Simulation of Time Delay Characteristics of Time Sensitive Networking Based on MATLAB/Simulink

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Abstract: In order to realize the optimal design of time sensitive networking flow scheduling strategy and meet the communication requirements of time sensitive applications to the greatest extent, it is necessary to conduct a comprehensive study on the delay characteristics by using effective simulation methods. Firstly, the working principle of time sensitive networking flow control mechanism and the influencing factors of time delay are analyzed, and the basic goal of simulation research on time delay characteristics is defined. Then, the technical characteristics of different network simulation methods are compared, and MATLAB/Simulink is selected as the simulation tool to design the time sensitive networking delay model and simulation algorithm. Finally, aiming at the main flow control mechanism application scenarios, the feasibility and correctness of the time sensitive networking delay simulation method based on MATLAB/Simulink are verified. The research results have reference value for the study of time delay characteristics and the optimization design of flow control strategy of time sensitive networking.

1. Introduction

Time Sensitive Networking (TSN) allows time-sensitive application data and Best Effort (BE) data to be transmitted simultaneously over traditional Ethernet, which can not only ensure low delay, low jitter and zero congestion loss of time-sensitive data transmission, but also ensure that the transmission quality of BE data stream will not be significantly affected[1]. Because TSN takes into account the mixed transmission of time-sensitive flow and BE flow on Ethernet, it has a wide application prospect in industrial automation and control systems[2]. In particular, TSN has been used as one of the standard implementation schemes of 5G forward transmission network[3]. However, many factors, such as end system application data, network operating environment, traffic scheduling strategy and network state parameters, will affect the data transmission performance of TSN, making TSN network delay characteristics show significant dynamics[4]. Therefore, it is necessary to choose effective simulation means to realize TSN traffic scheduling strategy and study the delay characteristics of TSN under different network environments and scheduling strategies, so as to better support TSN network design and application.

In this paper, using the technical advantages of MATLAB/Simulink in algorithm programming and simulation function customization modeling, the time delay modeling of TSN customization is
realized, and the simulation algorithm is designed in the application scenarios of different TSN flow control mechanisms, this paper simulates and analyzes the delay characteristics of TSN, and verifies the effectiveness of simulation using MATLAB/Simulink. The research results have reference value for TSN delay characteristic analysis and flow control strategy optimization.

2. Data transmission delay of TSN

2.1. Network flow model
TSN flow is defined as an end-to-end unicast or multicast network connection from the sender to the receiver through a time-sensitive enabling network\cite{5}. Let the flow set be \( F = \{ f_1, f_2, \ldots, f_n \} \) where \( f_i \) is the i-th flow. The path set is \( p_i = \{ V_{i,s}, h_{i,1}, h_{i,2}, \ldots, h_{i,n_i}, l_i, V_{i,t} \} \), where \( V_{i,s} \) is the sender of stream \( f_i \); \( h_{i,k} \) is the link and node combination from the (k-1) node exit to the k-th node exit, which is called "hop", \( k = 1, 2, \ldots, n_i \); \( l_i \) is the network connection line of the receiving end, \( f_i \) is the final link of the flow, and \( V_{i,t} \) is the receiving end.

2.2. TSN flow control mechanism
Relevant standardization organizations have determined a variety of TSN flow control mechanisms to improve the transmission delay characteristics of time-sensitive data frames, but the technical means adopted are different. Among them, Time-Aware Shaper (TAS), Frame Preemption (FP) and their combination are the most widely used in practical engineering\cite{6}. In order to avoid the waste of bandwidth resources caused by too long guard band setting, the flow control mechanism of TAS combined with FP can obviously reduce the length of guard band. This paper focuses on the influence of TAS, frame preemption and their combination on TSN delay characteristics.

2.3. TSN delay model
The end-to-end delay of TSN data transmission includes three parts: end device delay, link delay and TSN node delay. This paper focuses on link delay and TSN node delay. The main processing process of data frames at link and TSN nodes is shown in FIG. 1.

Fig. 1. TSN data frame processing.

In FIG. 1, after the data frame enters the switch, it needs to go through multiple processing links, and \( t_1 \sim t_7 \) indicates that each link will generate different time delays. The processed data frame is output from port OUT1 and sent out over the link. We define a data frame passing through 1 link and 1 TSN node as 1 hop, that is \( h_{i,k} \). Each hop \( h_{i,k} \) delay \( t_{d(k)} \) has seven time components. The time components and their descriptions are shown in Table 1.

| Time component | Explain                     |
|----------------|-----------------------------|
| \( t_{i,0} \)  | Link propagation delay.     |
| \( t_{f,0} \)  | Data frame transmission delay depends on link rate and frame length. |
The preprocessing time of TSN node to data frame depends on hardware implementation.

The queuing delay of data frame depends on the network environment and has uncertainty.

Delay caused by strict priority scheduling strategy.

The scheduling delay of TAs depends on the GCL scheduling strategy.

The data frame is divided into high-speed frame and preemptive frame, and preemptive operation is performed.

The end-to-end delay of the flow $f_i$ is

$$t_{E2E} = \sum_{k=1}^{n_i} t_{d}(k)$$  \hspace{1cm} (1)

Where $t_{E2E}$ is the end-to-end delay of flow $f_i$; $t_{d}(k)$ is the k-th hop delay; $n_i$ is the number of hops in the flow $f_i$ path. The delay $t_d(k)$ of the k-th hop is

$$t_d(k) = \sum_{m \in \mathcal{B}_j} t_m(k)$$  \hspace{1cm} (2)

Where $t_m(k)$ corresponds to the delay of a processing link in Fig 1.

Based on the simulation method of MATLAB/Simulink, this paper studies the delay characteristics of formulas (1) and (2).

3. Design of simulation method

3.1. Selection of simulation tools

Document [7] makes a comparative study on TSN delay characteristic simulation methods. It is believed that MATLAB/Simulink supports a variety of data link layer simulation controls, can provide users with customizable modeling tools, has high flexibility, and can also make full use of MATLAB’s powerful programming capability to improve simulation performance. In this paper, MATLAB/Simulink is used to simulate TSN delay.

3.2. TSN delay model based on Matlab/Simulink

According to the working principle of TAS flow control mechanism, it is divided into data flow generation module, priority queue module, gating module, frame preemption module and so on. The MATLAB/Simulink time delay simulation system designed in this paper is shown in Figure 2.
The simulation system in FIG. 2 consists of five parts, respectively represented as B1-B5. Among them, B1 realizes GCL function; B2 generate simulation data streams, include critical streams and non-critical streams; B3 implement priority queuing; B4 realizes logic gate control of TAS; B5 realizes single server port output according to strict priority scheduling strategy.

3.3. Algorithm design

Existing simulation tools can't directly simulate the flow control mechanism of TSN. Therefore, this paper uses the visual modeling function provided by MATLAB/Simulink toolbox and combines the programming ability of MATLAB to simulate the end-to-end delay of TAS and FP, two main flow control mechanisms of TSN. The overall flow of delay simulation is shown in FIG. 3.

### Fig. 3. Overall Flow

Fig. 3 vertical direction, the process is divided into two parts: MATLAB program development and Simulink toolbox modeling. MATLAB program realizes the generation of initial data sequence of network flow, the calculation of different control parameters, and the statistical analysis of simulation results. Simulink toolbox completes visual TSN modeling, and realizes queuing and sending services under given configuration parameters. Combining MATLAB program development with Simulink toolbox visual modeling function can give full play to the advantages of MATLAB/Simulink collaborative simulation. The dotted line in the figure shows the information interaction between MATLAB program and Simulink toolbox.

#### 3.3.1. Design of flow control simulation scenario

In this paper, six flow control scenarios are designed, and TSN delay characteristics under different flow control mechanisms are simulated. As shown in Table 2.

### Table 2. Flow control simulation scenario.

| Flow control mechanism | Abbreviation | Explain |
|------------------------|--------------|---------|
| Strict Priority        | RP           | In 8 grades, 0 is the lowest and 7 is the highest. |
TAS(Maximum protection belt) | TAS1 | The guard band is set to the maximum frame transmission time.
TAS(Dynamic protection belt) | TAS2 | According to the frame length, the protective belt is dynamically adjusted.
TAS(Gated compression) | TAS3 | The adjacent frame gated windows are merged to compress the guard band.
Frame preemption | FP | High speed frames preempt the transmission resources of low speed frames.
Frame preemption & TAS | FP+TAS | Frame preemption is combined with TAS.

3.3.2. Statistical analysis of simulation results
Module B1 is used to generate the corresponding event sequence \( Y_i=(y_{i,1},y_{i,2},...,y_{i,NF_i}) \). \( NF_i \) represents the number of data frames contained in the stream. The algorithm simulates \( Y_i \) according to the set stream transmission path, and obtains the event sequence \( \tilde{Y}_i=(\tilde{y}_{i,1},\tilde{y}_{i,2},...,\tilde{y}_{i,NF_i}) \) after the influence of delay. The end-to-end delay vector \( T_d,i=(t_{i,1},t_{i,2},...,t_{i,NF_i}) \) of flow \( f_i \) is obtained by subtracting two event sequences, where \( t_{i,j} \) is equivalent to \( t_{i,E2E} \) of equation (1).

4. Examples
4.1. Example description
In order to verify the feasibility and correctness of the simulation method based on MATLAB/Simulink, the TSN simulation calculation designed in this paper is shown in Figure 4. Among them, HA1, HA2, HB1 and HB2 are the key flows; BE1, BE2, and BE3 are non-critical flow. The transmission rate of the links is 100Mbps.

![Fig. 4. TSN system simulation example](image)

Information about the data flow is shown in Table 3.
Table 3 corresponds to the characteristic parameters of the flow. The frame length of the critical stream is fixed and transmitted periodically with a frame interval of 2ms. The frame length and frame
interval of non-critical streams are variable and obey uniform distribution. The data frame overhead is 42 bytes and the frame length range is [84,1542] bytes.

Table 3. Data flow information.

| Flow | Type | Priority | Load(Byte) | Frame interval(ms) |
|------|------|----------|------------|--------------------|
| HA1  | key  | 7        | 500        | 2                  |
| HA2  | key  | 7        | 500        | 2                  |
| HB1  | key  | 7        | 500        | 2                  |
| HB2  | key  | 7        | 500        | 2                  |
| BE1  | non-key | 0 | 1000–1500   | 0.45–0.55          |
| BE2  | non-key | 1 | 1000–1500   | 0.45–0.55          |
| BE3  | non-key | 2 | 1000–1500   | 0.45–0.55          |

According to the data provided in Table 3, this paper uses the proposed algorithm to simulate TSN delay characteristics in different scenarios. Using the modeling method of FIG. 2, this example establishes a MATLAB/Simulink simulation model of TSN system according to the network structure of FIG. 4.

4.2. Scene settings

In this paper, the ratio R of critical flow and non-critical flow is taken as the simulation scene partition criterion, and the definition is defined

\[ R = \frac{B_{CR}}{B_{CR} + B_{NR}} \times 100\% \quad B_{CR} + B_{NR} \leq 90\% \times B_{link} \quad (3) \]

\( B_{CR} \) is the sum of the critical flows; \( B_{NR} \) is the sum of non critical flows; \( B_{link} \) is the link rate. The distribution of various streams under different R is shown in Table 4.

Table 4. Flow allocation for different simulation scenarios.

| Scene | R  | Stream allocation                  |
|-------|----|-----------------------------------|
| 1     | 25%| HA1, BE1, BE2, BE3                |
| 2     | 50%| HA1, HA2, HB1, BE1, BE2, BE3      |
| 3     | 80%| HA1, HA2, HB1, HB2, BE1           |

The three flow allocations in Table 4 and the six flow control mechanisms in Table 2 are combined with each other to obtain 18 simulation scenarios, totaling 90 groups of delay data of different flows. Each set of data contains 400 sample values. After statistics, the time delay statistical features of each group of data are obtained.

4.3. Result analysis

(1) Time delay characteristics under different regulation mechanisms

In this paper, HA1 and BE1 flows are selected for analysis. Under three flow control mechanisms, such as strict priority (SP), maximum guard band TAS (TAS1) and frame preemption (FP), the delay mean and delay standard deviation of streams HA1 and BE1 are shown in Tables 5 and Tables 6.
Table 5. Average delay of streams HA1 and BE1 (ms).

| R   | SP_HA1 | SP_BE1 | TAS1_HA1 | TAS1_BE1 | FP_HA1 | FP_BE1 |
|-----|--------|--------|----------|----------|--------|--------|
| 25% | 0.2823 | 0.4788 | 0.1986   | 0.5032   | 0.1988 | 0.5032 |
| 50% | 0.2839 | 0.4864 | 0.1986   | 0.5572   | 0.199  | 0.5572 |
| 80% | 0.2086 | 0.4404 | 0.1986   | 0.4592   | 0.1986 | 0.4592 |

It can be seen that under different flow control mechanisms and different flow proportions, critical flow and non-critical flow have different delay characteristics.

Table 6. Delay standard deviation of streams HA1 and BE1 (ms).

| R   | SP_HA1 | SP_BE1 | TAS1_HA1 | TAS1_BE1 | FP_HA1 | FP_BE1 |
|-----|--------|--------|----------|----------|--------|--------|
| 25% | 0.545  | 0.066  | 0         | 0.0841   | 0.0004 | 0.0899 |
| 50% | 0.058  | 0.070  | 0         | 0.1256   | 0.0009 | 0.131  |
| 80% | 0.284  | 0.037  | 0         | 0.0687   | 0.0001 | 0.0874 |

The delay standard deviation reflects the degree of delay jitter. As can be seen from Table 6, the delay jitter performance of critical flow and non-critical flow is also different under different flow control mechanisms and different traffic proportions. This fully shows that the influence mechanism of TSN's flow configuration scenario and flow control mechanism on delay and jitter is complex, and comprehensive optimization is needed to make the overall delay performance of TSN meet the requirements.

(2) Effect of FP combined with TAS on time delay

In this paper, three flow control mechanisms, FP, TAS1 and FP combined with TAS, are simulated. Table 7 shows the delay averages for streams HA1 and BE1.

Table 7. Average delay of HA1 and BE1 streams under FP condition (unit: ms).

| R   | TAS1_HA1 | TAS1_BE1 | FP_HA1 | FP_BE1 | FP+TAS_HA1 | FP+TAS_BE1 |
|-----|----------|----------|--------|--------|------------|------------|
| 25% | 0.1986   | 0.5032   | 0.1988 | 0.5032 | 0.1988     | 0.4954     |
| 50% | 0.1986   | 0.5572   | 0.1990 | 0.5572 | 0.1988     | 0.5371     |
| 80% | 0.1986   | 0.4592   | 0.1986 | 0.4592 | 0.1986     | 0.4734     |

As can be seen from Table 7, the key flow has good delay characteristics under the three mechanisms, and TAS1 has the best performance. However, non-critical flow has the best delay performance under FP combined with TAS mechanism (FP + TAS).

Under different control mechanisms, the standard deviation of time delay of flows HA1 and BE1 is shown in Table 8.
Table 8. Delay standard deviation of HA1 and BE1 streams under FP condition (unit: ms).

| R   | TAS1_HA1 | TAS1_BE1 | FP_HA1 | FP_BE1 | FP+TAS_HA1 | FP+TAS_BE1 |
|-----|----------|----------|--------|--------|------------|------------|
| 25% | 0        | 0.0841   | 0.0004 | 0.0899 | 0.0004     | 0.0899     |
| 50% | 0        | 0.1256   | 0.0009 | 0.131  | 0.0003     | 0.1222     |
| 80% | 0        | 0.069    | 0.0001 | 0.0874 | 0.0001     | 0.0901     |

As can be seen from Table 8, TAS1 can achieve the jitter of critical streams to be approximately zero, but FP and FP + TAS cannot.

Only when the length of the preemptable frame meets the corresponding conditions can it be preempted, and the preempted initial frame fragment needs to add an additional 4 bytes of check field. Therefore, these factors will affect the delay and jitter of the data frame. The statistical histogram of streams HA1 and BE1 under the condition of R=25% is shown in FIG. 5:

As can be seen from FIG. 5 (a), the difference between the two types of maximum statistical samples of the key stream HA1 is 0.32 ms, which exactly corresponds to the transmission time of the 4-byte check field at the 100Mbps link rate. In contrast, the statistical histogram of non-critical flow
BE1 given in FIG. 5 (b) is close to lognormal distribution, while the time delay has obvious uncertainty.

5. Conclusion
According to the functional requirements of TSN delay characteristic simulation, this paper proposes a TSN delay characteristic simulation method based on MATLAB/Simulink toolbox, and verifies the feasibility and correctness of the method with an example. Compared with the conventional network simulation platform, this method has the characteristics of flexible modeling and convenient implementation. This method can customize and realize the modeling of TSN exclusive flow control mechanism, and give full play to the powerful data analysis ability of MATLAB; using a variety of visual basic controls provided by Simulink toolbox, the TSN simulation system model is established efficiently, which is suitable for the simulation of TSN and its application system. The research results show that the proposed simulation method has engineering reference value. The next step will be to carry out in-depth research on the optimization of flow control mechanism in TSN engineering application.

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