Research on Gating Scheduling of Time Sensitive Network Based on Constraint Strategy

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Abstract. With the continuous development of industry, information and intelligence have gradually become the keywords of industrial control. In modern industrial scenarios, more and more devices are connected to the factory network, and the complex network environment will greatly affect the end-to-end transmission performance of key control flows, which brings a huge impact to those high-precision control signal transmissions. With the development of Time Sensitive Network (TSN) in recent years, more and more people have introduced this technology to the field of industrial control. In this paper, we propose a scheduling scheme based on constraint strategy for the key technology of TSN—Time Aware Shaper (TAS). This scheme can derive the appropriate network constraint strategy and optimization scheme of network resource utilization according to the end-to-end Quality of Service (QoS) of multiple key data streams in the network, and finally obtain the configuration scheme of Gate Control Lists (GCLs).

1. Introduction
With the arrival of Industry 4.0, the manufacturing field will develop towards a more intelligent and information-based direction, which undoubtedly increases the amount of data information in the communication network in most industrial scenarios, and the network congestion caused by the increase of data information will become a difficult problem to solve for the traditional industrial network [1]. In this context, there is an urgent need for a communication technology that can be applied to future complex industrial networks. Fortunately, the IEEE 802.1 Time Sensitive Network (TSN) Task Group is doing such a thing [2]. TSN is based on real-time Ethernet and has the advantages of low latency, low jittering and high reliability. These characteristics enable TSN to achieve end-to-end deterministic transmission of data and meet the end-to-end QoS requirements of key data streams in industrial networks. Although TSN can achieve deterministic data transmission, and its standardization mechanism is well defined on the architecture, how to run this network effectively is a huge challenge.

2. TAS related work
As real-time and deterministic network, TSN divides traffic into 8 priority levels, and the priority level is 0 to 7, with 7 being the highest priority [3]. In order to schedule these eight priority traffic, the TSN working group proposed a time-aware traffic scheduling——TAS in IEEE802.1 Qbv, and defined a GCLs, as shown in Figure 1. In TAS, there are 8 gates corresponding to different priorities. When the gate state is "C", the frames of the corresponding priority cannot be transmitted; when the gate state is "O", the frames of the corresponding priority can be transmitted. The status of the 8 doors can be set...
freely, that is, the status of the 8 doors can be "C" or "O" at the same time [4]. In the gating scheduling mechanism, the GCLs controls the opening and closing states of 8 different priority doors at the corresponding time, the interval of time slot and the opening state of the gate can be configured by the program, and it supports real-time updating in the case of changes in the network environment [5].

![Figure 1. IEEE 802.1Qbv gate control scheduling mechanism](image)

In [6], author describes how to determine an effective GCLs formal constraint, and uses Satisfiability Modulo Theories (SMT) to determine feasible solutions. In [7], author proposes a joint configuration method, which can realize end-to-end scheduling optimization on the bridge network consisting of 5G Bridge, and obtain a GCLs configuration scheme that meets the end-to-end QoS requirements through appropriate constraint policies. The article [8] reduced the number of constraint strategies on the basis of the article [7], from the original 7 to 5, and also made reasonable constraints on the delay and jitter.

In response to the above analysis of reference articles and problems, the work of this article is as follows: (1) Propose reasonable restriction strategies based on the transmission mechanism of TAS to meet the end-to-end QoS requirements of data; (2) Reduce the number of restriction strategies and reduce the workload of calculation; (3) Propose optimization for the action time of door switch events in TAS transmission mechanism to reduce the waste of bandwidth resources caused by too many door events; (4) Simulate several input streams and calculate the configuration scheme of the CCLs.

3. TSN traffic model

In this chapter, according to the characteristics of TAS, the traffic with real-time requirements is modelled [9], and some important parameters are set to provide support for the design of constraints in the following sections.

3.1. Traffic parameter

In a TSN network, we define the set of all traffic as $S$, in this set, contains $n$ different critical data traffic, i.e

$$S_i \in S, \quad i \in [1, n]$$

For these key data flows, there are four important parameters, namely transmission period, frame size, time delay and jitter. In this article, we define a TSN traffic as $S_i \left( T_i, B_i, D_i^{\text{max}}, J_i^{\text{max}} \right)$. Among them, $T_i$, $B_i$, $D_i^{\text{max}}$, $J_i^{\text{max}}$ represent the transmission period, frame size, maximum delay and maximum jitter of the stream. Since scheduling is all traffic sent periodically, a minimum transmission cycle needs to be defined, which is calculated as the least common multiple of all key data flow cycles, i.e
\[ T_{\text{min}} = \text{lcm}(T_1, \ldots, T_i), \quad i \in [2, n] \]  

(2)

In TSN, frames are sent in fixed cycles. After calculating \( T_{\text{min}} \) of N streams, the number of frames transmitted by each stream in \( T_{\text{min}} \) can be obtained, i.e

\[ P_i = \frac{T_{\text{min}}}{T_i}, \quad i \in [1, n] \]  

(3)

Where \( P_i \) represents the number of frames transmitted by stream \( S_i \). In TSN, the switch forwards the traffic just as it forwards the frame. Here we introduce a transmission time—— \( L_i \), which represents the completion time of forwarding a frame of the stream on the switch, i.e

\[ L_i = \frac{B_i}{w}, \quad i \in [1, n] \]  

(4)

Where \( w \) indicates the bandwidth of the switch.

3.2. Traffic parameter

In the gating mechanism of TSN, a concept of transmission offset time is introduced in this paper, which represents the difference between the start time of each frame in stream \( S_i \) and the start time of the cycle in \( T_{\text{min}} \) [10]. It can also be understood as the moment when the state of the corresponding priority gating in the gating period is changed to "O", when the frame transmission is completed, the state of the gating is changed to "C". In this article, we define this transmission offset time as \( T_{(S_i,p)} \), where the superscript “p” represents the p-th frame transmitted in the stream. In figure 2, there are two gating periods with a time length of \( T_{\text{min}} \), each of which transmits three frames, namely one frame of stream \( S_1 \) and two frames of stream \( S_2 \), marked as blue and yellow respectively in the figure 3.

In TAS, in order to better ensure the transmission of frames, we set the door open time before the frame transmission offset, with the advance time of \( T_{\text{pre}} \). In the same way, set the door-closing time after the theoretical transmission of the frame is completed, and the delay time is also \( T_{\text{pre}} \), we can call \( T_{\text{pre}} \) the gate event preparation time.

4. TSN gate scheduling constraint strategy and optimization

This chapter will propose several constraint strategies for the network according to the characteristics of TSN to achieve the function and optimization of the output GCLs [11].
4.1. Transmission cycle constraint
In Section 3, it is mentioned that $P_i$ frames will be transmitted for stream $S_i$ within $T_{\text{min}}$, and we constrain that the transmission offset time of each frame should be greater than 0, and the interval between two adjacent transmission offset times should be greater than one cycle. At the same time, for each frame transmitted in $T_{\text{min}}$, we constrain that the transmission time of frame must be within its corresponding period, i.e.

$$p * T_i - L_i \geq T_{(S_i, p)} \geq (p - 1) * T_i$$

$$S_i \in S, p \in [1, P_i], i \in [1, n]$$

(5)

4.2. Transmission delay constraint
In this article, the traffic scheduling is for a single link, so the end-to-end delay of data transmission includes link transmission delay and switch forwarding delay. The forwarding delay of the switch includes two parts, one is the waiting time for gate control, and the other is the time for the switch to transmit frames. If the TAS door is opened before the frame is transmitted to the switch, then the frame will be directly transmitted after entering the switch, there is no waiting time, that is, the delay time of the frame waiting for transmission is 0; If the TAS gate is opened after the frame is transmitted to the switch, the frame transmitted to the switch needs to wait until the corresponding priority gate is opened before being transmitted, then the delay time of the frame needs to be added to the waiting time after the frame arrives at the switch, that is, the delay time of the frame waiting for transmission[13], i.e.

$$T_{\text{wait}} = \left(T_{(S_i, p)} - T_{(S_i, i)}\right) - (p - 1) * T_i$$

$$S_i \in S, p \in [1, P_i], i \in [1, n]$$

(6)

We set the link transmission time to $T_{\text{lt}}$. In order to meet the end-to-end delay requirement of the traffic, we set the transmission delay constraint, i.e.

$$\left((T_{(S_i, p)} - T_{(S_i, i)}) - (p - 1) * T_i\right) + L_i + T_{\text{wait}} \leq D_i^\text{max}$$

$$S_i \in S, p \in [1, P_i], i \in [1, n]$$

(7)

4.3. Transmission delay constraint
For stream $S_i$, its frames are sent periodically. In the case of scheduling based on TAS, when to open the corresponding priority gate is an important factor affecting delay jitter. In order to meet the jitter requirements of end-to-end traffic transmission, we need to strictly control the opening and closing time of TAS. Therefore, in $P_i$ frames transmitted within $T_{\text{min}}$, the change of transmission delay of two adjacent frames should be less than $J_i^\text{max}$. In Section 4.2, the transmission delay of frames is described in detail, and the constraint formula of transmission jitter can be obtained through calculation, i.e.

$$T_{(S_i, p)} - T_{(S_i, p - 1)} \leq T_i + J_i^\text{max}$$

$$S_i \in S, p \in [2, P_i], i \in [1, n]$$

(8)

4.4. Transmission time constraint
In the switch, only one frame can be transmitted at the same time, and the transmission time of any frame is different [11]. On the time axis with a time length of $T_{\text{min}}$, the length of the time axis occupied by each frame is the forwarding time of the frame in the switch, and the time length occupied by each
frame is independent of each other, namely the transmission time constraint [13], i.e

\[ T_{(S_i,p)} + L_i + T_{pre} \leq T_{(S_j,p')} - T_{pre} \land \frac{1}{T_{(S_j,p')}} + L_j + T_{pre} \leq T_{(S_k,p'')} - T_{pre} \]

(9)

4.5. Bandwidth loss optimization strategy

As set in this paper, the time of opening the door will be earlier and the time of closing the door will be delayed, so the duration of opening the gate is actually longer than the transmission time of frame theory, which will consume a part of the bandwidth resources. For this reason, we propose a scheduling optimization strategy, which makes the frames of two streams with the same priority transmitted by the switch can be transmitted continuously, so that only one gate event is needed to transmit two frames, thus reducing the bandwidth loss caused by the gate switch. We stipulate that the first frame transmitted within \( T_{min} \) by two streams of the same priority \( S_i \) and \( S_j \) is continuously transmitted, that is, the difference between \( T_{(S_i,i)} \) and \( T_{(S_j,i)} \) is the minimum. Under the constraints of the four constraint policies, as long as continuous transmission occurs, the transmission of two frames can be completed with only one gate event.

\[ \chi = \min \left| T_{(S_i,i)} - T_{(S_j,i)} \right| \]

(10)

5. Experimental results and analysis

5.1. Constraint programming

In this paper, constraint programming is adopted to complete the solution. The model language is Minizinc [14], and the solver is Gecode [15]. In writing the program, We use \( T_{i}, B_{i}, D_{i}^{max}, J_{i}^{max}, T_{pre}, w_{i}, T_{tra} \) as our input parameter, and the transmission offset time \( T_{(S_i,p)} \) as the decision variable. If the bandwidth loss optimization strategy is not adopted, multiple GCLs satisfying the four constraints will be obtained, while the optimal solution will be obtained after the bandwidth loss optimization strategy is adopted. We input three flows as examples to verify the feasibility of the scheme proposed in this article. The parameters of the three flows are shown in Table 1. At the same time, we enter the other three parameters \( T_{pre} = 1 \mu s, w = 100 \text{Mbit/s}, T_{tra} = 1 \mu s \).

| Number | Cycle(\( \mu s \)) | Frame size(Byte) | Maximum delay(\( \mu s \)) | Maximum jitter(\( \mu s \)) |
|--------|-------------------|-----------------|--------------------------|--------------------------|
| 1      | 500               | 256             | 100                      | 10                       |
| 2      | 1000              | 512             | 200                      | 20                       |
| 3      | 2000              | 1250            | 500                      | 50                       |

After entering the parameters mentioned above, we ran the program on a computer with a 2.8GHz i5-8400 CPU and 8GB RAM. After the program runs, we will get a group of time periods on the transmission cycle \( T_{min} \), and each time period represents the duration of the gated state "O". As shown in Table 2, there are a total of 7 gated events. In the brackets "(t_s,t_e)" in the Table 2, "t_s" represents the time when the door is opened, and "t_e" represents the time when the door is closed. Before optimization, there were 7 gate events. After optimization, the number of gate events was reduced to 4.
The reduction of gate events means that the $T_{pre}$ mentioned above will be reduced. As can be seen from Table 2, there were 14 $T_{pre}$ bandwidth losses before optimization, but they were reduced to 8 $T_{pre}$ after optimization, indicating a 42.8% reduction in bandwidth losses.

| Gate event number | Opening and closing time (µs) | Gate event number | Opening and closing time (µs) |
|-------------------|-------------------------------|-------------------|-------------------------------|
| G1                | (1,23)                        | G1                | (0,156)                       |
| G2                | (49,90)                       | G2                | (500,522)                     |
| G3                | (101,196)                     | G3                | (1000,1061)                   |
| G4                | (501,523)                     | G4                | (1500,1522)                   |
| G5                | (1001,1023)                   | G5                | (1000,1061)                   |
| G6                | (1049,1090)                   | G6                | (1049,1523)                   |
| G7                | (1501,1523)                   | G7                | (1001,1523)                   |

In order to better understand the differences before and after the optimization of the scheme, the performance of the two groups of schemes on the $T_{min}$ timeline is shown in Figure 3.

6. Experimental results and analysis

In this paper, we analyze the real-time traffic scheduling in TSN network, and model the traffic and gating mechanism in TSN with the TAS feature in IEEE 802.1 Qbv. Our model obtains the GCLs of TAS through four constraint policies, so as to realize the scheduling of traffic, so as to satisfy the end-to-end QoS of traffic. At the same time, we propose an optimization strategy for bandwidth loss. In the example of this paper, the bandwidth loss is reduced by 42.8% after adopting the optimization strategy. The experimental results show that the constraint strategy proposed in this paper is reliable and effective, and can quickly obtain the GCLs to meet the end-to-end QoS requirements of key data traffic in a simple network, which will have a great development prospect in the future small network in the factory. In the future work, in order to get a good application in a larger network, in addition to
scheduling critical real-time traffic, we will also optimize our scheduling model and improve our constraint strategy in the case of different priorities and multiple links.

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