One Study on IEEE1588 clock synchronization algorithm based on Kalman filter

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Abstract: Clock synchronization is a major indicator of the distributed network test and control system. The precise time synchronization is also one of the core technologies of the network communication of test and control system. The paper illustrates the fundamental principle for clock synchronization under IEEE1588 protocol and concludes that its synchronized accuracy is influenced by the accuracy of time stamp and transmission delay jitter through analysis. An autoregressive clock drift model has been put forward in the paper in an effort to improve the time synchronization accuracy. It makes use of the Kalman filter to estimate the deviation and drift of the master and slave clock so as to offset it. The results of simulation indicate that the method can effectively ease the impact on time synchronization for time stamp and improve its accuracy of the test and control system.

1. Introduction
With the increasing development of technology, the distributed test and control system through networked interconnection has been more and more widely applied to various industries. Maintaining the time synchronization of each terminal system is the prerequisite to ensure the cooperative work of each system, the correct data processing and the reliable information transmission. The time synchronization accuracy is also the major indicator of the distributed network test and control system. It has become the hot spot for researchers of such system about how to improve the time synchronization accuracy.

At present, in the data packet switched network, the accuracy of extensively used Network Time Protocol (NTP) 0 can be millisecond, which is mainly applied to the time synchronization of network computer. Its accuracy is far behind the requirements of the test and control device for the time synchronization. In 2002, IEEE1588 Precision Time Synchronization Protocol (PTP)[2] was released to meet the requirements of industrial ethernet. The PTP utilizes the ethernet and other networks that support multicast technology to synchronize the terminal device and its accuracy can be as high as sub-microsecond. With the hardware support, PTP can achieve the time synchronization more accurately. However, in terms of the ethernet network system with high compatibility, the addition of hardware has restrained the development and application of IEEE1588 network.

For the features of PTP, Li Xueqiao, Liu Jiancheng and others imported the asymmetric weighting factor to offset the slave clock by utilizing the arithmetic mean value of the sample deviation for the master and slave clock in a certain time window so as to largely reduce the impact on PTP time synchronization accuracy for transmission delay asymmetry[3-4]. Ye Ling et al. studied the time synchronization of wireless sensor network by utilizing Kalman filter. Zhuang Xiaoyan et al. optimized the PTP algorithm by making use of the time synchronization algorithm of the accelerated
motion model of the second order Kalman filter. The results indicated that the Kalman filter can improve the time synchronization accuracy of PTP significantly [5].

The paper attempts to apply the PTP to the test and control system network to mainly study the quantitative relation for PTP time synchronization accuracy and the uncertainty of time stamp and the delay jitter. Model the PTP to a set of observation equations and then follow up the clock offset and skew based on Kalman filter so as to improve the time synchronization performance of the test and control system for PTP synchronous protocol.

2. Synchronization Principle of IEEE1588

IEEE1588 identifies the time deviation of the Master and the Slave clock and the network delay of message transmission through the message exchange. Firstly, the node end of master periodically dispatches Sync message to the end of slave, which including the time t1 that left the master. If two-step mechanism is adopted, then, pack the time stamp t1 of sync message to the follow up message and dispatch the follow up message. The Slave receives the message and has it recorded as arrival time stamp t2. The slave dispatches the Delay_Req to the master and has it recorded as the departure time t3. The master records the arrival time of Delay_Req as t4 and sends it back to the slave through Delay_RESP. The slave calculates the time deviation and the network delay of transmission according to time stamp t1, t2, t3, t4 and offsets the time deviation until it synchronizes to the master, which is shown as figure 1. Taking the transmission delay of the master and the slave into consideration, the relation for the time deviation and t1, t2, t3 and t4 can be expressed in the following formula:

\[
\begin{align*}
    t_2[n] &= t_1[n] + \theta[n] + d_{ms}[n] \\
    t_4[n] &= t_3[n] + \theta[n] + d_{sm}[n]
\end{align*}
\]

In the formula, \(d_{ms}\) refers to the delay from the master to the slave; \(d_{sm}\) represents the time delay from the slave to the master; \(\theta\) is the time deviation of them, \(n\) shows the nth time synchronization. Then, the deviation for the master and the salve can be obtained from the formula (1):

![Figure 1 The synchronization mechanism of PTP](image-url)
In PTP, assuming the transmission delay is equal ($d_{ms} = d_{sm}$), then, the clock deviation can be obtained through $t_1$, $t_2$, $t_3$ and $t_4$.

The transmission delay of the master and the slave can be expressed as follows;

$$d = \frac{(t_2[n] - t_1[n]) + (t_3[n] - t_4[n])}{2}$$

(3)

From the perspective of principle, the time synchronization accuracy of PTP is mainly influenced by the time stamp accuracy and the symmetry of time synchronization transmission delay. In general, when the data size of the test and control system is small, the delay generated is stable. However, in the distributed test and control system, the data transmission delay is not equal due to various factors, such as the sudden increase of communication traffic, the selection of communication path and the introduction of wireless sensor.

3. Time System Model

Space model is a time domain model that describes the dynamic system with state vector. It is widely used in the fields including automatic control, state estimation and self-adaption signal processing. The state space model of PTP time synchronization and clock has been established in the paper.

3.1. Clock Model

The local clock in the test and control system generally generates the reference signal from the crystal oscillator and completes the calculation of time through the counting of the counter. Hence, the accuracy of the crystal oscillator and the value of counter determine the accuracy of local time. In the real environment, it is quite difficult to get the crystal oscillator with the identical characteristics and under different environment, it has different dynamic characteristics as well. Therefore, it is required to set up a model of clock so as to rectify the clock model with measuring value and improve the clock synchronization accuracy.

The clock model of the system is shown as following:

$$C(t) = \int_0^t \frac{dC(\tau)}{d\tau} d\tau + \theta_0$$

(4)

Among others, $C(t)$ refers to the local clock with error, $t$ is the precise clock, which means that in PTP, the node of the master is $T_m(t)$. $\theta_0$ is the initial time deviation, i.e., the initial time deviation of the slave. As certain deviation always exists for the real clock, then, the skew is represented by $dC(t) / dt$:

The expression of time deviation $\theta(t)$ and the clock skew $\alpha(t)$ can be obtained from the relation mentioned above.

$$\theta(t) = T_m(t) - C(t)$$

(5)
\[ \alpha(t) = 1 - \frac{dC(t)}{dt} \] (6)

If the local clock drifts, the value of \( \alpha(t) \) is not 0. With the time goes by, the deviation of local clock will be accumulated. In general, the physical clock will be affected by factors including temperature and generates the skew. Compared with time, temperature is slow variable, therefore, assuming that \( \alpha(t) \) in a short time period is constant, then, the continuous clock model (5) can be discretized as the state equation in the time domain through the discretization.

\[ \theta[n] = \sum_{i=0}^{k-1} \alpha[i] \tau[i] + \theta_0 + \psi_\theta[n] \] (7)

In the formula, \( \tau[i] \) represents the time interval counted each time, \( \psi_\theta[n] \) is the sum accumulation of clock offset error \( \psi_\theta[i] \) from time 0 to the n time.so the formula (7) can be rewrote to a recursive form.

\[ \theta[n+1] = \theta[n] + \alpha[n] \tau[n] + \psi_\theta[n] \] (8)

According to the demonstration of Hamilton et all[7]., the state of clock skew can be replaced by an AR process approximately. Hence, the recursive relation of \( \alpha \) can be expressed as below:

\[ \alpha[n+1] = p \alpha[n] + \psi_\alpha[n] \] (9)

In the formula, \( \tau[n] \) is the period of the time synchronization. A fixed time period \( T \) has been selected in the paper. \( P \) is a number proximity to 1. \( \psi_\theta \) refers to the deviation and jitter of the clock, while, \( \psi_\alpha \) is the clock skew jitter. It is believed that they are independent in the paper and they are the white noise of the mean value 0. The variance can be represented by \( \sigma^2_\theta \) and \( \sigma^2_\alpha \).

### 3.2. Observation System

The other core of state space modeling is the modeling of observation equation. The observation equation (2) of time deviation can be obtained based on the principle of PTPT. Assuming the observation quantity \( \theta^w \) of the time deviation in case of the asymmetry jitter of transmission jitter satisfies the normal distribution is:

\[ \theta^w[n] = \frac{(t_s[n] - t_i[n]) - (t_s[n] - t_i[n])}{2} + \nu_{\theta^w} \] (10)

In the formula, \( \nu_\theta \) is the observation noise of the deviation, its variance is represented by \( \sigma^2_{\theta^w} \), which consists of \( \sigma^2_{\text{MST}} \) (the time stamp error of the master), \( \sigma^2_{\text{STS}} \) (the time stamp error of the slave) and \( \sigma^2_d \) (the transmission jitter error). It can be expressed in the blow formula.

\[ \sigma^2_{\theta^w} = \sigma^2_{\text{MST}} + \sigma^2_{\text{STS}} + \sigma^2_d \] (11)
The observation equation for the system skew is:

$$\alpha_M[n] = \frac{\theta_M[n] - \theta[n-1]}{T} + v_{aM}$$

(12)

$v_{aM}$ is the observation noise of the system skew, which variance is:

$$\sigma^2_{aM} = \frac{2\sigma^2_{\theta M}}{T^2}$$

(13)

As known from formula (11), the clock deviation observation quantity is related to that of the clock skew, its covariance is:

$$\text{Cov}(\sigma_{aM}, \sigma_{\alpha}) = \sqrt{2} \frac{\sigma^2_{\theta M}}{T}$$

(14)

3.3. Kalman Filtering Model

The clock deviation and clock skew measured can be directly applied to the synchronization of the slave. However, in the actual practice, the measuring value needs to be processed by filtering due to the uncertainty caused by the noise transmission delay measured. Taking time deviation and skew as state variables, the paper makes use of the Kalman filtering technology to conduct the filtering process so as to improve the time synchronization accuracy.

The state space model of the system can be expressed as:

$$\begin{align*}
\dot{x}[n] &= A x[n-1] + w[n] \\
\dot{y}[n] &= H x[n-1] + v[n]
\end{align*}$$

(15)

In the formula, the state vector is $x[n]=[\theta[n]; \alpha[n]]$ and the observation vector is $y[n]=[\theta_M[n]; \alpha_M[n]]$. Assuming that the observed quantity is the calculated value itself, from the formula (7) and (8), we know that:

$$A = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \quad H = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

(16)

And as known from formula (15), the process noise can be referred to as $w[n]=[w_{\theta}[n]; w_{\alpha}[n]]$; the observation noise can be shown as $v[n]=[\nu_{\theta M}[n], \nu_{aM}[n]]$. Both of them can respectively meet $N(0,Q)$ and $N(0,R)$, among others:

$$Q = \begin{bmatrix} \sigma^2_{\theta} & 0 \\ 0 & \sigma^2_{\alpha} \end{bmatrix} \quad R = \begin{bmatrix} \sigma_{\theta M}^2 & \sqrt{2} \sigma^2_{\theta M} \\ \sqrt{2} \sigma^2_{\theta M} & 2\sigma^2_{\theta M} \\ \sqrt{2} \sigma^2_{\theta M} & 2\sigma^2_{\theta M} \\ 2\sigma^2_{\theta M} & 4\sigma^2_{\theta M} \end{bmatrix}$$

(17)

The iterative process of Kalman filtering:

$$\hat{x}(n/ n-1) = A\hat{x}(n-1)$$
\[ P(n / n - 1) = AP(n - 1)A^T + Q \]
\[ K(n) = P(n / n - 1)H^T[HP(n / n - 1)H^T + R]^{-1} \]
\[ \hat{x}(n) = \hat{x}(n / n - 1) + K(n)[y(n) - H\hat{x}(n - 1 / n)] \]
\[ P(n) = (I - K(k))P(n / n - 1) \]

(18)

4. Simulation Results

The clock synchronization for the node of the master and the slave in IEEE1588 protocol has been realized in the MATLAB software in order to verify the clock synchronization algorithm based on Kalman filtering put forward in the paper. The variation tendency of clock deviation, the mean value of estimated error of clock skew and the standard deviation between the master and the slave have been analyzed.

The parameters selected for simulation are shown in table 1.

| Name                                      | Value  |
|-------------------------------------------|--------|
| The variance of clock deviation \( \sigma_{\theta}^2 \) | \(10^{-14}\) |
| The variance of clock skew \( \sigma_{\alpha}^2 \)     | \(10^{-18}\) |
| The initial deviation of the slave \( \theta_0 \)      | 0      |
| The simulation step size                   | \(10^{-6}\) |
| The period of time synchronization \( T \)        | 0.1s    |

In order to make sure that the simulation experiment is closer to the real situation, the selected range of observation noise \( \sigma_{\theta}^2 \) is \([10^{-8}, 10^{-4}]\). When the observation noise is relatively smaller, the corresponding time stamp based on hardware and the asymmetry of transmission is smaller, otherwise, they are bigger. The simulation results are shown as figure 2 and figure 3.

Figure 1 The curve contrast diagram of clock deviation estimation and error
As known from figure 2, with the increase of the observation noise $\sigma^2_{\theta M}$, the mean value of clock deviation estimation error under both algorithms are showing a tendency of increase. However, the mean value of the IEEE1588 time synchronization algorithm based on Kalman filter is obviously smaller than that of the traditional IEEE1588. When the observation noise $\sigma^2_{\theta M}$ is smaller, the difference of the mean value of the clock deviation estimation error is not significant. However, with the increase of the uncertainty of time stamp, the advantage of IEEE time synchronization algorithm based on Kalman filtering is quite remarkable.

The similar conclusion can be drew from the figure 3. With the increase of the observation noise $\sigma^2_{\theta M}$, the mean value of clock skew estimation error under both algorithms are showing a tendency of increase. However, the mean value of the IEEE1588 time synchronization algorithm based on Kalman filter is obviously smaller than that of the traditional IEEE1588.

5. Conclusion
In this paper, the principle of time synchronization process has been analyzed, the time synchronization modeling based on Kalman filter has been established and simulated and the comparative study on the accuracy of the clock estimation error under IEEE1588 time synchronization algorithm with/without Kalman filtering has been conducted. The simulation results indicate that the method can effectively reduce the influence for the time stamp accuracy to the time synchronization and improve the time synchronization accuracy of the test and control system.

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