A Method for Non-line of Sight Identification and Delay Correction for UWB Indoor Positioning

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***Abstract*—UWB has a centimetre level of positioning accuracy in line of sight (LOS) environment, and is one of the most promoted indoor positioning technologies. However, when a wall or other objects block UWB signals, non-line of sight (NLOS) happens, which reduces the signal/noise ratio and causes signal transmission delay. As NLOS introduces large distance measurement error, UWB positioning accuracy is dramatically degraded. A new NLOS identification and distance correction method is introduced in this paper. The NLOS between a UWB anchor and a moving tag is identified by analysing the variance of the change of UWB measured distance in adjacent samples. The NLOS distance measurement error caused by walls is corrected by modelling the UWB signal transmission delay. Tests have been conducted to evaluate the new method performance for UWB indoor positioning. The results show that NLOS identification accuracy can reach more than 90%. The delay estimation model can effectively correct measurement errors and make positioning accuracy with NLOS appearance comparable to that in LOS.**

Keywords—UWB, NLOS, TOA, delay modelling

I. INTRODUCTION

With the development of the internet of things and location-based services, there is a high demand for precise locations in indoor and outdoor scenes [1]. Global Navigation Satellite System (GNSS) has been developed for several decades, and it can provide precise location information in outdoor open spaces. However, GNSS positioning needs a line of sight (LOS) between the satellites and the receiver, which is unsuitable for indoor positioning [2]. With the development of wireless communication technologies, such as Bluetooth, WIFI, RFDI, and Zigbee, they have been used for indoor positioning [3]. However, these technologies are developed for short-distance wireless communication, and their technical limitations lead to unsatisfactory indoor positioning accuracy. For example, Bluetooth and WIFI can only reach meter level accuracy. The positioning error can even reach several meters in a complex indoor environment, which cannot meet the requirements of many indoor positioning applications.

Ultra-wideband (UWB) is a new wireless communication technology that uses a narrow nanosecond pulse to transmit data. It has good anti-interference performance, high data transmission rate, low energy consumption, high positioning accuracy and multi-path robustness [4]. Therefore, UWB is considered the most promising indoor positioning technology. Some major smartphone manufacturers, such as Apple and Samsung, have launched some models supporting UWB positioning. It can be predicted that indoor positioning using UWB technology will be widely used in wearable equipment, intelligent homes, extended reality and mobile robots [5]. At the same time, UWB positioning also has a wide range of industrial applications, such as intelligent manufactory and warehouse etc. A UWB indoor positioning system consists of fixed anchor points and mobile tags that need to be located.

UWB positioning often uses Time of Arrival (TOA) [6], Two-Way-Ranging (TWR) [7], or Time Difference of Arrival (TDOA) [8] algorithms, and they have higher positioning accuracy than fingerprint positioning based on Received Signal Strength Indicator. However, TOA, TWR and TDOA all estimate a UWB tag's position by measuring the distance between the anchor points and the tag. The distance is measured by counting the time of UWB signal transmission. In the case of non-line of sight (NLOS), the UWB signal can only reach a tag by penetrating obstacles or reflection, so compared to in LOS, there is a transmission delay [9]. In indoor environments, obstacles such as walls and the human body often appear and lead to NLOS. If the distance error caused by NLOS is not corrected, the positioning accuracy of UWB in an indoor environment will be heavily degraded [10]. Therefore, identifying NLOS and reducing the ranging error caused by it is a major focus in UWB positioning research.

Many researchers have proposed their methods to identify NLOS and correct its error. NLOS identification methods can be classified into three categories [10]. The first category is based on statistical channel characteristics. Jiang et al. [10] proposed an NLOS recognition algorithm that combines convolutional neural network (CNN) and long-short-term Memory, which extracts channel impulse response features of UWB signals through CNN recognition and outputs them to LSTM for classification. The recognition accuracy of NLOS error can reach 81.56%. Cui et al. [11] proposed a method to identify NLOS based on Morlet wavelet transform and CNN. Its identification accuracy in different environments can reach 95%. Kai et al. [12] proposed a method that uses signal characteristic analysis for NLOS identification and fuzzy theory for error mitigation. It can reduce the measurements' root mean square error (RMSE) from 0.77 to 0.33 meters.

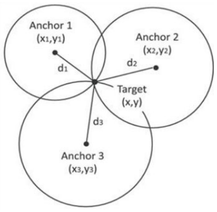


Fig. 1 TOA algorithm

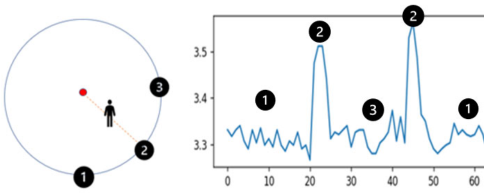


Fig. 2 NLOS error caused by the human body

Fig. 3 UWB module

Fig. 4 The experiment site and ichnography

The second category is based on the analysis of ranging measurement. The basic principle of this method is to analyse the ranging information in both LOS and NLOS and correct the meandering in the NLOS environment to improve the positioning accuracy. For example, Dong [13] uses Fresnel zone and Simple prior knowledge to identify NLOS and has a recognition accuracy of 96.41%. However, there is still a critical problem with this method. When verifying whether the tag is in the NLOS environment through this method, the tag position must be in the first Fresnel zones of the two fixed anchors. This leads to a severe limitation of the range of the tag movement. Therefore, this method cannot be applied to most indoor positioning scenarios.

The third category is to identify NLOS by combining other measurement data. For example, Tiwari et al. [14] and Zuo et al. [15] proposed to successfully identify LOS/NLOS paths by combining received-signal-Strength (RSS) and TOA and the accuracy of NLOS determination is over 75%.

The commonly used algorithms for UWB positioning are TOA, TDOA and hybrid methods [16]. This paper uses the TOA algorithm; the principle of the TOA algorithm is shown in Fig. 1. 2D space requires at least three fixed anchor points to solve the coordinate position of the tag. Given three fixed anchor points and their coordinates, the distance can be calculated by measuring the signal flight time between the tag and the three anchor points. Draw a circle with the three anchor points as the centres and the distance to the tag as the radius, so the tag coordinates at the intersection of the three circles [17]. The calculation formula is as follows.

$$d_i = t_i * C \tag{1}$$

d_i represents the distance from Tag to Anchor i, t_i is the time of flight, and C is the speed of light. Through the ranging data of the three anchors, the following equation can be obtained

$$\begin{aligned} d_1^2 &= (x - x_1)^2 + (y - y_1)^2 \\ d_2^2 &= (x - x_2)^2 + (y - y_2)^2 \\ d_3^2 &= (x - x_3)^2 + (y - y_3)^2 \end{aligned} \tag{2}$$

Where (x_i, y_i) represents the anchor point coordinates; (x, y) represents the Tag point coordinates. The Tag coordinates can be obtained by solving (2):

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) \end{bmatrix}^{-1} * \begin{bmatrix} d_2^2 - d_1^2 - x_2^2 + x_1^2 - y_2^2 + y_1^2 \\ d_3^2 - d_1^2 - x_3^2 + x_1^2 - y_3^2 + y_1^2 \end{bmatrix} \tag{3}$$

This equation shows that the UWB positioning accuracy merely depends on the accuracy of distance measurements and the anchor's location geometry.

This paper proposes a new method to identify NLOS in UWB indoor positioning based on analysing the variance of distance variation at two adjacent moments. The UWB ranging variations from a tag to the same anchor at two adjacent moments should be similar when the tag movers smoothly. Due to NLOS delay, the distance measurement has a sharp jump from LOS to NLOS and a sharp drop from NLOS to LOS. The variance of the distance difference can be used to detect whether a ranging measurement contains NLOS error.

After identifying which measurements have NLOS error, there is a couple of ways to process these measurements. If an NLOS delay estimation model is available to correct the error, the corrected measurements can be used for UWB indoor positioning. If there is no proper delay estimation model to correct the NLOS errors, the NLOS measurements can be put lighter weight than the LOS measurements during the position calculation. Experiment results of UWB indoor positioning tests show that the proposed method can effectively identify and mitigate NLOS errors and dramatically improve UWB positioning accuracy with NLOS appearance.

The rest of the paper is structured as follows: The second section introduces the proposed method to identify NLOS. The third section is about the NLOS delay correct model for walls. The fourth section shows the indoor positioning results with corrected NLOS measurements. The last section is a conclusion and future research plan.

II. Proposed Method for NLOS Identification

A. The Method to Identify NLOS

The principle of the proposed method to identify NLOS is based on the fact that when there is a switch between NLOS and LOS cases for a tag and an anchor point, the ranging measurement of this anchor point will change abruptly.

A preliminary verification test is shown in Fig. 2. The left figure shows the experimental scene setting. The red dot in the figure is the position of the fixed anchor point, and the black dots are the mobile tag's positions. In the test, a tag moves in a circle at a constant speed from position 1 to 3 and then back to position 1 from 3. When the tag passes through position 2, a human body blocks the signal, and NLOS occurs. The distance measurements are shown in the right figure. The X-axis represents time, and the Y-axis represents the distance measurements between the tag and the anchor. The distance measurement changed suddenly when the tag was in position 2, which is NLOS. The NLOS error caused by the human body is about 20cm.

The proposed NLOS identification method is designed as follows. The distance between the tag and anchor measured at moment n is d_n, and at the previous moment is d_{n-1}. Then the distance change in the adjacent sampling times is

$$\Delta d_n = |d_n - d_{n-1}| \quad (n = 2, 3...) \tag{4}$$

$$threshold = Var(\Delta d_n(LOS)) \tag{5}$$

$$Var(\Delta d_n)\begin{cases} > threshold & \rightarrow NLOS \\ \leq threshold & \rightarrow LOS \end{cases} \tag{6}$$

For automated ground vehicles (AGV) operating in an indoor environment, their moving speed is around 1m/s consistent during operation. When a AGV moves in a LOS environment, a UWB tag on it continuously measures the distance to anchor points, the distance variation Δd_n is small and relatively stable. But when NLOS occurs Δd_n will shake violently. Based on these characteristics, a method to identify NLOS errors is designed as (4) to (6). Using the variance of Δd_n in the LOS as the threshold, when the variance of Δd_n in real-time measurement exceeds this threshold, NLOS occurs. This method is simple but can accurately identify whether a ranging data contains NLOS error.

B. *Experimental design*

Fig. 3 shows the UWB module used in our experiment, which uses the DW1000 UWB chip. The UWB sampling rate is at 3Hz, and its average positioning error is less than 10cm in a LOS environment. The experimental scene and the floor plan are shown in Fig. 4. Two experiments were conducted. The first experiment used three fixed anchor points, and the second experiment used four fixed anchor points.

1) Experiment 1

Fig. 5 shows the anchor's setting, the tag's real trajectory and measured position, and the NLOS appearance of each anchor. Yellow squares represent the three anchor points. The UWB tag moves from Area 3 along the red track and passes through Areas 1 and 4 to the endpoint in Area 5. The purple trajectory is calculated with the TOA algorithm and the distance measurements to the three anchor points. It is observed that within Area3, all Anchor 2 ranging measurements and most Anchor 0 ranging measurements contain NLOS errors. In Area 1, all Anchors are in a LOS environment. After entering Area 4, Anchors 0 and 1 are still in the LOS environment, but Anchor 2 has NLOS errors. When in Area 5, all the three anchor points are NLOS. From the purple trajectory, it can be found that the NLOS error dramatically influences the accuracy of the UWB positioning.

The NLOS identification method proposed in this paper can accurately identify which data of the three anchor points have NLOS errors. Fig.5 a) – c) show the positioning corresponding to the three anchor points affected by NLOS. The blue dot represents that the ranging measurement of the current position is affected by NLOS.

In the experimental environment, the NLOS identification rate is shown in table 1. In this experimental environment, the identification of NLOS error is accurate. The accuracy of anchor 1 and anchor 2 is greater than 95%, and the accuracy of anchor 0 is close to 90%

TABLE I. THE SUCCESS RATE OF NLOS IDENTIFICATION (TEST 1)

Anchor	0	1	2
Identification rate	89.41%	100%	95.29%

2) Experiment 2

Experiment 2 uses four fixed anchor points, making the tag's trajectory more complex. It is designed to further verify the applicability of the method proposed in this paper.

As shown in Fig. 6, Anchor 3 is added in this experiment. The red dash line shows the actual trajectory of the mobile UWB tag. The tag starts from Area 2, passes through Area 1 to the marked point of Area 3, then starts from the marked point of Area 3 and follows the red trajectory through Area 1, 4 and 5 to reach the endpoint in Area 6. The purple trajectory is calculated based on the ranging measurement of the anchor point without NLOS correction.

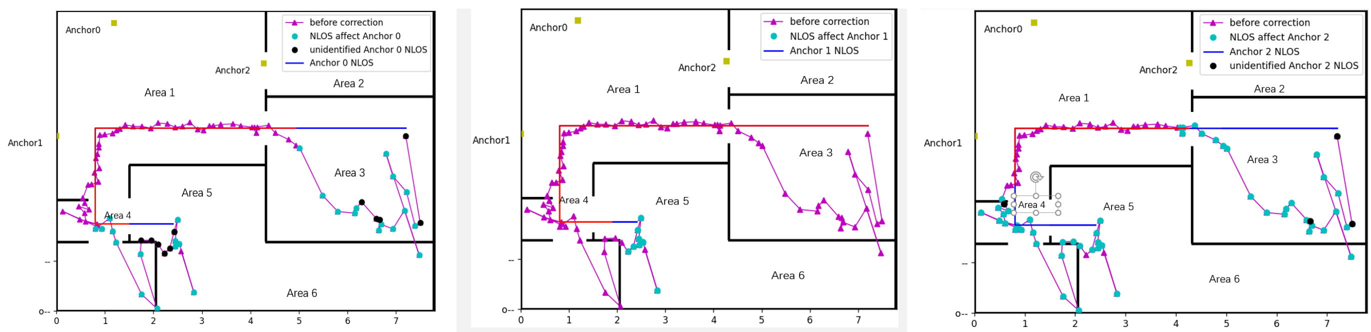
There are at least three anchor points in the LOS situation in Area 1, and the UWB positioning accuracy is very high. In other areas, at least two anchor points have NLOS, and the accuracy of positioning without NLOS error correction is much worse than LOS in Area 1. In Area 6, all the four anchor points are in NLOS state, and only the signal from Anchor 3 penetrating one wall has a ranging measurement. Multiple walls block the UWB signals from the other three anchor points, and the tag received signals are too weak to measure the distances. Therefore the position of the tag cannot be obtained in Area 6.

Similar to Experiment 1, the test data is processed to identify if the distance measurements contain NLOS errors. Fig. 6 a) – d) show the calculated locations where the ranging measurement of the four anchor points are affected by NLOS. A few positions have unexpected or undetected NLOS, which may be due to undesired settings in the experiment. In the current Experiment II environment, the NLOS identification success rate is shown in table 2.

As can be seen from Table II, the UWB tag's trajectory becomes more complex and covers more areas. The success rate of NLOS identification in Experiment 2 is slightly lower than that in Experiment 1. But still, most of the NLOS cases can be correctly identified, with the overall success rate around 90%. Unexpected factors in the experiment cause some worng identification cases.

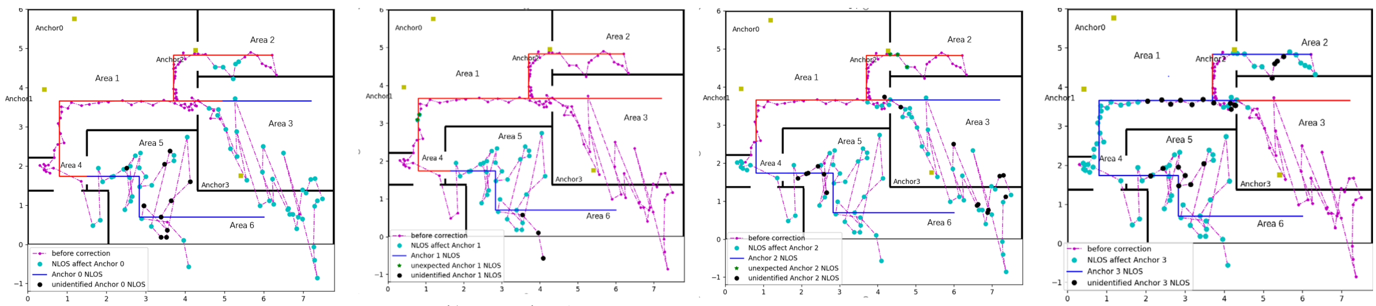
TABLE II. THE SUCCESS RATE OF NLOS IDENTIFICATION (TEST 2)

Anchor	0	1	2	3
Identification rate	91.22%	95.27%	89.19%	85.46%



a) Anchor 0 NLOS b) Anchor 1 NLOS c) Anchor 2 NLOS

Fig. 5 Tag position with NLOS (Experiment 1)



a) Anchor 0 NLOS b) Anchor 1 NLOS c) Anchor 2 NLOS d) Anchor 3 NLOS

Fig. 6 Tag position with NLOS (Experiment II)

III. NLOS Error Correction Model

A. Geometric Model of UWB Signal Through a Wall

In UWB indoor positioning, the occurrence of NLOS is mainly caused by the occlusion of walls. The UWB signal transmission delay caused by passing through walls can be estimated with a geometric model, dramatically reducing positioning errors in the NLOS environment. The specific model is shown in Fig. 7. A is a fixed anchor point, B is the Tag position, and the grey area represents the wall causing NLOS. ACDB is the actual path of the signal from A to B.

$$d_{real} = d_{AC} + d_{CD} + d_{DB} \tag{7}$$

d_{real} represent the actual distance the signal travels.

$$d_{AC} + d_{DB} = \frac{\Delta y - d_{wall}}{cos\theta_1} \tag{8}$$

$$\Delta y = d_{AB} * cos\theta \tag{9}$$

d_{wall} represent the wall thickness, θ_1 is the incline angle of the signal to the wall, θ_2 is the angle of emergence. Δy is the distance difference along Y-axis between the points A and B. θ is the complementary angle between the line AB and the wall; d_{AB} is the actual distance between A and B.

$$d_{CD} = \frac{d_{wall}}{cos\theta_2} \tag{10}$$

Because of the permittivity of the wall ε_{wall} is different from the air; the signal travels in the wall slower than in the air, resulting in additional time delay. The measured CD distance in practice should be the time of flight through the wall t_{wall} multiplied by the speed of light c, as the following formula.

$$d_{CD} = t_{wall} * c = \frac{d_{wall} * \sqrt{\varepsilon_{wall}}}{cos\theta_2} \tag{11}$$

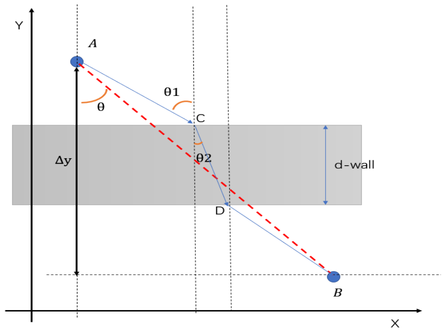


Fig. 7 Geometric model of UWB signal passing through a wall

So, the ranging delay is:

$$delay = d_{real} - d_{AB} \quad and \tag{12}$$

$$delay = d_{AB}\left(\frac{cos\theta}{cos\theta_1} - 1\right) + d_{wall}\left(\frac{\sqrt{\varepsilon_{wall}}}{cos\theta_2} - \frac{1}{cos\theta_1}\right) \tag{13}$$

where $sin\theta_2/sin\theta_1 = \sqrt{\varepsilon_{wall}}$ as the Snell's Law.

Equation (13) has two items $e_1 = d_{AB}(cos\theta/cos\theta_1 - 1)$ and $e_2 = d_{wall}\left(\frac{\sqrt{\varepsilon_{wall}}}{cos\theta_2} - 1/cos\theta_1\right)$. In general, $d_{wall} \ll d_{AB}$ and $\theta_1 \approx \theta$, so e_1 too small to affect NLOS delay. Therefore e_2 is the main factor affecting the NLOS delay.

Then the ranging delay can be approximately expressed to the following formula:

$$delay \approx d_{wall}\left(\frac{\varepsilon_{wall}^{\frac{3}{2}}}{\sqrt{\varepsilon_{wall} - 1 + cos^2\theta_1}} - \frac{1}{cos\theta_1}\right) \tag{14}$$

According to (14), the transmission delay is affected by the thickness and material of the wall and the incline angle. Therefore, an empirical model can be established wall caused transmission delay.

$$Delay = K1 * \frac{d_{wall}}{cos\theta_1} + K2 \tag{15}$$

K1 and K2 can be determined by conducting a test for a wall, as shown in Tables III and IV, by measuring the actual and UWB measured distances at different incline angles.

The wall thickness between Areas 2 and 3 is 26 cm, and between Areas 5 and 1 is 16 cm. The fitting equation for K1 and K2 was calculated based on UWB measured distances through a wall with NLOS delay, the real distance and the incline angle measurements shown in Tables III and IV. The coefficients K1 and K2 for each wall are then fit into (15) to calculate the NLOS delay of each wall at different angles.

TABLE III. Data for Fitting Equation (D_WALL = 26CM)

d-uwb (m)	d-real (m)	Delay (m)	θ (°)	Modelling Delay(m)	Difference (m)
1.965	1.788	0.177	0°	0.352	0.175
1.545	1.322	0.223	8.52°	0.355	0.132
2.21	1.716	0.494	30°	0.384	0.110
3.378	3.042	0.336	54°	0.497	0.161
3.65	2.972	0.678	60°	0.559	0.119
7.18	5.983	1.197	70.16°	0.754	0.443

TABLE IV. DATA FOR FITTING EQUATION (D_WALL = 16CM)

d-uwb (m)	d-real (m)	Delay (m)	θ (°)	Modelling Delay(m)	Difference (m)
3.87	3.587	0.283	13.37°	0.213	0.060
4.01	3.823	0.187	31.1°	0.225	0.038
3.67	3.526	0.144	42.2°	0.240	0.096
4.34	3.99	0.35	57.01°	0.280	0.069
5.07	4.748	0.322	61.57°	0.303	0.019
5.07	4.419	0.651	80.597°	0.577	0.074

The K1 and K2 obtained from Table III for the 26cm wall are: K1= 0.7943 and K2 = 0.1459; for the 16cm wall, K1= 0.5934 and K2 = 0.128. These parameters can be applied in (15) to calculate NLOS delay. The difference between the modelling delay and the actual delay is shown in the last column of Tables 3 and 4. It can be seen that only one data has a large difference (0.443m) that may be due to unexpected factors; the rest of the difference is about 10cm. The results show that model (15) can effectively predict the transmission delay of walls.

For a mobile UWB tag, the incline angle at a particular moment is calculated according to the tag position at the last moment and the motion state using (16).

$$\theta_{1n} = tan^{-1}\left(\frac{abs(y_{n-1} + v_y * \Delta t - X_N)}{abs(x_{n-1} + v_x * \Delta t - Y_N)}\right) \qquad (16)$$

where (x_{n-1}, y_{n-1}) are the coordinates of tag at time n-1, (X_N, Y_N) are the coordinates of the anchor N, Δt is sampling time, v_x,v_y are the tag's velocity components along the X and Y axes during the sampling time.

If the ranging measurement of an anchor has NLOS delay, it can be corrected according to (17).

$$d_{real} = d_{measure} - delay \qquad (17)$$

IV. EXPERIMENT RESULT

A. Experiment 1

Fig. 8 shows the positioning results in experiment 1. The green trajectory in the figure is calculated using the NLOS correction data. The golden dots in the trajectory before correction and the golden lines in the real trajectory represent one NLOS at these positions, orange for two and red for three NLOS. The positioning results before and after the correction are shown in Table V. The data in Area 1 has three anchor points in the LOS environment as the control group.

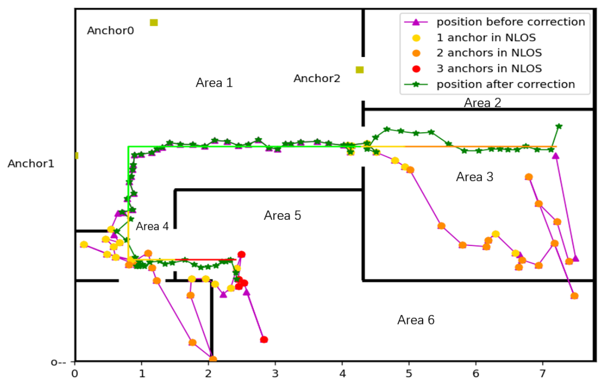


Fig. 8 Tag position with correction (Experiment 1)

TABLE V. POSITIONING ANALYSIS (EXPERIMENT I)

Positioning Error (m)	Area 1	Area 3 (2 NLOS)		Area 5 (3 NLOS)	
	LOS	Before	After	Before	After
Max (m)	**0.235**	2.541	**0.338**	1.694	**0.300**
Min (m)	**0.007**	0.518	**0.004**	0.144	**0.009**
Average (m)	**0.060**	1.701	**0.122**	0.653	**0.118**
RMSE (m)	**0.080**	1.759	**0.157**	0.824	**0.156**

Test results in Table V show that the accuracy of the UWB indoor positioning system in the LOS environment is pretty high. The average error is only 0.06m, with a PMSE of 0.08m. As a comparison, in the NLOS environment in Area 3 with 2 NLOS anchors, the average error before the correction reaches 1.7m, with an RMSE of 1.759m. After the correction, the average error is reduced to 0.122m and RMSE to 0.157m. A similar result is presented for Area 5 with 3 NLOS anchors, with dramatic positioning improvement after the proposed NLOS error correction. These results show that NLOS error can cause a large error for the UWB indoor positioning. The proposed NLOS error correction method can dramatically reduce the error in the NLOS environment. Its positioning accuracy is close to that in the LOS environment.

B. Experiment 2

Fig. 9 shows UWB positioning results for experiment 2. The green trajectory is the calculated position using the measurements after the correction. The trajectory is much more accurate than the one before the correction, specifically in the NLOS areas. The yellow line for the actual tag trajectory means that one anchor point is affected by NLOS, the orange line for two NLOS anchor points, and the red line means all anchor points are in the NLOS environment. The cyan triangle in Area 6 indicates insufficient ranging information available for the position calculation. Table VI shows the positioning results of experiment 2.

The UWB indoor positioning system can provide accurate and stable location information of the moving tag in the LOS environment, with an average error of 0.063m. However, the positioning accuracy in the NLOS environment is inferior before correction. The most significant average positioning error is in Area 3 at 1.78m due to a large incline angle of the wall, causing a large NLOS delay. In Areas 2 and 5, the NLOS delay is relatively small due to small incline angles. The positioning accuracy after the delay correction has been dramatically improved. The average positioning errors in the three NLOS areas are 0.082m, 0.08m and 0.14m, respectively, and corresponding RMSEs are 0.09m, 0.111m and 0.181m.

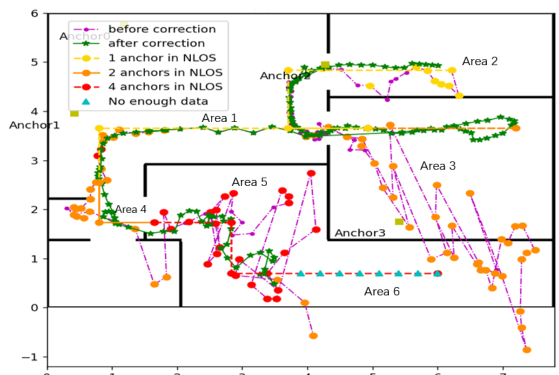


Fig. 9 Tag position with correction (Experiment 2)

TABLE VI. POSITIONING ANALYSIS (EXPERIMENT II)

Positioning Error	**Area 1 (3 LOS)**	**Area 2 (2 NLOS)**		**Area 3 (2 NLOS)**		**Area 5 (4 NLOS)**	
		Before	**After**	**Before**	**After**	**Before**	**After**
Max (m)	**0.177**	0.606	**0.133**	4.513	**0.247**	1.302	**0.454**
Min (m)	**0.002**	0.009	**0.102**	0.016	**0.003**	0.002	**0.003**
Average (m)	**0.063**	0.232	**0.082**	1.780	**0.080**	0.443	**0.142**
RMSE (m)	**0.081**	0.299	**0.090**	2.173	**0.111**	0.578	**0.181**

It can be concluded that the accuracy of UWB positioning after NLOS error correction is close to the positioning accuracy in the LOS environment. The proposed method can accurately identify NLOS error and mitigate it by applying a correction model for wall caused NLOS delay.

A problem can be found in Fig. 9. When the tag moves to Area 6, the UWB system can no longer obtain the location information of the tag, so the Tag trajectory in Area 6 is missing, as indicated by the blue triangle trace in Fig. 9. This problem is because when the tag is in Area 6, except that the UWB signal of Anchor 3 reaches the tag through one wall, the signals of Anchor 0, 1 and 2 have to pass through at least two walls to reach the tag. After the actual measurement, anchors 0, 1 and 2 have been unable to obtain the ranging information of the tag, so only the ranging information of Anchor 3 can no longer calculate the position information of the tag through the TOA algorithm.

V. CONCLUSION AND FUTURE WORK

This paper introduces a new method to identify UWB NLOS and the transmission delay caused by walls. The NLOS identification uses the variance of the difference between the tag ranging from the adjacent sampling time. The transmission delay correction for walls in the NLOS environment uses the geometric signal propagation model. The performance of the proposed method for NLOS identification and correction is evaluated with two experiments. Experiment results show that the method can effectively identify NLOS and dramatically improve UWB positioning accuracy in a NLOS environment. The NLOS identification accuracy can reach more than 90%. For NLOS caused by walls, the proposed correction model can correct the UWB signal transmission delay. Test results show that the UWB positioning accuracy with the correction in the NLOS environment is close to the accuracy in the LOS environment. The proposed method can effectively improve UWB positioning accuracy in an NLOS environment.

Our experiments found a couple of potentials to further improve UWB positioning accuracy in a complex indoor environment with the NLOS appearance. Other objects instead of walls cause some NLOS; their transmission delay correction model can be investigated. Their precision is lower for UWB measurements with NLOS errors than LOS. The position calculation with both LOS and NLOS measurements should count the precision difference between LOS and NLOS measurements. There are some locations the UWB tag cannot get enough ranging measurements for its positioning. UWB needs to be combined with other positioning technologies, such as IMU and SLAM, to make indoor positioning more robust and reliable.

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