A New Method of D-TDOA Time Measurement Based on RTT

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Abstract. In this paper, a novel difference-time difference of arrival (D-TDOA) time measurement method based on round-trip transmission (RTT) is proposed. The accuracy of time measurement is critical for high accuracy positioning, yet the traditional time difference of arrival (TDOA) time measurement method cannot deal well with the problem of time synchronization error, such as the initial time offset and transmission cumulate time error caused by clock frequency offset and drift. We formulate a D-TDOA time measurement mechanism to overcome the shortcoming of the traditional TDOA method in eliminating the influence of clock error. It is proved that the D-TDOA method can effectively eliminate the influence of initial time offset by analyzing the simulation data, which can also reduce the cumulate time error remarkably. The simulation results demonstrate that the D-TDOA method can significantly enhance the accuracy of time measurement in the circumstance that the AP clock synchronization is not required seriously.

Key Words： D-TDOA;RTT;time measurement; clock errors

1 Introduction

In recent years, with the rapid development of communication and navigation technology, location services as a new strategic industry has become an indispensable part. A variety of indoor positioning technologies have been proposed, such as RFID,Bluetooth, UWB, WIFI, A-GPS, ZigBee, etc..

At present, the common indoor positioning methods are generally defined as the following four categories: Time of arrival (TOA), Time Difference of Arrival (TDOA),Arrival of Angle (AOA) and Received Signal Strength Indication (RSSI). Among them, TOA and TDOA are required to get the accuracy time parameters. The TOA method determines the location of the unknown node by measuring the signal transmission and reception time of the location node and the unknown node, and the TDOA method measures the distance by measuring the time difference of the same signal from the unknown node to the difference location nodes. Compared with other positioning methods, the positioning method based on time measurement has the advantages of simple and universal, so it has a wide application prospect. However,due to the indoor environment is complex and changeable that the measurement precision of time is influenced by many factors, such as the multipath[1], the interference of the same frequency and the error of the node clock. Therefore, how to get the accurate time information is very significant for the realization of high precision indoor positioning. Authors in[2] achieved the high accuracy positioning method whose accuracy is 1m by using timing resolution of 1μs. However, their final measurement result is the average of 500 times repeated measurements. Obviously, it is not desirable in practical applications. Reference[3] has been proposed through the integrated application of multi-hop latency compensation and asymmetric compensation algorithm to ensure nanosecond clock synchronization between the various WLAN access points (AP) accuracy. The traditional TDOA [4-5] positioning method cannot deal well with the initial time offset and the cumulate time error caused by clock oscillator frequency drift, so it’ unable to meet the demand of indoor high accuracy positioning. In order to overcome the time measurement error,Difference-Time Difference of Arrival (D-TDOA) time measuring method is proposed in this paper. Theoretical analysis and experimental results show that the method can greatly improve the accuracy of time measurement.

This paper is organized as follows. In Section II, this part illustrates the main sources of time measurement errors and the necessity of eliminating clock errors. The description of the D-TDOA time measurement method based on RTT as described in Section III. In Section IV, the simulation results show that the D-TDOA method can effectively mitigate the influence of the main clock error on time measurement accuracy. Finally, In Section V conclusions are provided.

2 TIME MEASUREMENT ERRORS

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2.1 Formatting the title, authors and affiliations

The main source of time measurement errors can be summarized as the following three aspects.

Firstly, the additional time delay caused by the non-line of sight (NLOS) propagation and the multipath effect is the main factor to affect the accuracy of time measurement. Existing research shows that the error can be mitigated to a certain extent by using biased Kalman filtering[6].Authors in [7] proposed a new positioning algorithm (N-CHAN) to overcome an obvious shortcoming that the accuracy of traditional CHAN algorithm effected by no-line-of-sight (NLOS).

Secondly, timing resolution plays an important role in the accuracy of time measurement. Usually if the resolution of the timer is low, its measurement time will be smaller than the real time. For example, assuming the real time is 333.33ns, then 333ns will be getting when the timing resolution is 1ns. Therefore, with the enhancement of timing resolution, the more precise time information and accurate location information can be obtained.

Thirdly, the reason for the stability of the clock will cause time error, while the difference of clocks between the different nodes also presents a great challenge to the accuracy of the timing, which is not negligible for high precision indoor positioning.Obviously, how to effectively restrain the clock errors is worth in-depth study.

2.2 Clock errors

It's very difficult for the normal TDOA positioning mechanism to realize clock synchronization [8-9]among AP nodes. GPS, the most accurate time synchronization system, can achieve the accuracy of 15-30ns. Usually clock synchronization mainly depending on the standard clock to periodically sends clock synchronization signal to other slave clocks. Then, the slave clocks would calculate the path delay, time offset and frequency offset by using the information from the signal, and adjust their time and frequency offset close to the standard clock as much as possible. However, the clock error still has a negative impact on time measurement accuracy.

The main sources of clock errors are concluded as follows. On the one hand, the clocks of the AP still have small time offset compared to the standard clock after the time compensation. It is called the initial time offset. On the other hand, the crystal frequency offset and drift of clocks will cause transmission cumulate time offset that named as cumulate time error. Therefore, the clock errors discussed in this paper are consisted of initial time offset and cumulate time error.

In the actual situation, although most of the crystal frequency offset is usually as small as dozens of ppm and the cumulate time error caused by crystal frequency drift can be ignored in minimal period, it is difficult to overlook the impact of the errors on timing measurement accuracy, during a relatively long period. Meanwhile, the initial time offset also seriously affects the time accuracy. The above problems can be dealt well with the D-TDOA time measurement method.

3 D-TDOA METHOD

3.1 Measuring mechanism

D-TDOA measurement mechanism is based on the traditional TDOA signal transmission mechanism combined with RTT to transmit signal. Regard AP_0 as the central reference point, AP_1, AP_2 and AP_3 as auxiliary reference points, respectively.Taking the signal transmission process that the signal transmits from the MT to AP_0 and AP_1 for example.

The MT sends the WIFI signal at t_0, AP_0 receives the signal at t_1 and AP_1 receives the signal at t_2. After that AP_1 immediately has a RTT with AP_0. The frame leaves AP_1 at t_3 and reaches AP_0 at t_4, then leaves AP_0 at t_5 and reaches AP_1 at t_6. AP1 sends data frame composed of t_2, t_3 and t_6 to AP_0. The transmission process above shows as in Figure 1. In the case that clock synchronization is not required, in order to eliminate the initial time offset and reduce the cumulate time error caused by clock crystal oscillator frequency drift, the following method is used to calculate the time difference of the MT to the center reference point AP_0 and the auxiliary reference point AP_1.

In the case depicted in Figure 1, the transmission time from MT to AP_0:

$$\Delta_1 = t_1 - t_0 \tag{1}$$

The transmission time from AP_1 to AP_0:

$$\Delta_3 = \frac{(t_6 - t_3) - (t_5 - t_4)}{2} \tag{2}$$

The transmission time from MT to AP_1:

$$\Delta_2 = (t_4 - t_0) - (t_3 - t_2) - \Delta_3 \tag{3}$$

The TDOA of MT to AP_0 and MT to AP_1:

$$T_{TDOA} = \Delta_2 - \Delta_1 = (t_4 - t_1) - (t_3 - t_2) - \frac{(t_6 - t_3) - (t_5 - t_4)}{2} \tag{4}$$

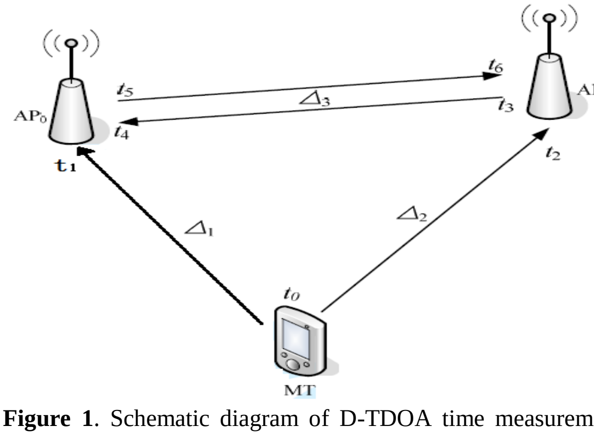


Figure 1. Schematic diagram of D-TDOA time measurement method.

3.2 Analysis of the D-TDOA time measurement method

In this paper, a simplified time model is used. Suppose that the moment of the standard clock is M when the last clock synchronization is finished. And after a period of time T_i(i=0,1,2…) , the standard time is t_i=M+T_i.The corresponding time of AP_i clock is:

$$t_i = t_i^{'} + u_i + \eta_i (t_i^{'} - M) \quad (5)$$

u_i is the initial time offset between standard clock and AP_i clock after the last clock synchronization. η_i is crystal frequency drift of AP_i. Thus $\eta_i(t_i'-M)$ is the cumulate time error of crystal oscillator frequency offset of AP_i from standard time M to t_i'.Then the following expression can be obtained:

$$t_i = t_i^{'}(1+\eta_i) + u_i - \eta_i M = (M + T_i)(1+\eta_i) + u_i - \eta_i M = M + u + T_i(1+\eta_i) \quad (6)$$

Suppose the TDOA is TTDOA in the traditional TDOA time measurement method，so the following expression can be obtained:

$$T_{TDOA} = (t_2 - t_0) - (t_1 - t_0) \quad (7)$$

And according to expression (6), the following expression can be obtained

$$(t_0^{'} = M + T_0; T_1 = T_0 + \Delta_1; T_2 = T_0 + \Delta_2):$$

$$T_{TDOA} = u_1 - u_0 + T_2 - T_1 + T_2\eta_1 - T_1\eta_0 = u_1 - u_0 + \Delta_2 - \Delta_1 + \Delta_2\eta_1 - \Delta_1\eta_0 + T_0(\eta_1 - \eta_0) \quad (8)$$

While according to the expression (4) of D-TDOA method, the following expression can be obtained:

$$T_{TDOA} = (t_4 - t_1) - (t_3 - t_2) - \frac{(t_6 - t_3) - (t_5 - t_4)}{2} = a - b - \frac{c-d}{2} \quad (9)$$

Where $a = (1+\eta_0)(T_4 - T_1)$, $b = (1+\eta_1)(T_3 - T_2)$, $c = (1+\eta_1)(T_6 - T_3)$ and $d = (1+\eta_0)(T_5 - T_4)$, we can see that the parameters of each equation are from the same clock, and it contains the difference of time parameters, so this method can eliminate the partial errors of clock.

As can be seen from Figure 1, $T_3 = T_2 + p_1;\ T_4 = T_3 + \Delta_3,\ T_5 = T_4 + p_0;\ T_6 = T_5 + \Delta_3;\ p_0$ represents $t_5 - t_4;\ p_1$ represents $t_3 - t_2$, expression (9) can be represents as:

$$T_{D-TOA} = \Delta_2 - \Delta_1 + \eta_0(\Delta_2 - \Delta_1) + (\eta_0 - \eta_1)(\frac{1}{2}P_0 + P_1 + \Delta_3) \quad (10)$$

In the expression (10), assuming the crystal frequency drift coefficient η_0 and η_1 are ±25ppm . The covering radius of WIFI signals is smaller than 100m, thus the maximum time difference $(\Delta_2 - \Delta_1)$ is approximately 333ns. So the error of $\eta_0(\Delta_2 - \Delta_1)$ is at 10^{-11} order magnitude, and it is negligible for the time measurement resolution of 1ns. In the term of $(\eta_0 - \eta_1)(\frac{1}{2}p_0 + p_1 + \Delta_3)$, the order of the first part is at 10^{-5} order magnitude. In the second part, assuming p0 and p1 are consist of the time of processing frames and waiting period (the node needs to monitor whether the channel is idle before starting to send data) in the case of neglecting other influencing factors, Meanwhile, the frame processing time can be also ignored relative to the frame waiting time. The IEEE802.11 MAC provides three kinds of access priority, including DIFS, PIFS and SIFS, where DIFS is the longest frame interval that be set at 50 microseconds in IEEE802.11b. So the part $(\frac{1}{2}p_0 + p_1 + \Delta_3)$ is at 10^{-4} order magnitude. Thus, the multiply of the two parts might bring several nanoseconds to the time measurement error.

Comparing the expression (8) and (10), it can be found that u0 and u1 are counteracted by D-TDOA measurement method of the same clock, so the initial time offset between the AP clock and the standard clock can be eliminated. Meanwhile, the terms containing T_0 is also counteracted so that the main time measurement errors in the process of clock synchronization have been avoided. That is to say, the time measurement cumulate error of D-TDOA method will not increase with the increase of the time after the previous synchronization. Consequently, the accuracy of time difference which is measured by D-TDOA measurement method can be improved substantially, thus the positioning accuracy will be greatly enhanced.

4 SIMULATION RESULTS

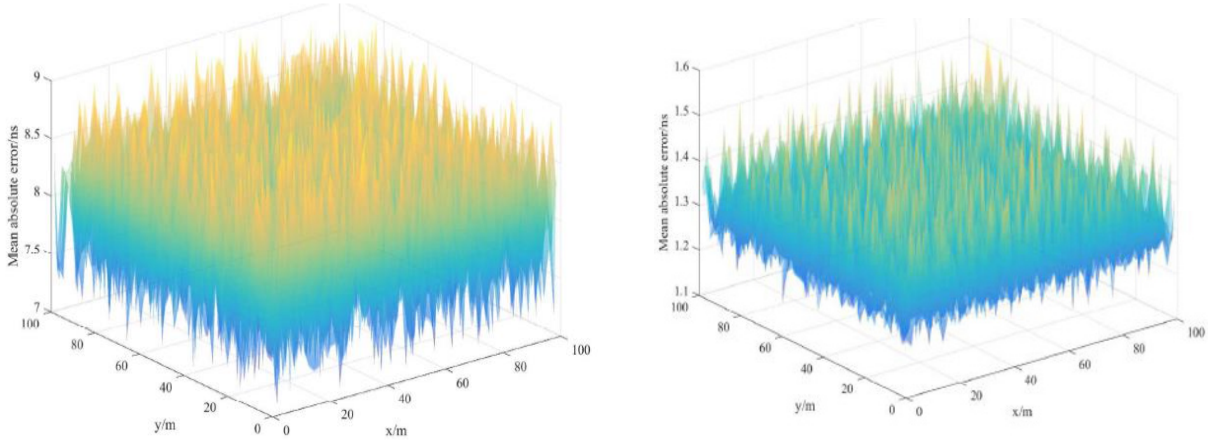
This section consists of two groups of simulations and a summary of results. The simulation A compared the influence of initial time offset to the time measurement accuracy on traditional TDOA method and the D-TDOA method. Simulation B illustrates the influence of cumulate time error to the time measurement accuracy on traditional TDOA method and the D-TDOA method.

Assume that the channel environment is ideal in all simulations. The experimental environment is set in a square region $(x \in [1,100],\ y \in [1,100])$, the default clock timing resolution of each AP is 1ns. Suppose η_0 and η_1 are taken from a uniform distribution with range of [-25×10^{-6}，25×10^{-6}], where a negative value indicates the crystal frequency is slower than the standard clock frequency, and positive value indicates that the crystal frequency is faster than the standard clock frequency.

4.1 Simulation about initial time offset

In this simulation, the AP_0 is set at (36, 28) and AP1 is set at (71, 84). Assume the T_0 = 0; u_1- u_0=u; u_0 and u_1 are taken from a discrete uniform distribution whose range is ±[15,30] ns, and can only be integers.

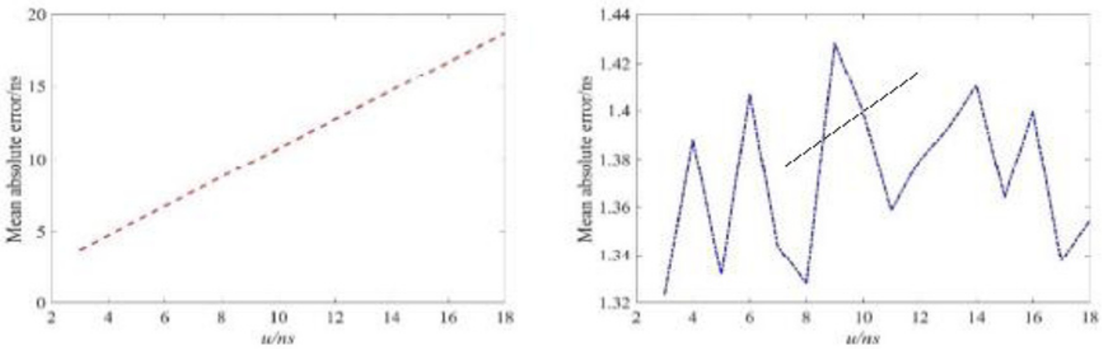
Figure 2 shows the distribution of the average absolute error when u=8ns and the computer simulation is performed 1,000 times that MT at each point. The mean absolute error of TDOA method is fluctuating near 8ns. However, the mean absolute error of D-TDOA method is just between 1.17ns-1.54ns.



(a) TDOA method (b) D-TDOA method

Figure 2.Distribution of the mean absolute error when u =8ns

The mean absolute error curve, we show in Figure 3, the mean absolute error of TDOA method is proportional to u and it is closely related to the value of u, while the mean absolute error of D-TDOA method fluctuates between 1.32ns-1.43ns.



(a)TDOAmethod (b) D-TDOA method

Figure 3. Mean absolute error curve with the change of u.

Compared to the results of the traditional TDOA method with D-TDOA method in the case of T_0 =0, the mean absolute errors of D-TDOA method are less than the traditional TDOA method. Theoretical analysis and simulation results show, the mean absolute error of the traditional TDOA method is mainly caused by the initial clock error, and it is close to the initial time offset difference between AP_1's clock and AP_0's clock. For the D-TDOA method, the error is primarily due to the processing time of the AP, and it basically remains invariant. It can be possible to conclude that the D-TDOA method can significantly eliminate initial synchronization error and extremely improve the accuracy of time measurement.

4.2 Simulation about cumulate time error

In this simulation, mainly compare the influence of two timing measurement methods on cumulate time error. Assume the u_0=u_1=0ns, the AP_0 is set at (25, 25), the AP_1 is set at (75, 75) and the MT is set at (60,45). Because of crystal oscillator frequency drift coefficient remaining unchanged in a short time, the value of η_0 and η_1 in each group remains unchanged. Usually the value range of T_0 is from 0 to synchronization period, and T_0 is defined as 0-2.0ms in this simulation. We define P=MSETDOA/MSED-TDOA as gain reference value and repeated 10000 times to ensure the accuracy of the experiments. Then we have the simulation results in Table 1.

Table 1 shows the variation of the mean absolute error, mean square error and the gain with the change of T_0. The simulation results indicate that, under the traditional TDOA method, with the increase of T_0, the mean and mean square value of cumulative time error of the crystal frequency drift increases sharply, and the mean absolute error is proportional to the time T_0. However, the mean absolute error of D-TDOA measurement method remains the same value, which is due to the time measurement results under this method is independent of T_0. Therefore, the crystal frequency shift for traditional TDOA method will have a bad impact on the precision of time measurement, but the D-TDOA method can overcome the negative effects effectively. Considering the results, the proposed method has better performance than the traditional TDOA method.

Table 1 The influence of cumulate time error on two methods

$T_0(ms)$	$E[TDOA]$ (ns)	$E[D\text{-}TDOA]$ (ns)	MSE_{TDOA} (ns^2)	$MSE_{D\text{-}TDOA}$ (ns^2)	P
0	0.4324	1.3049	0.1870	2.5629	0.0730
0.5	8.3407		104.4024		40.7360
1.0	16.6701		417.1569		162.7675
1.5	25.0020		938.4505		366.1674
2.0	33.3347		1668.2832		650.9357

4.3 Summary of results

From the results of the two simulations, we can get the following:

1) Initial time offset after previous clock synchronization has no effect on D-TDOA measurement method.

2) D-TDOA method can effectively overcome cumulate time error caused by clock crystal oscillator frequency drift.

5 CONCLUSION

The D-TDOA time measurement method presented in this paper is simple and does not require additional cost, while it can also overcome major clock errors in the traditional TDOA method. The D-TDOA time measurement mechanism can enhances the accuracy of timing and avoids the problem of clock synchronization. Obviously,the initial time offset and cumulate time error has been eliminated effectively. The theoretical analysis and simulations results prove that the D-TDOA method significantly improves the precision of the time measurement.

With extensive coverage of wireless signal, D-TDOA method can be widely employed in indoor and outdoor positioning system. Simultaneously, D-TDOA method can also be used in the traditional 3-dementional TDOA positioning system to improve the positioning accuracy. In addition, the system which fuses the method with error correction and adaptive positioning algorithm can achieve the positioning accuracy of less than 1m. Apparently, D-TDOA method has a good application prospects.

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