Delay optimization strategy based on aperiodic traffic in time-sensitive networking

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Abstract. Time-Sensitive Networking (TSN) is a cluster of protocols working in the data link layer of the OSI reference model, which has been introduced into the industrial Internet due to its ability to ensure the deterministic transmission of data. Through IEEE 802.1AS clock synchronization and IEEE 802.1 Qbv gating mechanism, TSN networks allocate separate transmission time slots for periodic signals to ensure low delay and jitter, but this increases the delay of aperiodic stream to some extent. In this paper, a scheduling scheme of Grouping transmission is proposed. By changing the sending time of periodic data stream, the periodic data stream which is originally continuously transmitted is divided into several groups to be transmitted in different time periods in a cycle, so as to reduce the real-time aperiodic data stream delay. Experimental results show that the proposed scheduling scheme can reduce the transmission delay of the non-periodic traffic without affecting the quality of service (QoS) of the periodic traffic.

1. Introduction
The rapid development of industrial communication system promotes the construction of intelligent factories, and the demand for real-time communication is getting more precise. IEEE 802.1 Time-Sensitive Networking Task Group provides a series of open standards for traffic management and scheduling in industrial networks at the data link layer to ensure low latency and low jitter of industrial data flows [1]. TSN defines the Time Awareness Shaper (TAS) [2] through IEEE 802.1 Qbv [3] standard. TAS circularly controls the switching state of the queue transmission gate, forwarding the periodic flow in the separately allocated Time slot to ensure low delay and zero jittering of periodic flow. If there are too many continuous transmission slots for periodic flows, the maximum delay for aperiodic flows will be increased.

2. Related work
The scheduling problem of TSN cannot be studied without gated list. In [4], the author studied the influence of Gate Control List (GCL) parameters on network service quality (QoS), and the increase of Gate cycle will reduce the delay of non-cycle data flow. In [5], This paper introduced the scheduling constraints of TSN in industrial mixed networks, and analyzed the schedulability of a group of periodic traffic. In [6], the author introduced the basic principle and scheduling strategy of real-time guarantee of Time-triggered Ethernet (TTE) and TSN, and two scheduling modes of TTE for time-triggered streams, namely close to transmission and gap transmission. In the vehicle-mounted network, the period and offset of the sensitive flow have an effect on the best effort flow [7]. In [8], the author
proposed a configuration method of random search for GCL to schedule periodic flow, which reduced the maximum time delay of aperiodic flow. All the above studies have shown that in the mixed transmission network of periodic flow and aperiodic flow, the transmission delay of aperiodic flow can be reduced by changing the scheduling parameters of periodic flow. But the factors causing the increase of aperiodic flow delay have not been analyzed and the solutions have not been proposed. Aiming at the hybrid transmission mechanism of periodic and aperiodic flow in TSN network, this paper proposes a gate configuration method for grouping transmission of periodic flow, which can reduce the transmission delay of aperiodic flow without affecting the transmission quality of periodic flow.

3. Problem Description

3.1. Transfer flow
In the industrial field network, it mainly includes the equipment such as controller, actuator and sensor. We define traffic in industrial field networks as three types of data:

- Periodic flow: the controller and the actuator periodically interactively control the data flow, which has periodicity and high real-time performance, and should be guaranteed first in the network.
- Real-time aperiodic flow: when the operating state changes or the monitoring parameter value exceeds the threshold value in the system, the alarm device sends out the alarm data stream to the controller. It has aperiodic and weak real-time characteristics, and the transmission delay should be reduced as much as possible.
- Best effort flow: data streams such as data backup, file transfer and interface web display in industrial networks do not require too much real-time performance. Transmission is usually carried out after the transmission of periodic and aperiodic streams is completed.

3.2. Time delay analysis
TAS allocates different types of traffic to different queues. By configuring the gate control list, separate slots are allocated for the periodic flow to ensure that the periodic flow completes transmission at the agreed time. We define the set of periodic flows \( F = \{ (P_i, L_i), i = 1, 2...n \} \) in the network, where \( P_i \) denotes the period of \( i \)th periodic flow, and where \( L_i \) denotes the frame length of \( i \)th periodic stream. Given the frame length of the periodic stream \( L_i \) and the switch port rate \( C(100\text{Mbit/s}) \), the sending time \( T_i \) of the periodic stream can be calculated, which is also used as the scheduling time slot assigned by GCL to the periodic stream.

\[
T_i = \frac{L_i}{C}
\]

The end-to-end delay of traffic refers to the time difference between the sending of a frame from a source device and the receiving of a destination device, mainly including line transmission delay, switching delay, frame sending delay and frame queuing delay. Only the frame queuing delay will be affected by GCL. Periodic flow has almost no port queuing delay because of priority scheduling in TSN. However, the real-time aperiodic data flow needs to keep the transmission gate of the queue closed during the transmission of the periodic data flow, resulting in the port queuing delay. In the worst case, the port queuing delay \( T_q \) is the sum of the transmission times of the periodic streams within the periodic.

\[
T_q = \sum_{i=1}^{n} T_i
\]
4. Optimizing Strategy

For the problem of real-time aperiodic flow delay mentioned in Section 3, the maximum time delay of real-time aperiodic flow will increase successively with the increase of the number of periodic flows. This paper presents a scheme for grouping transmission of periodic flows, which can reduce the maximum time delay of real-time aperiodic flows.

For the convenience of the study, it is assumed that all periodic flows in the network have the same scheduling period \( P \), so \( P=P_1=P_2=...=P_n \). As shown in Figure 1, when the real-time aperiodic flow data frame arrives at the switch, the aperiodic flow frame is in transmission. The real-time aperiodic flow frame can only wait at the output port until the transmission of the periodic flow is completed, which reduce the delay of the real-time aperiodic flow.

![Fig 1. Mixed transmission of periodic and real-time aperiodic streams](image)

4.1. Parameter Selection

In the scheduling periodic \( P \) of the mixed transmission network, in order to avoid the overlap of the time slots of the periodic data flows, each periodic flow needs to be allocated a separate time slot. The proportion of the sum of the scheduling time slots allocated by the periodic flows to the scheduling periodic \( P \) can be calculated.

\[
\eta = \frac{\sum_{i=1}^{n} T_i}{P} \quad (3)
\]

The periodic flow time slot set \( S \) is generated by sorting the scheduling time slot length from large to small. In the set \( S=\{T^*_j, j=1,2,...,n\} \), where \( T^*_j \) is the time slot required for the transmission of the \( i \)th periodic flow. The more time slots occupied by periodic flows, the less time slots are transmitted for real-time aperiodic flows, and the number of groups that periodic flows are grouped is inversely proportional to the proportion of total time slots scheduled for periodic flows. As shown in Formula (4), the number of packet transmission groups of periodic flows can be determined according to the time slot ratio of periodic flow scheduling and the number of periodic flows, where \( k \) is a constant.

\[
\hat{\lambda} \leq \frac{k}{\eta}, \quad \lambda \leq n \quad (4)
\]

4.2. Periodic Flow Rescheduling

After confirming the number of transmission groups of periodic flows, the time slots that can be transmitted by real-time aperiodic flows are equally divided into \( \hat{\lambda} \) groups. Then, the time slots that
can be transmitted by real-time aperiodic flows in each group is:

\[ P_n = (1 - \eta) \times \frac{P}{\lambda} \]  \hspace{1cm} (5)

As shown in Figure 2, the scheduling periodic is re-divided into \( \lambda \) groups. The scheduling slot sets of periodic flows are successively allocated into \( \lambda \) grouping time slots. In (10), where \( \alpha_{(p,q)} \) represents the time slot allocated by the \( q \)-th scheduling unit in the \( p \)-th group.

\[ \alpha_{(p,q)} = T^*_j, \hspace{0.5cm} 1 \leq p \leq \lambda, \hspace{0.5cm} 1 \leq q \leq n, \hspace{0.5cm} 1 \leq j \leq n \]  \hspace{1cm} (6)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Slot reallocation diagram}
\end{figure}

We define the sum of allocated time slots for periodic flows in \( \lambda \) groups as set 
\[ B = \{ Q_i, i = 1, 2, ..., \lambda \} \], and \( Q_i \) is the sum of allocated time slots for periodic flows in the \( i \)-th group. When set \( S \) is assigned to groups, the group with the smallest sum of allocated slots should be selected.

After the initial allocation, in order to reduce the maximum value in the allocated time slot set \( Q \), the allocated time slots in the packet can be swapped so that \( Q \) in the group satisfies Formula (7), and the final gated list can be obtained.

\[ 0 \leq Q_i - Q_j \leq 2 \left( \alpha_{(i,k)} - \alpha_{(j,l)} \right), \hspace{0.5cm} 1 \leq i, j \leq \lambda, \hspace{0.5cm} 1 \leq k, l \leq n \]  \hspace{1cm} (7)

5. Experimental results and analysis

In this section, the periodic flow is configured according to the parameters in Table 1, and the gated list of TSN switch is set according to the optimization strategy given in the paper. The experimental results verify the feasibility of the "grouping transmission" gated scheduling scheme.

In Table 1, periodic flows are calculated by formula (3,4), and three groups of periodic flows are transmitted, with slot lengths of 116\( \mu \)s, 108\( \mu \)s and 106\( \mu \)s respectively. The gate control list is calculated as shown in Fig. 3. In the worst case, the maximum frame queuing delay of the real-time aperiodic stream is reduced from the sum of all the time slots of the periodic flow to the sum of the schedules of the second, fourth, and eighth periodic streams.
Table 1. Parameter setting of periodic data flow

| Number | Period(μs) | Frame size(Byte) |
|--------|------------|------------------|
| 1      | 1000       | 600              |
| 2      | 1000       | 768              |
| 3      | 1000       | 275              |
| 4      | 1000       | 600              |
| 5      | 1000       | 575              |
| 6      | 1000       | 400              |
| 7      | 1000       | 575              |
| 8      | 1000       | 350              |

During the experimental test, the periodic flow sends data according to the parameters given in Table 2; Real-time aperiodic stream sends data randomly; Best effort stream sends data with bandwidth of 5M, 10M, 15M gradually increase. Finally, we counted the delay of real-time aperiodic flow and Best-effort flow in the worst case, and compared the delay results before and after optimization, as shown in Fig. 4.
The experimental results show that the maximum time delay of the real-time aperiodic flow is 611μs before optimization and 393μs after optimization. The experimental data is consistent with the theoretical calculation results, which verifies the feasibility of the proposed scheme.

6. Conclusion
In this paper, we consider a hybrid network in TSN industrial network with GCL managed periodic flow, real time aperiodic flow and best effort flow. In the case of the same period, the periodic flow can be transmitted by grouping to reduce the time that the periodic flow continues to occupy the port, which can reduce the maximum delay of the real-time aperiodic flow and the best effort stream. In the case of different cycles, the next step is how to set the restriction condition of periodic flow scheduling to improve the real-time aperiodic delay.

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