that may be less effective in indoor environments.

References

[1] Li, M., Zou, F., Wu, H., Wang, X., & Zhang, Q. (2021). Research on Pedestrian Indoor Positioning Algorithm based on TDOA and Chan Algorithm. Journal of Physics: Conference Series, 1831(1), 012024.

[2] Chen, Y., Gao, W., & Zhou, Y. (2021). FDM-TDOA Indoor Positioning System based on Chan's Algorithm. IEEE Access, 9, 129965-129975.

[3] Li, H., Yang, R., Li, Y., & Chen, Y. (2020). Analysis of the TDOA Algorithm for Indoor Positioning Based on Multiple Ultrasonic Sensors. Proceedings of the 4th International Conference on Communications, Signal Processing, and Systems, 1-6.

[4] Yu, J., Zhang, H., & Li, Y. (2020). A Hybrid Indoor Positioning Method Based on TDOA using a Single Frequency. IEEE Access, 8, 95711-95720.

[5] Yu, S., Li, M., & Xiao, X. (2020). Improved Chan Algorithm for Low-Complexity Indoor Positioning. IEEE Communications Letters, 24(4), 857-861.

[6] Zhang, Y., Zheng, B., & Liu, C. (2020). Novel Method of Indoor Positioning based on TDOA and Chan Algorithm. The Journal of Engineering, 2020(19), 4061-4065.

[7] Ding, J., & Lu, P. (2019). Improved TDOA Algorithm for Indoor Positioning. Journal of Physics: Conference Series, 1364(5), 052030.

[8] Zhang, X., Wei, Z., Zhang, Y., & Chen, X. (2019). A New Hybrid Indoor Positioning Algorithm based on TDOA and Chan Algorithm. Proceedings of the 3rd International Conference on Networking, Information Systems & Security, 279-286.

[9] Wang, G., Xu, R., & Wang, Y. (2018). A High Precision Indoor Positioning Algorithm Based on the TDOA and Chan Algorithms. Proceedings of the 4th International Conference on Mechatronics and Robotics Engineering, 28-34.

[10] Feng, Y., & Chen, L. (2018). A Novel Indoor Positioning Algorithm Based on TDOA and Chan Algorithm. Proceedings of the 2018 3rd International Conference on Computer and Communication Systems, 336-341.