A Kalman-filter-based wireless clock synchronization method in indoor localization

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ABSTRACT

In low-power and high-density real time locating systems, time difference of arrival (TDOA) technique outperforms other ranging techniques. The realization of TDOA-based high resolution indoor localization directly depends on the performance of clock synchronization. In this paper, we introduce a clock synchronization method based on the Kalman filter. The updated clock skew from the Kalman filter is incorporated into the calibration of the difference of arrival time to achieve highly accurate localization of moving targets. Experiments show that our method provides a nanosecond level synchronization resolution and has good robustness to clock synchronization period and non-line-of-sight error, which is quite suitable for indoor localization scenario.

Keywords: wireless clock synchronization, TDOA-based localization, Kalman filter, non-line-of-sight

1. INTRODUCTION

Localization is the process of determining the positions of the targets in the reference coordinate system. Highly accurate position information is of great significance in military, communicating and industrial applications[1]. Time of arrival (TOA) technique and time difference of arrival (TDOA) technique are two classical ranging methods in time-based localization. For low-power and high-density real time locating systems (RTLS), TDOA scheme has more advantages over TOA scheme. In an indoor location system, the reference nodes with known positions are named anchors and the unknown nodes to be located are called tags. In TDOA location the tag broadcasts a reference signal periodically and the signal is received by some anchors. Then the difference in the arrival time of the signal between the anchors can be estimated so that there is no need for the knowledge of absolute time of the transmission. But it is worth noting that high precise clock synchronization between anchors is essential to achieve accurate localization.

On the other hand, clock synchronization is a critical issue in the operation of wireless sensor networks (WSNs). As the basic building block of WSNs, clock synchronization is the fundamental guarantee for the normal operation of various applications. At the same time, the accuracy of clock synchronization has a direct influence on the quality of other services. In the past few decades, the studies on clock synchronization paid more attention to protocol design, power consumption and network scalability. So far, there have been proposed various time synchronization methods such as reference broadcast synchronization (RBS), timing synch protocol for sensor networks (TPSN), and flooding time synch protocol (FTSP) [2-4]. Unfortunately, these methods can only deliver precision in the microsecond range.

In high precision indoor localization applications, the accuracy of clock synchronization has a direct impact on the localization performance. Small clock synchronization errors may lead to significant localization errors. That is, a microsecond level precision of clock synchronization is far from satisfactory for localization because one nanosecond error in time is equivalent to 30cm error in distance. What’s worse, traditional clock synchronization techniques assume that the transmissions are in line of sight (LOS) scenario and the positions of anchors are perfectly accurate[5]. However, in the complex and harsh indoor environment these two assumptions may not be valid in practice. Last but not the least, given that clock synchronization signal and localization signal are propagated within the same channel, the frequency of clock synchronization has a close relationship with tag capacity of the system. The higher frequency of clock synchronization is the more information about the anchor clock but at the cost of a smaller tag capacity.

In this paper, in order to realize TDOA-based localization with high accuracy, we propose a clock synchronization method based on the Kalman filter. We firstly collect the TOA received by the slave anchor as measurements, and then get the real-time clock skew between the slave anchor and the master anchor using the Kalman filter. Finally, we incorporate the clock skew into the calibration of the TDOA for subsequent position calculation. As a consequence, we mitigate the clock difference and further realize high resolution real time localization. In addition, experimental results show that the approach we proposed can achieve a nanosecond level synchronization resolution and have good robustness to non-line-of-sight propagation and clock synchronization period.

The remainder of the paper is organized as follows: in section 2 we present the basic theory of clock model. Section 3 describes the detail of implementation of clock synchronization in TDOA-based localization. Section 4 analyzes the performance of our method, and we draw our conclusion in section 5.

2. BASIC THEORY OF CLOCK MODEL

In the computer system, a clock can be usually viewed as a counter getting incremented with a crystal oscillator. The count rates are not completely consistent with each other because of the imperfections of the frequency of the oscillators at any two nodes. Therefore, modeling the clock and rectifying the clock difference caused by unstable oscillators will definitely improve the clock accuracy. In general, the clock function of a sensor node is modeled as:

$$c(t) = \frac{1}{\omega_0}\int_{t_0}^{t} \omega(t)dt + c(t_0) \tag{1}$$

Where t denotes the real time variable and $c(t)$ denotes the local time of the node. $\omega(t)$ is the angular frequency of the node's oscillator and ω_0 is the standard angular frequency. When $\omega(t) = \omega_0, t_0 = 0$, the model degrades into the ideal clock, that is $c(t) = t$. Moreover, (1) can be simply written as $c(t) = \omega / \omega_0 \times (t - t_0) + c(t_0)$ if $\omega(t)$ is equal to constant ω. In the practical environment, the angular frequency of the oscillator always presents instability and is subject to the effects such as humidity, temperature, voltage changes and hardware aging. Hence, we define $r(t) = dc(t)/dt$ as the change rate of the clock.

Especially, two important parameters which reflect the performance of the clock model should not be ignored. They are clock offset and clock skew. Clock offset is the difference between the local time and the real time at the time instant t, which is given by $\mu(t) = c(t) - t$. Clock skew is the difference between the frequency of the local clock and the frequency of the reference clock. And clock skew is given by $\delta(t) = dc(t)/t - 1$. In addition, there is a strong correlation between clock offset and clock skew. Clock offset can be regarded as an absolute time error caused by clock skew. In this paper clock offset can be described as a function of clock skew with the simplified clock model. The relationship of clock offset and clock skew is written as:

$$\mu(t) = c(t) - t = \delta \times (t - t_0) + c(t_0) - t_0 \tag{2}$$

3. THE IMPLEMENTATION OF CLOCK SYNCHRONIZATION IN TDOA-BASED LOCALIZATION

Clock synchronization between nodes is the foundation of the realization of network-wide synchronization. Hence, here we focus our study on the scenario that only one node to be synchronized at a time. In the considered system, it is assumed that there are two anchors and a tag. The distance of the two anchors is known and these two anchors have a relationship of master and slave. Therefore, the task of clock synchronization is to estimate the relative clock skew and clock offset between the master and slave anchors such that the slave anchor can translate its timing information to the time domain of the master anchor.

3.1 Message exchange in clock synchronization

In our proposed method, two kinds of messages are used to realize clock synchronization and localization, which are called ccp message and blink message respectively. In the process of ccp message, the master anchor periodically sends a clock synchronization packet. And the slave anchor captures it and records the arrival time of the packet. Then we can get the real-time updates on the relative clock skew by using the Kalman filter at the slave anchor. The sequence diagram of ccp message is depicted in Fig.1 (a). The master anchor A sends a ccp message at $T1_A$ to the slave anchor B, which records its time of arrival $T2_B$ according to its own time scale. Similarly, after an interval T_{ccp} next ccp message is sent at $T3_A$ and is received at $T4_B$. Without loss of generality, it is assumed that there is no clock offset between the master and slave anchors at the very beginning time instant $T0$. From the sequence diagram we can easily derive the clock skew as:

$$\delta = \frac{T4_B - T2_B}{T3_A - T1_A} - 1 = \frac{T4_B - T2_B}{T_{ccp}} - 1 \tag{3}$$

From (3) the relationship between $T4_B$ and $T2_B$ can be expressed as:

$$T4_B = T2_B + T_{ccp}(1+\delta) \tag{4}$$

Besides, in the process of blink message, the tag periodically sends the location packets to the master anchor and slave anchor. As shown in Fig.1 (b), the location message is received by anchor A and B at $T2_A$ and $T3_B$ respectively. In the TDOA schedule, the distance difference between the tag and anchor A, B can be calculated by $R_{AB} = (T3_B - T2_A) \times c$, where c is the speed of electromagnetic wave. However, as discussed in section 2, the time of arrival $T2_A$ and $T3_B$ cannot be directly compared because each node has its own unique clock. Therefore, we should take some measures to calibrate the time of arrival received by the slave anchor B. For the sake of simplicity, we consider that the tag and the master anchor A have the same clock reference, ignoring the clock error between them. Finally, the calibrated arrival time $\hat{T}3_{B\_blink}$ can be written as:

$$\hat{T}3_{B\_blink} = T3_{B\_blink} - \mu_{T3\_blink} = T3_{B\_blink} \times (1-\delta) + T1_{A\_ccp} + T_{flight\_ccp} - T2_{B\_ccp}(1-\delta) \tag{5}$$

Where $T3_{B\_blink}$ denotes the uncorrected arrival time of the blink message at the slave anchor B. μ_{T3_blink} denotes the clock offset between anchor A and B at the time instant $T3$. In addition, $T1_{A\_ccp}$, $T2_{B\_ccp}$ and T_{flight_ccp} are the sending time at anchor A, the receiving time at anchor B and the fight time of the ccp message respectively.

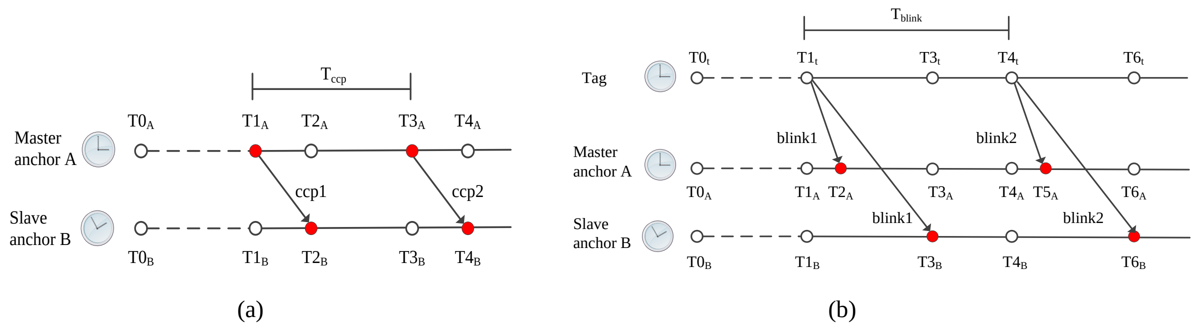

Figure 1. Sequence diagrams. (a)Ccp message. (b)Blink message.

3.2 Clock skew estimation using the Kalman filter

The Kalman filter is an efficient recursive filter proposed by R.E. Kalman in 1960[6]. The core concept of the Kalman filter is prediction and correction by minimizing the mean of the squared error. In other words, we first estimate the state of a process with historical parameters, and then correct the estimates with a new current measurement. Specifically, in the process of realization of the Kalman filter, we should establish the state equation and observation equation and accomplish parameter estimation. The state equation and observation equation can be described as:

$$X(k) = AX(k-1) + BU(k) + W(k) \tag{6}$$

$$Z(k) = HX(k) + V(k) \tag{7}$$

Where $X(k)$, $U(k)$ and $Z(k)$ are the state variable, control variable and observation variable at step k respectively; $W(k)$ and $V(k)$ represent the process and measurement noise respectively. They are assumed to be white Gaussian noise with covariance Q and R.

After analyzing the message exchange in clock synchronization, we can model a 2D Kalman filter at the slave anchor. In the process of ccp message, the relative clock skew and the arrival time of the ccp message are state variables. At the same time, the arrival time of the ccp message is also regarded as the observation variable. Hence, we can model the state equation and observation equation as:

$$t_{TOA}(k) = t_{TOA}(k-1) + T_{ccp} \times (1+\delta(k)) \tag{8}$$

$$\delta(k) = \delta(k-1) \tag{9}$$

$$Z(k) = t_{TOA}(k) \tag{10}$$

Equation (8) derives from (4). And (9) means that the clock skew at time instant k is ideally equal to the clock skew at the last time instant $k-1$.

Equation (8), (9) and (10) are written in matrix form as:

$$\begin{bmatrix} t_{TOA}(k) \\ \delta(k) \end{bmatrix} = \begin{bmatrix} 1 & T_{ccp} \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} t_{TOA}(k-1) \\ \delta(k-1) \end{bmatrix} + \begin{bmatrix} T_{ccp} \\ 0 \end{bmatrix} \tag{11}$$

$$Z(k) = \begin{bmatrix} 1 & 0 \end{bmatrix} \times \begin{bmatrix} t_{TOA}(k) \\ \delta(k) \end{bmatrix} \tag{12}$$

Furthermore, the state transition matrix A in (11) and the matrix H in (12) are given by:

$$A = \begin{bmatrix} 1 & T_{ccp} \\ 0 & 1 \end{bmatrix}, H = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

Then the process noise covariance Q and measurement noise covariance R can be estimated based on experimental data. When correct initial values are chosen, the iteration of the Kalman filter will sequentially start. At every iteration time, the Kalman filter generates a real-time relative clock skew, which will be later employed for calibrating the arrival time of the blink message at the slave anchor. Here the frequency errors of the clock are not constant in our proposed method, which is in accordance with practical situation. So far, we have solved the problem of clock synchronization between the master anchor and the slave anchor and finally achieved high resolution localization with TDOA algorithm.

3.3 NLOS mitigation in clock synchronization

In time-based indoor location system, the performance of localization depends on the precise estimates of the arrival time. However, non-line-of-sight (NLOS) error and multipath fading are two major factors which can severely affect the accuracy of the arrival time estimates. In NLOS environment, the received signals arrive with additional time delay because the signals penetrate the obstacles or arrive at the receiver through reflective and diffractive path. This can directly lead to a positive bias in range measurement and finally cause significant errors in localization. Specifically, in TDOA scheme, the source of the localization error mainly derives from the error of distance difference. Distance difference is the result of time difference multiplying speed of electromagnetic wave. Accordingly NLOS propagation also has a serious impact on clock synchronization. Therefore, solving the problem of the influence of NLOS propagation on clock synchronization is the key for accurate TDOA-based indoor localization.

In order to mitigate the NLOS error, post-processing is taken into account for the output of the Kalman filter. In the process of Kalman filter, the clock skew as the state variable will converge to a stable value after several times of iteration. Based on this observation, if now there appears sudden large fluctuation in the value of clock skew, we can easily deduce that this is caused by NLOS propagation. Therefore, a limit range filter is appended after the Kalman filter. The difference of clock skew between adjacent iteration is defined as $\delta_{diff} = \delta(k) - \delta(k-1)$ to limit the value of clock skew less than a certain threshold. In that case, the relative clock offset between the master anchor and the slave anchor maintains a constant range after entering the convergence state.

4. PERFORMANCE ANALYSIS AND DISCUSSION

In this section, a series of experiments are implemented to validate the efficiency of clock synchronization based on the Kalman filter. Given that the Kalman filter is actually a feedback control system, we will analyze the performance of clock synchronization in terms of rapidity, accuracy and stability in line with the demand of automatic control system. The experiments were conducted in the hallway of the eighth floor of automation building at institute of automation, Chinese academy of sciences. Two anchors were arranged in a line at the coordinates of (0,0) and (6000,0) respectively. And the tag was placed in the middle of the two anchors. In the experiments, the master anchor periodically sent ccp messages to the slave anchor. The two anchors received blink messages from the tag at a certain frequency simultaneously. The data for analysis were collected from experiments instead of simulation in Matlab.

4.1 Rapidity analysis

Rapidity analysis is to measure how quickly the clock skew can converge to a stable state. The speed of convergence reflects the dynamic response of the Kalman filter. In order to judge the influence of clock synchronization period on the rapidity of the Kalman filter, we record the convergence time of the clock skew at the slave anchor with different ccp message periods. Here values of ccp message period are as follows: $T_{ccp} = \{0.15s, 0.60s, 1.00s, 2.00s, 4.00s\}$ .Fig.2 shows that the relationship between the convergence time and clock synchronization period is approximately linear. The convergence speed become slowly as the clock synchronization period is increased. And the convergence time is about 9.45s when ccp message period is 150ms.

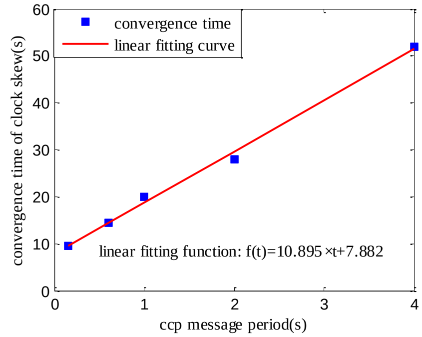

Figure 2. Convergence time of clock skew with different ccp message periods.

4.2 Accuracy analysis

Accuracy analysis is the process of calculating the steady-state errors after the Kalman filter finished the dynamic iteration, which reflects the static performance of the Kalman filter. Here accuracy analysis is equivalent to measure the synchronization resolution. Hence, the synchronized time at the slave anchor and the local time at the master anchor are both got in the experiments for comparison. We firstly recorded the synchronized time at the slave anchor with different ccp message periods. Secondly we got the clock model of the slave anchor with linear fitting. And finally we compared it with the clock model of the master anchor, which is given by $c(t) = 1 \times t + 0$.

Table 1. Accuracy analysis of the proposed method with different ccp message periods.

Ccp message period(s)	Clock skew(s)		Rmse of synchronized time(s)
	Before synchronization	After synchronization	
0.15	2.904e-07	1.203e-11	1.352e-09
0.60	3.325e-05	1.058e-11	1.020e-09
1.00	2.863e-07	5.753e-11	1.630e-09
2.00	3.003e-07	5.168e-11	5.108e-09
4.00	3.051e-07	1.687e-12	1.605e-09

As shown in table 1, with the proposed clock synchronization method, the synchronization accuracy hold the order of nanosecond, not degrading as the clock synchronization period becomes larger. However, the author mentioned that the clock synchronization period involved a trade-off between the clock synchronization performance and the system capacity[7-8]. Because the clock synchronization messages share the same channel with the location messages, the shorter the clock synchronization period is the more accurate clock synchronization, along with a smaller quantity of tags in service. Obviously, clock synchronization period has little influence on the clock synchronization performance with our algorithm, which is suitable for high density indoor localization.

4.3 Stability analysis

The Kalman filter is of good stability if it has the ability of maintaining the performance when the system suffers some external interference. Here the external interference is specified NLOS propagation. In the experiments, the slave anchor was blocked by a person, creating the NLOS environment. Then the synchronized local time at the slave anchor was sampled simultaneously with two different clock synchronization methods. One is the method we proposed in this paper, another is a similar algorithm proposed in Ref. 8. The clock synchronization errors are compared with these two methods in NLOS scenario.

Fig.3 (a) shows the results of clock synchronization errors with two different methods. The clock synchronization errors are within the range of 0.01ns to 0.1ns when the communication channels are line of sight, while the clock synchronization errors sharply increase when the salve anchor was blocked. Fig.3 (b) is the amplified effect of Fig.3 (a) in NLOS scenario. We can clearly see that the clock synchronization accuracy even dropped to 10ns with the method in

Ref. 8 while it changed less significantly with our algorithm. As mentioned in section 3, a limit range filter was driven after the clock skew has been converged. The limit range filter limited the difference of the clock skew to a given range and replaced the value with last one if the difference was beyond the threshold. Obviously, our algorithm performs better than the clock synchronization in Ref. 8 due to the essential function of the limit range filter.

From the analysis of rapidity and accuracy, we can easily come to the conclusion that increasing the clock synchronization period will lead to a slow convergence speed. On the contrary, the advantages of increasing tag capacity due to a larger clock synchronization period far overweigh the cost of a long convergence time. Hence, an appropriate large value of ccp message period is chosen for practical implementation.

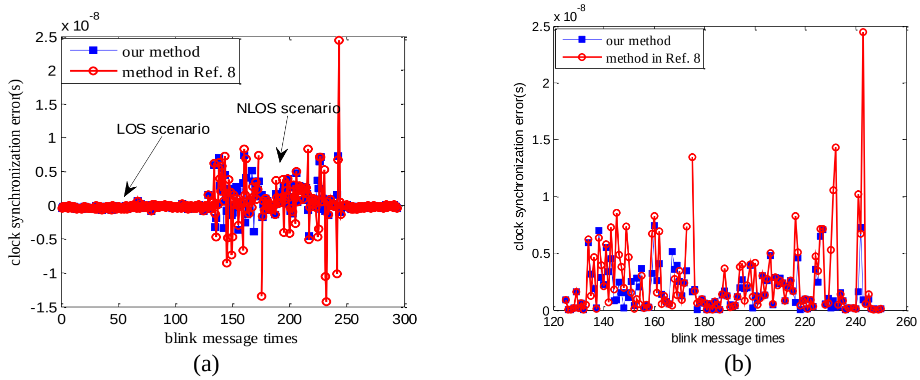

Figure 3. Stability analysis of clock synchronization with different methods. (a) The overall effect. (b) The amplified effect of figure 3(a) in NLOS scenario.

5. CONCLUSION

In this paper, we propose a clock synchronization method based on the Kalman filter for TDOA location application. We firstly take the relative clock skew between two anchors and the arrival time of the signal as state variables to model the Kalman filter. Then we update the result of the Kalman filter at every iteration time. Finally the relative clock skew is employed to calibrate the difference of the arrival time for location calculation. The experimental results show that our algorithm provides a synchronization resolution of nanosecond. Increasing the clock synchronization period hardly has impact on the synchronization resolution and adversely is good for the expansion of system capacity. In addition, this method is also robust to NLOS error in harsh indoor environments. In the future, our work will focus on how to improve the convergence speed of the Kalman filter.

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