Performance Analysis and Simulation of JTIDS Network Time Synchronization

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Abstract—Round Trip Timing (RTT) and PPLI message are two ways of time synchronization in the Joint Tactical Information Distribution System (JTIDS) network. The former is a kind of active time synchronization, which could make the user have high timing level directly. The latter is completely passive and could provide low level time synchronization as a byproduct of navigation. This paper begins with the introduction of the two timing mechanisms of JTIDS network. Models of passive and active time synchronization are built up respectively. Two filters, one is navigation filter and the other is RTT filter, are designed based on the models. Simulation validates the design of the two filters, and effects of major error sources and model uncertainty are analyzed.

I. Introduction

The Joint Tactical Information Distribution System (JTIDS) is a synchronous, time-division multiple-access (TDMA), spread spectrum system, with integrated ability of communication, navigation and identification [1]. All user terminals operate on the common time base which is synchronized to the network time reference (NTR). They send messages in the allocated slots and receive in the others.

Round Trip Timing (RTT) and Precise Position Location and Identification (PPLI) message are two means of maintaining time synchronization in JTIDS network [2]. The former is a kind of active time synchronization, which operates independently of Relative Navigation (RELNAV). The latter is completely passive, and which is intrinsic to RELNAV function. Superior users in JTIDS network are assigned some fixed time slots to send RTT message to keep synchronization with NTR. However, inferior users must be capable of performing clock synchronization completely passively by receiving PPLI message.

Time synchronization and navigation performance are interactive in JTIDS network. On the one hand, RTT makes the user have higher timing level directly, which leads to a good navigation performance. On the other hand, good position information makes the passive synchronization more effective. Because of the complexity of complete theory analysis, finding the relationship between time dissemination and navigation error sources in JTIDS network using computer is very important.

This paper begins with the introduction of the two timing mechanisms of JTIDS network. Based on the clock model, RTT filter and navigation filter are designed for processing RTT message and PPLI message respectively. Finally, the two timing modules are used in a JTIDS network simulation platform to test the effectiveness of model uncertainty and the effect of error sources on time synchronization and navigation.

II. Model of Time Synchronization

Before we start the analysis and simulation, models of the two time synchronization have to be built up first.

A. Passive Synchronization by PPLI Message

Passive synchronization is the main method for some inferior users, which often have to be radio silence, to maintain synchronization in JTIDS network. A RELNAV user's clock error adds linearly and equally to the observed one-way radio ranges to all the PPLI sources. The RELNAV Kalman filter of passive users minimizes this common range bias by assigning it to the clock state carried in the filter.

The basic passive synchronization and ranging observation model can be expressed by [3]

$$\begin{cases} R_o = c(TOA) = R_c + b_t * c - b * c + N \\ R_c = \sqrt{(X_t - X)^2 + (Y_t - Y)^2 + (Z_t - Z)^2} \end{cases}$$

where R_o is the observed ranged to the source; R_c is the computed range to the source based on the information in PPLI message and user's own position prediction; c is the speed of light; TOA is the observed time of arrival with respect to the user's own clock time; X_t, Y_t, Z_t are position coordinates of the transmitter; X, Y, Z are position coordinates of the user; b_t is the time bias of the source with respect to system time, which is unknown to source and user; b is the time bias of the user; N is the sum of measurement noises. Each user should try to minimize b by passive or active synchronization. Generally, b_t could be considered included in N.

Because the observation equation of JTIDS passive synchronization and ranging is nonlinear, we have to linearize the observation equation and use the extended Kalman filter (EKF) equations as follow

predicted covariance:

$$P_{k|k-1} = \Phi P_{k-1|k-1}\Phi^T + \Gamma Q \Gamma^T \tag{1}$$

predicted state vector:

$$X_{k|k-1} = \Phi_{k|k-1}\hat{X}_{k-1|k-1} \tag{2}$$

gain:

$$K_k = P_{k|k-1}H_k^T\left[H_k P_{k|k-1}H_k^T + R\right]^{-1} \tag{3}$$

filtered state vector:

$$\hat{X}_{k|k} = X_{k|k-1} + K_k\left[R_O - \hat{R}_O\right] \tag{4}$$

filtered covariance:

$$P_{k|k} = \left[I - K_k H_k\right]P_{k|k-1} \tag{5}$$

where H is the linearized observation matrix which contains such elements as

$$-c,\ \left(X_t - X\right)/R_c,\ \left(Y_t - Y\right)/R_c,\ \left(Z_t - Z\right)/R_c$$

Details about EKF can be found in [4], and will not be covered in this paper.

Terminal users will process the equations above in sequence. However, not every PPLI message received is used to update EKF equations. In consideration of system stability and operation precision, received PPLI messages will first be stored. Then, the optimal source will be chosen according to the source selection algorithm [5]. Integrated quality of source can be obtained by

$$Q_{total} = \left(H_p + H_t\right)W_1 + H_g W_2$$

where, H_p and H_t are source quality of position and timing; H_g is the quality of relative position relation of source and user; W_1 and W_2 are two weighed coefficients. Source with maximal integrated quality Q_{total} will be used to update the EKF equations, which will give new estimate about timing and position.

B. Active Synchronization by RTT

Active synchronization by RTT is a very important method in JTIDS network time dissemination. Compared to passive synchronization by PPLI message, RTT is much more effective. It can make the user have good time quality after only one slot time, which is 7.8125 milliseconds in JTIDS network, and with very high precision.

Generally, the NTR transmits first in any new net and establishes the system time to which all other units synchronize by the exchange of round-trip timing interrogation (RTTI) and round-trip timing reply (RTTB) messages either directly with the NTR or with another unit already synchronized to the NTR. RTTIs are very short messages containing only the addresses of the interrogator and of the desired donor. The donor responds at a fixed time later in the same time slot with an RTTR message containing the address of the interrogator and the time of arrival (TOA) of the RTTI as measured on the donor's clock. The interrogator measures the TOA of the reply and computes the adjustment to its own clock necessary to make the donor's reported TOA equal the TOA of the reply at the interrogator.

Fig.1 illustrates the message exchange of RTT process. Observation equation of RTT can be expressed by

$$err(i) = \left[TOA(s) - TOA(i) + t(d)\right]/2$$

where, *err(i)* is the interrogator clock error; *TOA(s)* is the time of arrival of interrogation on source clock; *TOA(i)* is the time of arrival of reply on interrogator clock; *t(o)* is the slot start time, which is different for interrogator and source; *t(d)* is the standard reply delay time.

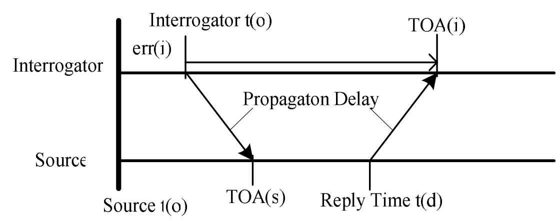

Fig. 1 Message exchange of RTT process

A series of RTT transactions over a period of a few minutes provides an estimate of the interrogator's clock drift rate; i.e., the frequency error of its clock oscillator and the frequency error estimate is then used to retune the oscillator driving the clock. The estimation of clock bias and frequency errors is carried out in a small Kalman filter which provides error uncertainties in its covariance matrix.

III. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

We have presented that time synchronization and navigation performances are interactive. However, the accuracy performance of navigation is a complex function of several error sources. So, the use of computer simulation for algorithm design and for performance evaluation is necessary. Based on a TDMA message distribution mechanism, JTIDS time synchronization modules including passive mode and active mode are designed to test the performance of time dissemination, and relationship between time synchronization and navigation error sources is discussed too.

In passive synchronization by receiving PPLI message, an 8 states extended Kalman filter is used. The state vector is

$$X^T = [bt \quad bf \quad X \quad Y \quad Z \quad vx \quad vy \quad vz]$$

where, bt is time offset; bf is time rate (frequency) offset; X, Y, Z are three relative grid coordinates; vx, vy and vz are the velocities in three directions. Considering the nonlinearity of the observation function, the linearized observation matrix is given by

$$H = \begin{bmatrix} -c & 0 & \frac{(X-X_t)}{R_c} & \frac{(Y-Y_t)}{R_c} & \frac{(Z-Z_t)}{R_c} & 0 & 0 & 0 \end{bmatrix}$$

The state transition matrix Φ and plant noise transition matrix Γ are given by

$$\Phi = \begin{bmatrix} 1 & T & & & & & & \\ & 1 & & & & & & \\ & & 1 & & & T & & \\ & & & 1 & & & T & \\ & & & & 1 & & & T \\ & & & & & 1 & & \\ & & & & & & 1 & \\ & & & & & & & 1 \end{bmatrix}_{8\times 8} \qquad \Gamma = \begin{bmatrix} 1 & & & & \\ & 1 & & & \\ & & T & & \\ & & & T & \\ & & & & T \\ & & 1 & & \\ & & & 1 & \\ & & & & 1 \end{bmatrix}_{8\times 5}$$

where, $T=T_k-T_{k-1}$. The plant covariance matrix Q is given by

$$Q = \begin{bmatrix} \sigma^2{}_{W1} & & & & \\ & \sigma^2{}_{W2} & & & \\ & & \sigma^2{}_{W3} & & \\ & & & \sigma^2{}_{W4} & \\ & & & & \sigma^2{}_{W5} \end{bmatrix}_{5\times 5}$$

where, $\sigma^2{}_{W1}$ and $\sigma^2{}_{W2}$ are clock random walk offset noise and clock flicker noise respectively; $\sigma^2{}_{W3}$, $\sigma^2{}_{W4}$ and $\sigma^2{}_{W5}$ are velocity noise in three directions. The measurement noise model V is a scalar denoted by $\sigma^2{}_{TOA}$.

Compared to passive synchronization by PPLI message, active synchronization by RTT uses a small basic Kalman filter which has only 2 states, bf and bt. Other key matrixes are given by

$$H = [1 \quad 0] \qquad \Phi = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \qquad \Gamma = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad Q = \begin{bmatrix} \sigma^2{}_{W1} & \\ & \sigma^2{}_{W2} \end{bmatrix}$$

In our simulations, every terminal user had a initial time offset uniformly distributed on [-2ms, 2ms], the initial time rate was selected from a zero mean Gaussian distribution having a standard deviation (S.D.) of 10^{-8} s/s.

A. *Effect of TOA measurement error*

We first analyze the effect of TOA measurement error to time synchronization. Assume the measurement TOA at time k is $\hat{T}$, the real TOA is T , and the error is ΔT, that is $\hat{T} = T + \Delta T$. By (2) and (4), we get

$$\hat{X}_{k|k} = \Phi_{k|k-1}\hat{X}_{k-1|k-1} + K_k\left[c\hat{T} - \hat{R}_O\right] \tag{6}$$

The real state at time k is

$$X_{k|k} = \Phi_{k|k-1}X_{k-1|k-1} + \Gamma_{k-1}W_{k-1} \tag{7}$$

By (6) and (7), we can get state error at time k

$$\begin{aligned} \Delta X_{k|k} &= \hat{X}_{k|k} - X_{k|k} \\ &= \Phi_{k|k-1}\left(\hat{X}_{k-1|k-1} - X_{k-1|k-1}\right) + \Gamma_{k-1}W_{k-1} + K_k\left(cT + c\Delta T - \hat{R}_{O_k}\right) \\ &= \left[\Phi_{k|k-1}\left(\hat{X}_{k-1|k-1} - X_{k-1|k-1}\right) + \Gamma_{k-1}W_{k-1} + K_k\left(cT - \hat{R}_{O_k}\right)\right] + K_k c\Delta T \end{aligned} \tag{8}$$

In the steady state of Kalman filter, the terms in square brackets will be minimized to zero by sources with high quality level and precise TOA measurement T. So (8) can be approximate to

$$\Delta X_{k|k} \approx K_k c\Delta T$$

When the sources and user distribute uniformly, and the distances of them do not change significantly, K_k approximate to a constant. In this specific situation, state error is in proportion to TOA measurement error. In real situation, due to the effect of source quality level, position variation and the other error sources, state error is not strictly in proportion to TOA measurement error, but the approximate proportion relationship still exists.

To verify the analysis result above, we made a simulation. There were 15 terminal users in JTIDS network, 1 of them was NTR, and 3 of them were ground sites which were position references at the same time. The TOA measurement noise was assumed normal with zero mean, and S.D. varies from 10ns to 1000ns. Table I shows the simulation results of S.D. of time bias and navigation circular error probability (CEP) in different S.D. of TOA measurement error. From the data in the table, we could see that when S.D. of TOA measurement error is larger than 100ns, S.D. of time bias and the navigation CEP are almost linear with S.D. of TOA measurement error. When the S.D. of TOA measurement error is smaller than 100ns, observe noise is not the major error source in timing and navigation error sources anymore, and the linearity does not exist. This simulation results verify our analysis about the effect of TOA measurement error on the state error.

TABLE I. EFFECT OF TOA MEASUREMENT ERROR

S.D.TOA_Err[a]	**10**	**100**	**500**	**1000**
S.D. of Time Bias (ns)	37.1	44.6	314.9	689.9
CEP (m)	51.5	55.0	189.5	369.4

a. Standard deviation of TOA measurement error.

In real project, in order to have definite time synchronization accuracy, S.D. of TOA measurement error has to be controlled within a certain value. Increase bandwidth of receiver and improve SNR will decrease TOA measurement error and improve the time accuracy.

B. Effect of PPLI message receiving rate

PPLI message receiving rate is anther important factor which will impact the performance of time synchronization and navigation. The rate depends on PPLI message sending rate of terminals and the number of users in the network. In general, the higher the PPLI message rate, the higher the time and navigation accuracy.

A simulation was made to test the effect of PPLI message receiving rate on the performance of time synchronization. The rate varies from 0.2 to 4 messages per second. Simulation results are shown in Table II. When the PPLI message receiving rate is more than 3 messages per second, it is no longer the major error source in JTIDS time synchronization. So S.D. of time bias will not decrease significantly.

TABLE II. EFFECT OF PPLI MESSAGE RECEIVING RATE

PPLI rate[a] (message/s)	**0.2[b]**	**1**	**2**	**3**
S.D. of Time Bias (ns)	192.1	65.4	39.6	30.5

a. PPLI message receiving rate.
b. One message per five second

C. Effect of model uncertainty

It is well known that Kalman filter is vulnerable to model uncertainty. It makes the implicitly assumption that the model and noise character statistic is known perfectly. So when we can not get the real model characteristic, solution of Kalman filter will not be optimal and even diverge.

We made a simulation to test the effect of model uncertainty on the two filters. In our simulation, there were model uncertainty in both state and observation equations. The observation noise was assumed zero mean Gaussian distribution having a S.D. of 10ns, and the uncertainty were 10ns. The real S.D. equaled to the sum of assumed S.D. and uncertainty. Simulation results show that the two filters were not stable when model uncertainty exists. When the proper model can not be obtained, we can use a robust Kalman filter to minimize the effect of unknown parameters in the model [6]. However, computation of robust Kalman filter is more complex than the original one.

IV. CONCLUSION

Time dissemination in JTIDS network is achieved by RTT message and PPLI message. The former is an active mode and often be used by superior users in the network to get accurate time synchronization directly. The latter is more popular with inferior users who do not have enough transmission slots. According to the models of the two synchronization mechanism, RTT filter and navigation filter are designed respectively for active and passive synchronization mode. Effect of TOA measurement error and PPLI message receiving rate are analyzed and computer simulated. Results show that TOA measurement error is almost linear with time bias and position error, and it is a major error source that impact both active and passive synchronization. PPLI message receiving rate impact only the passive mode and its effect is not as significant as TOA measurement error when the rate is not very low. Simulation results show that Kalman filter is vulnerable to the model uncertainty. A robust Kalman filter can be used at a cost of computation complexity.

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