Method of TDMA Highly Mobile SatcomStation Network Synchronization

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Abstracts. In a TDMA Satcom system, network synchronization methods for highly mobile Satcom stations produce serious timing error. In order to solve this problem, an open-loop network synchronization method based on Kalman filtering estimation principle is proposed. While maintaining the advantages of traditional open-loop network synchronization methods, such as simple implementation, the new method will greatly improve timing accuracy.

Keywords: TDMA Satcom, high mobility, open-loop synchronization, Kalman filter

1. Introduction

In a TDMA Satcom system, network synchronization mechanism is used to avoid inter-slot interference of terminal stations caused by delay jitter, so as to reduce system overhead of time slot protection. In the closed-loop synchronization mode, the system operates in self-transmit and self-receive mode or in the mode of sending a test packet to the target station and then receiving the response message. The distance between different stations can be calculated based on the time difference of data transmission and reception. Time synchronization can be achieved through transmit time. The shortest synchronization process is about 0.27s (for the self-transmit and self-receive mode). This method of synchronization has a high accuracy, but the adjustment cycle is longer. So it is not suitable for TDMA satellite network operating in high mobility mode. Traditional open-loop synchronization method requires accurate satellite orbit ephemeris data and real-time location of the Satcom station. It is seldom used in practical systems.

In this paper, the motion law of highly mobile Satcom stations is analyzed, an improved open-loop network synchronization timing method based on Kalman filter tracking prediction principle is proposed based on the traditional open-loop network synchronization timing method. The new method has higher synchronization accuracy, lower implementation complexity and higher practical application value.

2. TDMA Satcom Business Burst Timing Principle

The central station or reference station, as well as the mechanism to send the periodic reference frame R are critical to TDMA Satcom system business burst timing. As shown in Figure 1, terminal station “n” first receives the reference frame R, delays for a corresponding delay Tₙ according to the system assigned time slot position, and then send business burst data. When the business burst frame Bₙ reaches the satellite transponder, its position will be number “n” time slot length Dₙ, from the number “m” reference frame Rₘ.
In Figure 1, \( T_f \) is a super frame cycle. \( RT_r(n) \) is the link delay of the reference frame \( R \) from the satellite transponder to the terminal station “\( n \)”. \( RT_t(n) \) is the delay of the terminal station “\( n \)” burst traffic to the satellite transponder. \( TOF \) is the time of the satellite transponder transmitting the reference frame. When the terminal station “\( n \)” receives the reference frame, it will send the business burst data frame after a delay \( T_n \). When the business burst data frame arrives at the satellite transponder, the time slot position shall be reached at the same time, then the following equation shall be satisfied:

\[
mT_f + d_n = RT_r(n) + RT_t(n) + T_n
\] (1)

The time of the terminal station “\( n \)” receiving the reference frame is AORFn, then the terminal station “\( n \)” sending time \( T_t(n) \) will be AORFn+ \( T_n \). That is:

\[
T_t(n) = AORFn + mT_f + d_n - (RT_r(n) + RT_t(n))
\] (2)

It can be seen from Equation (2) that, key factors in determining the sending time of the terminal station “\( n \)” are the accurate values of \( RT_r(n) \) and \( RT_t(n) \). At the same time, in order to make \( T_n > 0 \), the value of \( M \) should be \( mT_f > RT_r(n) + RT_t(n) \).

In the existing systems, in order to accurately determine the business burst frame transmission time, Satcom terminal station adopts the closed-loop synchronization mode. The feedback value of difference between the actual reception time and the target reception time is used to correct the business burst transmission time. Synchronization accuracy can reach 10^{-6}s level. Highly mobile Satcom systems not only requires higher synchronization accuracy, but also requires shorter synchronization cycle.

3. Effects of High Speed Movement on Network Synchronization and Time Delay Variation Characteristics

3.1. Effects of High Speed Movement on Network Synchronization

At present, the speed of common high speed flying vehicles can reach hundreds of meters per second. The speed of super high velocity weapon can reach 10 times the speed of sound, that is, 3400m/s. Let’s take a flying vehicle with the radial sonic velocity, that is, 340m/s as an example, the timing error of the airborne TDMA Satcom system produced by movement per second will reach 2.25\( \mu \)s. In the commonly used TDMA Satcom systems, if synchronization error is corrected per 5s, then timing error produced by high speed movement will reach 9\( \mu \)s. Even if the closed-loop synchronization method is used for real-time synchronization error correction, 1s error will be introduced by the transmission delay. Therefore, we need to further study the characteristics of Satcom station transmission delay variation in high speed motion mode.

3.2. Transmission Delay Variation Characteristics of Highly Mobile Satcom Station

When the Satcom station works in fixed mode, the value of delay between it and the satellite is fixed. When the Satcom station works in high speed movement mode, the value of delay \( RT \) between it and the satellite changes with the variation of the distance. The following equation is used to calculate the transmission delay between the Satcom station and the satellite transponder as measured in closed-loop:

\[
x(n) = RT(n) + w(n)
\] (3)

In this equation, \( RT(n) \) is the real dynamic value of RT for the Satcom station in high-speed motion mode. \( w(n) \) is the random disturbance signal, assuming that the mean value is 0, variance is \( \sigma^2 \). The station terminal receives the reference frame time \( RT(n) \) value of \( RT_r(n) \) statistics, constitute an unknown deterministic parameter discrete sequence \( S(n) = \{RT_r(0), RT_r(1), ..., RT_r(n), ...\} \) is constituted by counting the delay value \( RT_r(n) \) when the Satcom station terminal receives the reference frame.
At present, the actual effective airspace where most aircrafts operate is below 20000 meters. Therefore, the maximum RT error introduced by distance changes is 20000 x 3.3ns=66 μs. As compared with the 130ms delay between the Satcom station terminal and the satellite, 66 μs value fluctuation is very small and convergence. The speed of commonly used flying platforms is generally below 1000km/h. The transmission cycle Tf of a TDMA Satcom system is generally set to 120ms. The timing error introduced by the movement of the Satcom station between two data transmission periods, that is, \( RT_r(n + 1) - RT_r(n) \) is not more than 1μs. The values are highly "relativity". A flying platform will change flying height in flight according to its task and environmental changes. The whole flight process can be viewed as the aircraft is flying at a mean height fluctuation. The corresponding RT value \( S(n) \) can be considered as a one time implementation of a random process. The average value is a fixed value \( RT(0), a^{n+1} \)

It is clear that the model of this sample can be represented by the following equation:

\[
RT_r(n) = a \ast RT_r(n - 1) + w(n) \quad n \geq 0
\]  
(4)

Through recurrence relation, equation (4) can be converted into the following equation:

\[
RT_r(n) = a^{n+1} \ast RT_r(-1) + \sum_{k=0}^{n} a^k w(n-k)
\]  
(5)

The expected value can be calculated via the following equation:

\[
E(RT_r(n)) = a^{n+1}E(RT_r(-1)) = a^{n+1} \mu_s \quad (\mu_s is the initial value of RT_r(-1))
\]  
(6)

The covariance of samples \( S(n) \) and \( S(m) \) is:

\[
Cs[m,n] = E[(RT_r(m) - E(RT_r(m)))(RT_r(n) - E(RT_r(n)))]
\]

\[
= a^{m+n+2} \sigma^2 + \sum_{k=0}^{m} a^{k+1} \sum_{l=0}^{n} E(u(m-k) - w(n-l))
\]  
(7)

Obviously, the mean value of the sequence \( RT_r(n) \) is related to “n”, and the covariance value depends on “m” and “n”, not on the difference between “m” and “n”. Therefore, \( RT_r(n) \) is not the Gauss white noise. Moreover, as constrained by the vehicle flying height, \( |a|<1 \) is a must. As can be seen from equation (7), when \( n->\infty \), the process is stable.

4. Open-loop Synchronization Method Suitable for Highly Mobile Satcom Station

Through the analysis of the RT value variation characteristics of highly mobile Satcom stations, we learn that the sample discrete periodic sequence, comprised of RT values at the time of Satcom terminal station receiving reference frames, has the characteristics of linear correlation and stability. After \( RT_r(n) \) value of Satcom station at the time of reference frame reception \( Rn \) is estimated, Kalman filtering can be used to predict the \( RT_r(n + 1) \) value of the Satcom station at the time of the next periodic reference frame arrival value. Because the sequence \( S(n) = \{ RT_r(0), RT_r(1),..., RT_r(n),... \} \) has a high linear correlation, the Satcom station can use linear interpolation method to calculate the accurate business burst transmission time according to the values of \( RT_r(n) \) and \( RT_r(n + 1) \).

Therefore, this paper proposes a new open-loop network synchronization method. The core idea is to use the traditional open-loop synchronization method to calculate the \( RT_r \) value of the Satcom station at the time of reference frame reception. \( RT_r \) value is used as the measurement value. Kalman filtering estimation principle is then used to track and predict the \( RT_r \) value of the highly mobile Satcom station. Accurate \( RT_r \) value of the Satcom station is estimated.

4.1. Modeling Analysis and Calculation Method of \( RT_r \) Estimation

Based on the above analysis, the relationship between the \( RT_r(n) \) value of the Satcom station at the time of reference frame reception and \( RT_r(n-1) \) value of the last cycle at the time of reference frame reception can be described as a first-order system sate equation:

\[
RT_r(n) = a \ast RT_r(n - 1) + u(n)
\]  
(8)

In addition, according to the latitude, longitude and elevation information provided by the flying vehicle navigation system, the distance between the vehicle and the communication satellite can be calculated. The delay value between the Satcom station and the satellite transponder can then be calculated, which can be
represented by \( y(n) \). This value is defined as the measured signal value, which can be represented by the following equation:

\[
y(n) = RT_r(n) + w(n)
\]  

(9)

In this equation, \( u(n) \) and \( w(n) \) are two uncorrelated random disturbance signals. The mean value is 0. The variance values are respectively \( \sigma_u^2(n) \) and \( \sigma_w^2(n) \). It can be seen from equation (9) that, the measured value is not accurate, and \( w(n) \) is the error introduced by measurement.

Assume a spanning space \( Y_{n-1} \) is constructed by \{\( y(1), y(2),..., Y(n-1) \}\), then the predictive value of \( RT_r \) can be obtained, that is, \( RT_r(n| Y_{n-1}) \). When a new value of \( Y(n) \) is observed, a spanning space \( Y_n \) is constructed by \{\( y(1), y(2),..., Y(n) \)\}. then \( RT_r(n + 1| Y_n) \) can be obtained via the following equation:

\[
RT_r(n + 1| Y_n) = \sum_{k=1}^{n} a_k(n)y(k)
\]  

(10)

The next problem is the calculation of coefficient \( a_k(n) \). For the convenience of the recursive equation computation, we can generate an orthogonal "new information" sequence:

\[
a(k) = f_{k-1}(k) = y(k) - y(k| Y_{k-1}) , \ k=1,2,...,n
\]  

(11)

According to the orthogonality principle, predicting the value of \( RT_r(n+1) \) by \( Y_n \) is entirely equivalent to predicting the value of \( RT_r(n+1) \) by \{\( a(1), a(2),..., A(n) \)\}. Therefore, equation (11) can be rewritten as

\[
RT_r(n + 1| Y_n) = \sum_{k=1}^{n} g_k(n)a(k)
\]  

(12)

In this equation, \( g_k(n)=\frac{E[RT_r(n+1)a^*(k)]}{E[|a(k)|^2]} \)

Equation (13) can be used to calculate the best business burst transmission time for the “n” transmission cycle:

\[
T_r(n)=AORF_n+ mT_f+d_n *(RT_r(n)*\frac{T_f+d_n}{r_f} +RT_r(n + 1)*\frac{T_f-d_n}{r_f})
\]  

(13)

It can be seen from equation (13) that, for a high speed flying vehicle operating in the TDMA satellite communication mode, network synchronization error correction does not require any feedback information. By using the open-loop synchronization information which may has bigger error, Kalman prediction method can be used to achieve high network synchronization accuracy.

5. Algorithm Simulation and Result Analysis

5.1. Simulation Assumptions

In setting the simulation conditions, we assume that the Satcom station is a super high speed aircraft, its speed is 5 times the speed of sound, that is, 1700m/s. Asiasat 4 communication satellite is used. the pitch angle range in PRC is 25 to 65 degree. The delay variation from the Satcom station to the satellite transponder is from 120ms to 140ms. The flying height changes along a parabolic line. The highest height is 20km. The radial satellite velocity range for the Satcom station is from 719m/s to 1541m/s.

Let’s assume that the system operates in Ka band. The observation noise is set to 1μs. The reference burst transmission cycle is 120ms. In order to highlight the distinction from the closed-loop synchronous method, the closed-loop synchronization correction cycle is set to 25 frames, that is, 3s.

5.2. Simulation Result Analysis

The absolute error value is used as a index for the comparison of different synchronization methods. Figure 2 shows the synchronization error curve for the improved open-loop network synchronization method based on Kalman filtering. As is shown in Figure 4, when the filter converges, the network synchronization timing accuracy is less than 0.6μs. We can see from Figure 3 that the network synchronization error for the uncorrected traditional open-loop network synchronization method is greater that 40μs. The network timing error for the closed-loop network synchronization method is greater than 20μs. Therefore, it is clear that these methods can not meet the need of TDMA satellite communication system network timing under the
background of high speed movement. The timing accuracy of the open-loop network synchronization timing method based on Kalman filtering correction proposed in this paper can deliver higher timing accuracy, and can satisfy the requirements of practical application.

6. Conclusions

Under the background of high speed movement, traditional synchronization methods can't satisfy TDMA satellite communication network timing synchronization accuracy requirements. This paper studies the RT value variation characteristics of highly mobile Satcom stations, puts forward a new open-loop network synchronization method based on the idea of Kalman filtering. The new method can track the variation of RT value of the Satcom station at the time of reference frame reception, accurately predict the RT value of the next cycle, and calculate the business burst sending time using the linear interpolation method. Simulation is conducted to verify the feasibility of this method. This method does not require feedback information, is easy to implement, and can satisfy the high network timing accuracy requirements in high-speed motion mode.

7. References:


