Predictive Scheme for Mixed Transmission in Time-Sensitive Networking

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Abstract: Time-sensitive networking (TSN) is an important research area for updating the infrastructure of industrial Internet of Things. As a product of the integration of the operation technology (OT) and the information technology (IT), it meets the real-time and deterministic nature of industrial control and is compatible with Ethernet to support the mixed transmission of industrial control data and Ethernet data. This paper systematically summarizes and analyzes the shortcomings of the current mixed transmission technologies of the bursty flows and the periodic flows. To conquer these shortages, we propose a predictive mixed-transmission scheme of the bursty flows and the periodic flows. The core idea is to use the predictability of time-triggered transmission of TSN to further reduce bandwidth loss of the previous mixed-transmission methods. This paper formalizes the probabilistic model of the predictive mixed transmission mechanism and proves that the proposed mechanism can effectively reduce the loss of bandwidth. Finally, based on the formalized probabilistic model, we simulate the bandwidth loss of the proposed mechanism. The results demonstrate that compared with the previous mixed-transmission method, the bandwidth loss of the proposed mechanism achieves a 79.48% reduction on average.

Keywords: time-sensitive networking; 802.1Qbv; 802.1Qbu; guard band strategy; preemption strategy

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1 Introduction

At present, the vigorous development of artificial intelligence and the industrial Internet of Things (IoT) presents new requirements and challenges for traditional industrial control networks[1], for example, high-bandwidth and highly reliable transmission to support comprehensive IoT sensing and breaking the barriers between information technology (IT) networks and operation technology (OT) networks to realize the integration and real-time linkage of IT and OT. However, traditional industrial control networks widely use bus-type networks, such as the controller area network (CAN)[2] in the field of automotive and numerical control machine tools and Multifunction Vehicle Bus (MVB)[3] in the field of rail transportation. Their low transmission bandwidth is not conducive to the access of more and more sensor nodes, which affects the efficiency of data transmission and seriously restricts the development of industrial IoT. Industrial Ethernet as an alternative to bus-based networks, has a wide range of standards[4]. The real-time and deterministic mechanisms adopted by different industrial Ethernet standards are different from each other, which makes it hard to achieve connectivity between them. To solve the low bandwidth of the bus-based networks and the poor compatibility of existing industrial Ethernet standards, IEEE 802.1 initiated the establishment of time-sensitive networking (TSN)[5] working group in November 2012, responsible for extending the standard Ethernet Net 802.3 to support the real-time and deterministic data transmission of industrial control and realize the integration of IT and OT.

According to different requirements, the TSN divides flows into three categories: first, periodic flows, mainly used in industrial control to meet the real-time and deterministic requirements of industrial applications; second, bursty real-time flows, mainly used for bursty services that have certain delay

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requirements, such as message data, video and audio data in train control networks; third, bursty non-real-time flows, mainly used for services that do not require real-time transmission, such as file transfer, web browsing, etc. For periodic flows, TSN introduces a time-triggered (TT) transmission mechanism[6–8], which takes into account the topology, bandwidth, cache and other network resources and the real-time and deterministic requirements of applications to calculate the sending time of flows in each network device (including switches and terminals) with global scheduling, and then the devices send flows periodically at these time points. Such a transmission method can customize the end-to-end delay of each flow to meet the period and delay requirements of different control services for different industrial applications. The jitter of delay depends on the accuracy of time synchronization, that is, the maximum time deviation between any two devices in a time-synchronized network. TSN uses simplified IEEE 1588[9] to achieve network time synchronization, which is standardized as IEEE 802.1AS[10]. Generally, the accuracy of time synchronization can reach the microsecond or even sub-microsecond level. Periodic flows are also called time-triggered flows. Both bursty real-time and non-real-time flows use the best-effort transmission and provide different quality of service by prioritization[11–12] and traffic shaping like the credit-based shaper (CBS)[13–14]. Therefore, if no distinction is necessary, the two kinds of flows are collectively referred to as bursty flows, abbreviated as best-effort (BE) flows.

In order to achieve mixed transmission of bursty and periodic flows, TSN first defines a time-aware shaper (TAS) in 802.1Qbv[15]. The TAS stores periodic flows in high-priority queues and bursty flows in low-priority queues. Periodic flows are transmitted at precise sending points that are transformed into a gate control list (GCL) of the TAS. The GCL periodically turns on the high-priority queues and turns off the low-priority queues at the precise sending points to realize the accurate transmission of periodic flows. After the periodic flows are sent, the high-priority queues are turned off, and in the meantime, the low-priority queues are turned on to transmit bursty flows.

TAS uses GCL to accurately reserve bandwidth for periodic flows, but it does not solve the problem of wasting reserved bandwidth caused by the lack of periodic flows. Moreover, due to the uncertainty of bursty flows, it is possible that the bursty flows are being sent when the periodic flow starts to be sent. To avoid the conflicts between the bursty flows and the periodic flows, 802.1Qbv defines a guard band strategy, but the strategy leads to a waste of bandwidth. In order to save bandwidth, 802.1Qbu[16] defines a frame preemption strategy, but it causes delay jitters of periodic service flows. To avoid delay jitters, the mixed strategy of the guard band and frame preemption still results in a waste of bandwidth. In order to solve the bandwidth wastage problem caused by the mixed strategy, we propose a predictive mixed transmission mechanism for the bursty flows and periodic flows.

This paper constructs a probabilistic model of the predictive mixed transmission mechanism, and proves that the mechanism can effectively reduce bandwidth loss while avoiding the conflicts between the periodic flows and the bursty flows. By simulating the arrival of the bursty flows under different probability distributions, the predictive mixed transmission mechanism reduces the expectation of bandwidth loss to one-fifth of that compared with the previous mixed strategy, namely the combination of guard band (802.1 Qbv) and frame preemption (802.1 Qbu). Our main contributions are fourfold as follows.

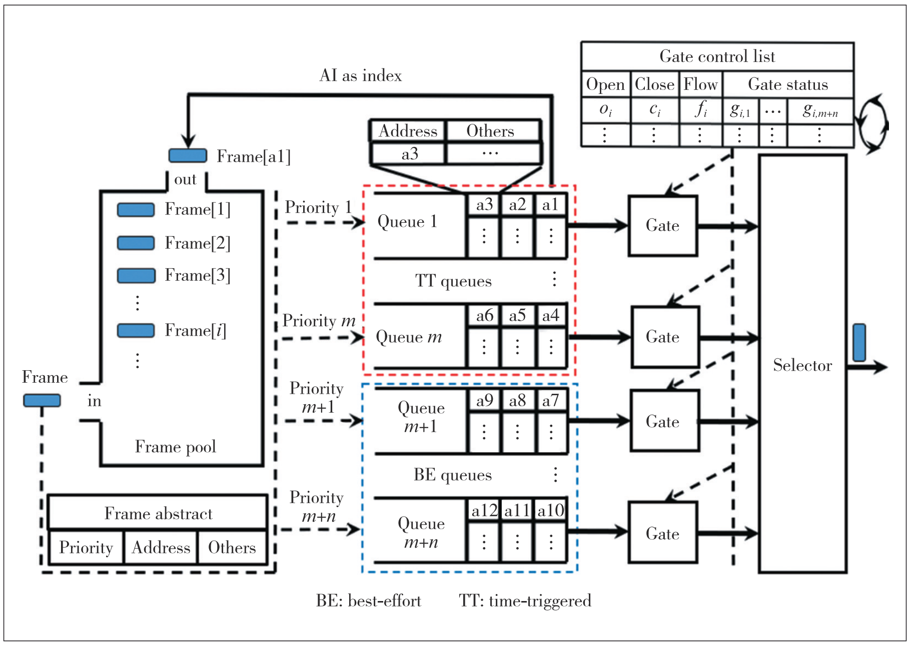
- First, we propose a predictive mixed transmission mechanism to further reduce the bandwidth loss by the predictability of time-triggered transmission.
- Second, we formalize the predictive mechanism to minimize the bandwidth loss by computing the optimized preemption positions for bursty frames.
- Third, we present probabilistic models of mixed transmission strategies and prove that the proposed predictive mechanism can effectively reduce bandwidth loss.
- Finally, we verify the effectiveness of the proposed predictive mechanism by simulating the probabilistic models.

The rest of the paper is organized as follows. Section 2 reviews related work. The background of the mixed transmission of TT and BE flows is described in Section 3. Section 4 presents the proposed predictive mixed transmission mechanism, gives the corresponding algorithm and mathematical model, and proves its advantages in reducing bandwidth loss by comparing it with the previous mixed-transmission strategies. Section 5 conducts experimental tests by simulating the probabilistic models of different mixed-transmission strategies. Finally, we conclude this paper in Section 6.

2 Related Work

TAS is the core mechanism of TSN to realize the deterministic real-time transmission of the periodic flow, which is standardized as 802.1Qbv, and Fig. 1 illustrates the TAS in 802.1Qbv.

A frame is received and stored in the frame pool. The abstract information, such as priority, length, and the address in a frame pool, is usually extracted from the frame when it is received. The abstract information is stored in different queues according to priority. The priority queues are divided into two types: storing periodic flows and storing bursty flows. Periodic flows are transmitted deterministically with the gate control list (GCL) and bursty flows are transmitted in the interval of periodic flows. Different output selectors, such as the strict priority transmission and the credit-based traffic shaper, are used to guarantee Quality of Service (QoS) of bursty flows. The table items of GCL usually include w_i (the duration of the window), o_i (the start time of the window), $f_{i,1} \cdots f_{i,j}$ (the periodic flows that need to be transmitted within the duration of the



▲**Figure 1. Time-aware shaper (TAS) defined by IEEE 802.1Qbv**

window), and gate status (consisting of 0 or 1, where 0 means gate control is turned on and 1 means gate control is turned off). GCL is executed in order of o_i to control the gates of different queues. At the start time of the window, the gate of the corresponding queue is turned on and the gates of other queues are turned off to realize the accurate transmission of periodic flows at the scheduled time. As soon as the TT flows are sent, the corresponding gate is turned off and the gates of other queues are turned on to enable the transmission of bursty flows. After GCL finishes executing the last entry, it starts from the first entry again and loops periodically.

Because of the uncertainty of bursty flows, when the sending points of periodic flows arrive, the bursty flows may be transmitted. In order to avoid conflicts between bursty flows and periodic flows, 802.1Qbv defines a guard band strategy to turn off the bursty flow queues at the time Δt prior to the sending points of periodic flows so that the remained part of bursty frames can be sent within Δt time. The Δt is the guard band which ensures that periodic flows will not conflict with bursty flows when it is sent, but the size of the guard band is the length of the maximum frame of bursty flows, which leads to a waste of bandwidth.

To save bandwidth, 802.1Qbu[16] defines a frame preemption strategy. That is, when a bursty flow is being sent and a periodic flow is ready to be sent, the bursty flow is filled with the correct cyclic redundancy check (CRC), and the transmission is interrupted. And the transmission is not resumed until the transmission of the periodic flow is completed. Each preemption will cause an additional 24 bytes (4-byte CRC, 12-byte minimum inter-frame spacing, 6-byte leading code, 1-byte preempted-frame start, and 1-byte frame number) of bandwidth loss and delay jitter. Furthermore, since the minimum length of an Ethernet frame is 64 bytes, to prevent the sent length and remaining length from being less than 64 bytes, the minimum frame length to be preempted is 124 bytes. Therefore, in the worst case, the delay jitter of periodic flows caused by frame preemption is 123 bytes. In order to avoid the delay jitter of 123 bytes, combining the guard band strategy of 802.1Qbv and the frame preemption strategy of 802.1Qbu, the size of Δt can be set to 123 bytes, and the frame preemption strategy is executed at Δt prior to the sending points of the periodic flows. The mixed strategy avoids the delay jitter caused by frame preemption, and at the same time reduces the size of the guard band to 123 bytes. But as long as the preemption is successful, the 123-byte guard band consumes only 4 bytes (CRC), resulting in a waste of 119 bytes, and an additional 20 bytes of bandwidth waste (including 12-byte minimum inter-frame spacing, 6-byte preamble, 1-byte preemption frame start character, and 1-byte frame sequence number) for the remaining transmission of the preempted frame.

To further reduce bandwidth wastage of the mixed strategy namely the combination of 802.1Qbv and 802.1Qbu, this paper proposes a predictive mixed transmission mechanism for bursty flows and periodic flows. Its core idea is to use the predictability of time-triggered transmission in TSN:

• The upcoming periodic flow is predictable because it can be obtained by querying the GCL. So, when the bursty flow is to be sent, we first calculate the remaining time to the sending point of the upcoming periodic flow. If the remaining time is enough to finish sending the bursty flow, the bursty flow is sent immediately; otherwise, it will be sent after the periodic flow.

• The current bursty flow to be sent is predictable because the flow is the header frame in bursty flow queues. So, when there is no enough time left to send the complete frame, the optimal preemption position can be calculated based on the frame length of the bursty flow and the time left to the sending point of the upcoming periodic flow, to minimize bandwidth loss.

3 Background

This section details the existing TSN standards for the mixed transmission of bursty flows and periodic flows, and analyzes their impact on bandwidth loss and delay jitter.

3.1 Guard Band Strategy

We define the sending time point of a periodic flow f_i as o_i, and Δt is the guard band, the size of which is the maximum frame length of bursty flows. To formalize the bandwidth loss (also denoted as GuardLoss) of the guard band strategy, we define the length of the bursty flow as a random variable X when a periodic flow f_i conflicts with a bursty flow at the start time of GCL. The maximum length of bursty flows is denoted as $L_{BE}^{\max}$, and the minimum length as $L_{BE}^{\min}$. At the sending point of f_i, the sent length of the bursty frame is defined as a random variable Y.

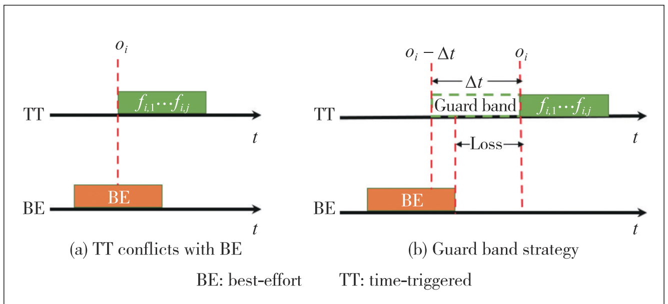
When the sending time point of a periodic flow (TT) arrives and if a bursty flow has not finished its transmission yet, a conflict happens. Fig. 2(a) shows a conflict that the i-th entry in GCL is sent at the sending time o_i, and the BE data have not finished transmission yet. To resolve the conflict, 802.1Qbv defines a guard band strategy, as shown in Fig. 2(b). It turns off the transmission gates of bursty flow queues at Δt prior to the arrival of the periodic flow sending time o_i, that is, at $o_i - \Delta t$. The Δt time must be big enough to make any bursty flow being sent complete so that there is no conflict with bursty flows when periodic flows are sent. Therefore, the size of Δt is the maximum frame length of bursty flows, and Δt is called the guard band.

The guard band strategy ensures the conflict-free transmission of periodic flows and bursty flows. But depending on the arrival timing of bursty flows, the part of bandwidth not occupied by burst flows is wasted, as illustrated in the "Loss" part of Fig. 2b. The size of the guard band is $L_{BE}^{\max}$ and thus the unused length of the guard band is $L_{BE}^{\max} - (X - Y)$. The bandwidth loss caused by the guard b of f_i can be expressed as follows:

$$f_i.\text{GuardLoss} = L_{BE}^{\max} - (X - Y)\,. \tag{1}$$

Periodic flows and bursty flows are conflict-free transmission, so the jitter caused by the guard band strategy is 0:

$$f_i.\text{GuardLoss} = 0\,. \tag{2}$$

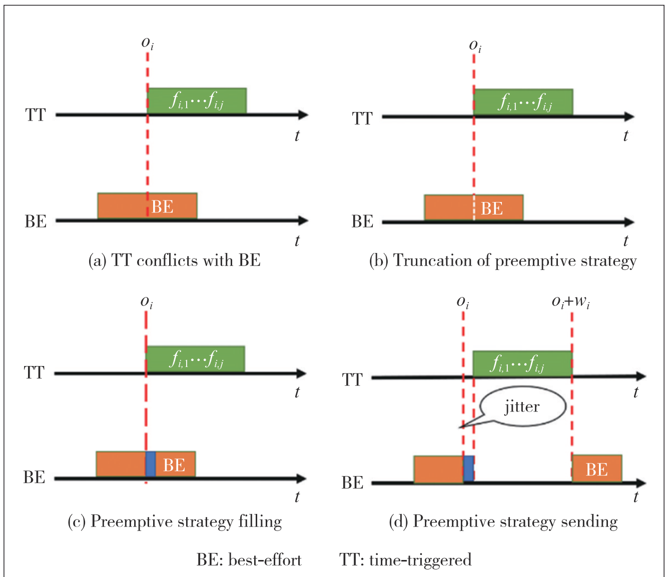


▲**Figure 2. Guard band strategy defined by 802.1Qbv**

3.2 Preemption Strategy

To reduce bandwidth loss of the guard band strategy, 802.1Qbu defines a preemption strategy, as shown in Figs. 3 (b), 3(c), and 3(d). Fig. 3(a) illustrates a periodic flow in conflict with a bursty flow. Fig. 3(b) shows a periodic flow truncating a bursty frame at the moment of transmission. Fig. 3(c) illustrates the truncated bursty frame filled with a 4-byte CRC and interrupting its transmission and then starting the transmission of the periodic flow. Fig. 3(d) illustrates that the transmission of the remaining part of the truncated frame in the bursty flow is resuming after the periodic flow is completed.

In order to ensure that the truncated frame is a legal Ethernet frame, the preemptive strategy requires that the length of the two parts of the truncated frame cannot be less than the minimum Ethernet frame length, namely 64 bytes. Therefore, the minimum length of an Ethernet frame that can be truncated is 124 bytes (60 bytes and 64 bytes). Meantime, due to the truncation, the original frame is divided into two frames to be sent, so the additional required bandwidth includes 4-byte CRC, 12-byte minimum inter-frame spacing, 6-byte preamble, 1-byte preempted frame start and 1-byte frame number, a total of 24 bytes. The following still uses random variables X and Y to analyze the bandwidth loss and delay jitter caused by the preemption strategy.



▲**Figure 3. Preemption strategy defined by 802.1Qbu**

1) When the bursty flow length is less than 124 bytes, that is, $L_{BE}^{\min} \leqslant X < 124$, the frame cannot be truncated, and the bandwidth loss (denoted as PreemptionLoss) and delay jitter (denoted as PreemptionJitter), are formulated as follows:

$$\begin{aligned} &f_i.\text{PreemptionLoss} = 0,\ \text{if}\ L_{BE}^{\min} \leqslant X < 124 \\ &f_i.\text{PreemptionJitter} = X - Y,\ \text{if}\ L_{BE}^{\min} \leqslant X < 124\,. \end{aligned} \tag{3}$$

2) When the length of the bursty flow is greater than or equal to 124 bytes, that is, $124 \leqslant X < L_{BE}^{max}$.

• If $0 \leqslant Y < 60$, the periodic flow f_i cannot be truncated until the bursty flow has been sent out of 60 bytes. As a result, bandwidth loss (PreemptionLoss) and delay jitter (PreemptionJitter) are as follows:

$$f_i.\text{PreemptionLoss} = 24,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 0 \leqslant Y < 60$$
$$f_i.\text{PreemptionJitter} = (60 - Y) + 4,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 0 \leqslant Y < 60\ . \tag{4}$$

• If $60 \leqslant Y$ and the remaining unsent part of the bursty flow is greater than or equal to 64 bytes, that is, $64 \leqslant X - Y$, the periodic flow f_i can directly cut off the bursty flow. As a result, the bandwidth loss (PreemptionLoss) and delay jitter (PreemptionJitter) are as follows:

$$f_i.\text{PreemptionLoss} = 24,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, 64 \leqslant X - Y$$
$$f_i.\text{PreemptionJitter} = 4,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, 64 \leqslant X - Y. \tag{5}$$

• If $60 \leqslant Y$ and the remaining unsent part of the bursty flow is less than 64 bytes, that is, $X - Y < 64$, the periodic flow f_i cannot intercept the bursty flow. As a result, the bandwidth loss (PreemptionLoss) and delay jitter (PreemptionJitter) are as follows:

$$f_i.\text{PreemptionLoss} = 0,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, X - Y < 64$$
$$f_i.\text{PreemptionJitter} = X - Y,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, X - Y < 64\ . \tag{6}$$

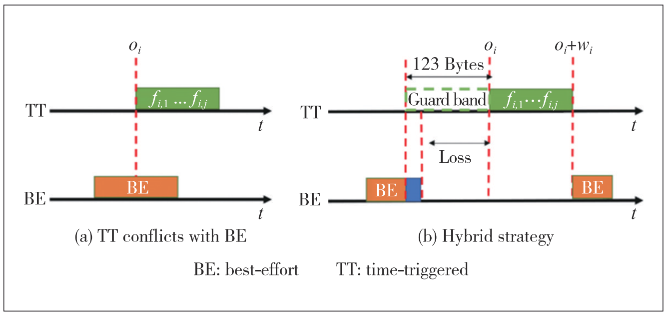
In summary, when the periodic flow f_i conflicts with the bursty flow, the bandwidth loss and delay jitter caused by the preemption strategy are formalized as follows:

$$f_i.\text{PreemptionLoss} = \begin{cases} 0, & \text{if } L_{BE}^{min} \leqslant X < 124, \\ 24, & \text{if } 124 \leqslant X < L_{BE}^{max}, 1 \leqslant Y < 60, \\ 24, & \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, 64 \leqslant X - Y, \\ 0, & \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, X - Y < 64\ . \end{cases} \tag{7}$$

$$f_i.\text{PreemptionJitter} = \begin{cases} X - Y, & \text{if } L_{BE}^{min} \leqslant X < 124, \\ (60 - Y) + 4, & \text{if } 124 \leqslant X < L_{BE}^{max}, 1 \leqslant Y < 60, \\ 4, & \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, 64 \leqslant X - Y, \\ X - Y, & \text{if } 124 \leqslant X < L_{BE}^{max}, 60 \leqslant Y, X - Y < 64\ . \end{cases} \tag{8}$$

3.3 Mixed Strategy of Guard Band and Preemption

Although the preemptive strategy reduces the bandwidth loss compared with the guard band strategy, it brings in additional delay jitter and weakens the certainty of time-triggered transmission. To eliminate the delay jitter of the preemptive strategy and reduce the bandwidth loss of the guard band strategy, we combine the guard band with the preemption strategy. Fig. 4 illustrates the mixed strategy.



▲ **Figure 4. Mixed strategy of guard band and preemption**

To eliminate the delay jitter of up to 123 bytes caused by the preemptive strategy, the mixed strategy sets the guard band to 123 bytes. That is, we close the queues of bursty flows at 123 bytes prior to the start of periodic flows, and follow the preemption strategy to preempt bursty flows at this time. The bandwidth loss and delay jitter caused by the mixed strategy are analyzed as follows:

1) Since the mixed strategy brings in a 123-byte guard band that eliminates the delay jitter caused by the preemptive strategy, the delay jitter caused by the mixed strategy is 0.

2) The emergence of the guard band in the mixed strategy increases the bandwidth loss of the preemptive strategy.

• If the length of a bursty flow is less than 124 bytes, that is, $L_{BE}^{min} \leqslant X < 124$, the frame cannot be preempted, and the unused part of the guard band is the loss of bandwidth denoted as MixedLoss:

$$f_i.\text{MixedLoss} = 123 - (X - Y),\ if\ L_{BE}^{min} \leqslant X < 124\ . \tag{9}$$

• If the length of a bursty flow is greater than or equal to 124 bytes, that is, $124 \leqslant X < L_{BE}^{max}$. At the beginning of the guard band, $(o_i - 123)$, if the sent part of the bursty flow is less than 60 bytes, that is, $0 \leqslant Y < 60$, it cannot be preempted until the sent part reaches 60 bytes. The loss of bandwidth includes the unused part of the guard band and the additional number of bytes caused by preemption:

$$f_i.\text{MixedLoss} = \big(123 - (60 - Y + 4)\big) + 24,\ \text{if } 124 \leqslant X < L_{BE}^{max}, 0 \leqslant Y < 60\ . \tag{10}$$

• If the length of a bursty flow is greater than or equal to 124 bytes, it means that $124 \leqslant X < L_{BE}^{max}$. At the beginning of the guard band, $(o_i - 123)$, if the sent part of the bursty flow is greater than or equal to 60 bytes, namely, $60 \leqslant Y$, and the remaining part is also greater than or equal to 64 bytes, namely, $64 \leqslant X - Y$, the bursty frame can be directly cut off. The loss of bandwidth includes the unused part of the guard band and the additional number of bytes caused by preemption:

$$f_i.\text{MixedLoss} = (123 - 4) + 24,\ \text{if } 124 \leqslant X < L_{BE}^{\max}, 60 \leqslant Y, 64 \leqslant X - Y. \tag{11}$$

• If the length of a bursty flow is greater than or equal to 124 bytes, it means that $124 \leqslant X < L_{BE}^{\max}$. At the beginning of the guard band, $(o_i - 123)$, if the sent part of the bursty flow is greater than or equal to 60 bytes, namely, $60 \leqslant Y$, but the remaining part is less than 64 bytes, namely, $X - Y < 64$, the bursty frame cannot be truncated, and the unused part of the guard band is the loss of bandwidth:

$$f_i.\text{MixedLoss} = 123 - (X - Y),\ \text{if } 124 \leqslant X < L_{BE}^{\max}, 60 \leqslant Y, X - Y < 64. \tag{12}$$

In summary, the bandwidth loss caused by the mixed strategy is presented as follows:

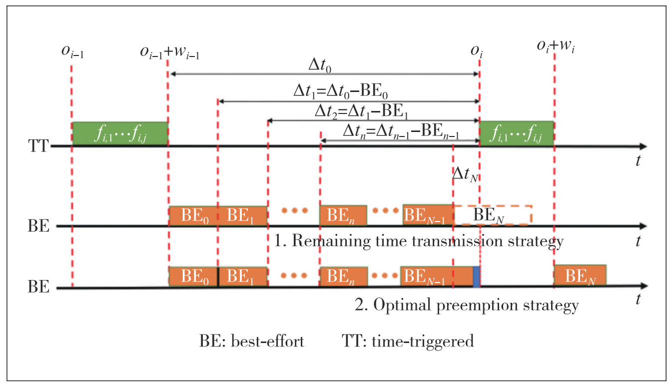
$$f_i.\text{MixedLoss} = \begin{cases} 123 - (X - Y), & \text{if } L_{BE}^{\min} \leqslant X < 124, \\ 83 + Y, & \text{if } 124 \leqslant X < L_{BE}^{\max}, \\ & 0 \leqslant Y < 60, \\ 143, & \text{if } 124 \leqslant X < L_{BE}^{\max}, \\ & 60 \leqslant Y, 64 \leqslant X - Y, \\ 123 - (X - Y), & \text{if } 124 \leqslant X < L_{BE}^{\max}, \\ & 60 \leqslant Y, X - Y < 64. \end{cases} \tag{13}$$

4 Predictive Mixed Transmission Mechanism

To conquer the shortcomings of the existing mixed transmission mechanism for the bursty flow and the periodic flow, this part presents the proposed predictive mixed transmission mechanism including its principle, probability model, and algorithms in detail.

4.1 Remaining Time Transmission Strategy

Bursty flows are always sent in the gap between periodic flows, and the size of the gap is predictable. Fig. 5 shows two adjacent items $i - 1$ and i in GCL. When the $(i - 1)$-th item finishes sending its corresponding periodic flows, bursty flows start to be sent and stop when the i-th entry starts to be executed. The duration for sending bursty flows is the gap. In Fig. 5, Δt_0 is the initial value of the gap, namely, from the end time of the execution of the $(i - 1)$-th item, $o_{i-1} + w_{i-1}$, to the start time of the i-th entry, o_i. With the transmission of bursty flows, $BE_0, BE_1, \cdots$, going on, when BE_n is to be sent, the remaining gap is $\Delta t_n = \Delta t_{n-1} - BE_{n-1}$. We define that the frame is sent immediately if the remaining time is sufficient to send the frame completely. After the frame is sent, it is evaluated again whether the remaining time is sufficient to completely send the next bursty frame, and if possible, continue to send, until the remaining time is not enough to send the frame completely. Algorithm 1 illustrates the process of the remaining time transmission strategy. The remaining time Δt_N shown in Fig. 5 is not enough to send the frame BE_N completely, and the transmission is terminated. As a result, the remaining time Δt_N is the bandwidth loss caused by the transmission strategy. According to the definition of the random variable Y, the bandwidth loss denoted as RemainedTimeLoss is presented as follows:



▲Figure 5. Remaining time transmission strategy and optimal preemption strategy

$$f_i.\text{RemainedTimeLoss} = Y. \tag{14}$$

Algorithm 1: Remaining Time Transmission Strategy

Input: BE, o_{i-1}, w_{i-1}, o_i
Output: Δt

```
begin
    // The execution of entry i-1 is completed
    SetTimer(o_{i-1} + w_{i-1});
    Δt = o_i − (o_{i-1} + w_{i-1});
    // Initialization remaining time
    while (BE.Queues.top().length ≤ Δt) do
        // Check whether the header frame can be sent com-
pletely
        Frame frame = BEQueues.dequeue();
        // Fetch header frame
       Transmit(frame); // Send frame
       // Update remaining time
       Δt = Δt − BE.length;
    end
end
```

4.2 Optimal Preemption Strategy

In order to further reduce the bandwidth loss caused by the remaining time transmission strategy without causing any additional delay jitter, as shown in Fig. 5, when the remaining time Δt_N is not enough to send the frame BE_N completely, the optimal preemption is proposed and illustrated in Fig. 5. It predicts the optimal preemption position (the position corresponding to the first bit of the frame) is based on the remaining time Δt_N and the frame length BE_N.length, and minimizes the bandwidth loss, namely minimizing Δt_N − position. Moreover, the preemption position needs to satisfy the following conditions:

1) The part of the frame before the preemption position and the filled 4-byte CRC due to truncation must be sent within Δt_N, otherwise, delay jitter will be brought in.

$$\Delta t_N \geqslant \text{position} + 4\,. \tag{15}$$

2) The part of the frame before the preemption position needs to be greater than or equal to 60 bytes since the minimum length of an Ethernet frame is 64 bytes.

$$\text{position} \geqslant 60\,. \tag{16}$$

3) The remaining part of the frame after the preemption position needs to be greater than or equal to 64 bytes since the minimum length of an Ethernet frame is 64 bytes.

$$BE_N.\text{length} - \text{position} \geqslant 64\,. \tag{17}$$

Therefore, the problem of the optimal preemption strategy can be formalized as:

$$\min_{\text{position}} \left(\Delta t_N - \text{position}\right).$$

The constraints are:

$$\begin{cases} \Delta t_N \geqslant \text{position} + 4 \\ \text{position} \geqslant 60 \\ BE_N.\text{length} - \text{position} \geqslant 64 \\ BE_N.\text{length} > \Delta t_N \end{cases}. \tag{18}$$

We solve the problem above and give the optimal positions in terms of different Δt_N and BE_N.length.

• When BE_N.length < 124, BE_N cannot be preempted, the bandwidth loss is Δt_N, and the position is 0.

• When BE_N.length ⩾ 124, $\Delta t_N < 64$, BE_N cannot be preempted, the bandwidth loss is Δt_N, and the position is 0.

• When BE_N.length ⩾ 124, $\Delta t_N \geqslant 64$, BE_N.length − (Δt_N − 4) ⩾ 64, BE_N can be preempted, and the preempted position is position=(Δt_N − 4). The bandwidth loss is 24 bytes of bandwidth consumption caused by frame preemption.

• When BE_N.length ⩾ 124, $\Delta t_N \geqslant 64$, BE_N.length − (Δt_N − 4) < 64, BE_N can also be preempted, and the preempted position is position= BE_N.length − 64. The bandwidth loss is Δt_N − (BE_N.length − 64)+ 24 = Δt_N − BE_N.length + 88.

That is,

$$\text{position} = \begin{cases} 0, & BE_N.\text{length} < 124 \\ 0, & BE_N.\text{length} \geqslant 124, \Delta t_N < 64 \\ \Delta t_N - 4, & BE_N.\text{length} \geqslant 124, \Delta t_N \geqslant 64, \\ & BE_N.\text{length} - \Delta t_N \geqslant 60 \\ BE_N.\text{length} - 64, & BE_N.\text{length} \geqslant 124, \Delta t_N \geqslant 64, \\ & BE_N.\text{length} - \Delta t_N < 60\,. \end{cases} \tag{19}$$

According to the definition of random variables X and Y, X is equal to BE_N.length and Y is equal to BE_N. So, we directly give the probability model of bandwidth loss caused by the optimal preemption strategy as below:

$$f_i.\text{OptPreemptionLoss} = \begin{cases} Y, & X < 124 \\ Y, & X \geqslant 124, Y < 64 \\ 24, & X \geqslant 128, Y \geqslant 64, X - Y \geqslant 60 \\ (Y - X) + 88, & X \geqslant 128, Y \geqslant 64, X - Y < 60\,. \end{cases} \tag{20}$$

When the remaining time transmission strategy cannot continue sending a busty frame, the optimal preemption strategy can be applied to send the busty frame by evaluating the optimal preemption position. So, the predictive mixed transmission mechanism consists of the two strategies. Algorithm 2 gives the whole process of the proposed predictive mixed transmission mechanism.

4.3 Guaranteed Advantages

Compared with the guard band strategy defined in 802.1Qbv, the proposed remaining time transmission strategy can iteratively use the gap between periodic flows till the remaining time is insufficient to send the current bursty frame. The core improvement of the strategy is to use the remaining time to adapt to the frame length of bursty flows, instead of selecting the maximum length as the fixed size of the guard band. We prove that the remaining time transmission strategy is better than the guard band strategy by their probabilistic models of bandwidth loss.

Theorem 1: The bandwidth loss of the remaining time transmission strategy is better than the guard band strategy of 802.1Qbv.

Proof: The bandwidth-loss probability model of the guard band strategy is:

$$f_i.\text{GuardLoss} = L_{BE}^{\max} - (X - Y)\,. \tag{21}$$

Algorithm 2: Predictive Mixed Transmission Mechanism

Input: BE, o_{i-1}, w_{i-1}, o_i
Output: position

```
begin
    // The execution of entry i−1 is completed
    SetTimer(o_{i-1} + w_{i-1});
    // Initialization remaining time
    Δt = o_i − (o_{i-1} + w_{i-1});
    // Initialization remaining time
    while (BE.Queues.top().length ⩽ Δt) do
        // Check whether the header frame can be sent completely
        Frame frame = BEQueues.dequeue();
        // Fetch header frame
        Transmit(frame); // Send frame
        // Update remaining time
        Δt = Δt − frame.length;
    end
    // Optimal Preemption Strategy
    length = BE.Queues.top().length;
    switch (Δt, length) do
        case length < 124 do
            position = 0;
            break;
        end
        case length ⩾ 124, Δt < 64 do
            position = 0;
            break;
        end
        case length ⩾ 124, Δt ⩾ 64,
            length − (Δt − 4) ⩾ 64 do
            position = Δt − 4;
            break;
        end
        case length ⩾ 124, Δt ⩾ 64,
            length − (Δt − 4) < 64 do
            position = BE_N.length − 64;
            break;
        end
    end
    Preemption(BEQueues,position);
end
```

The bandwidth-loss probability model of the remaining time transmission strategy is:

$$f_i.\text{RemainedTimeLoss} = Y \ . \tag{22}$$

Since $L_{BE}^{\max} - X \geqslant 0$, $f_i.\text{GuardLoss} = L_{BE}^{\max} - (X - Y) = (L_{BE}^{\max} - X) + Y \geqslant Y = f_i.\text{RemainedTimeLoss}$. Thus, $f_i.\text{GuardLoss} \geqslant f_i.\text{RemainedTimeLoss}$.

Therefore, the bandwidth loss of the remaining time transmission strategy is better than that of the guard band strategy.

In order to further reduce the bandwidth loss, this paper proposes an optimal preemption strategy. The strategy further reduces bandwidth loss by selecting the optimal preemption position when the remaining time is insufficient to completely send the current burst frame. Compared with the mixed strategy of the guard band strategy in 802.1Qbv and the frame preemption strategy in 802.1Qbu, the proposed optimal preemption strategy has obvious advantages. To prove the advantage, we give Theorem 2 as follows.

Theorem 2: The proposed optimal preemption strategy is better than the mixed strategy of the guard band strategy and the frame preemption strategy.

Proof: The bandwidth-loss probability model of the mixed strategy of guard band strategy and frame preemption strategy is:

$$f_i.\text{MixedLoss} = \begin{cases} 123 - (X - Y), & X < 124, \\ 83 + Y, & 124 \leqslant X, Y < 60, \\ 143, & 124 \leqslant X, 60 \leqslant Y, 64 \leqslant X - Y, \\ 123 - (X - Y), & 124 \leqslant X, 60 \leqslant Y, X - Y < 64. \end{cases} \tag{23}$$

The bandwidth-loss probability model of the optimal preemption strategy is:

$$f_i.\text{OptPreemptionLoss} = \begin{cases} Y, & X < 124 \\ Y, & X \geqslant 124, Y < 64 \\ 24, & X \geqslant 124, Y \geqslant 64, X - Y \geqslant 60 \\ (Y - X) + 88, & X \geqslant 124, Y \geqslant 64, X - Y < 60. \end{cases} \tag{24}$$

To prove the advantage of the proposed strategy, we compare the bandwidth loss in terms of different X and Y as below.

1) When $X < 124$, $f_i.\text{MixedLoss} = 123 - (X - Y) = (123 - X) + Y \geqslant Y = f_i.\text{OptPreemptionLoss}$.

2) When $124 \leqslant X$ and $Y < 60$, $f_i.\text{MixedLoss} = 83 + Y > Y = f_i.\text{OptPreemptionLoss}$.

3) When $124 \leqslant X$, $60 \leqslant Y$ and $64 \leqslant X - Y$, $f_i.\text{MixedLoss} = 143$.

- When $60 \leqslant Y < 64$, $f_i.\text{OptPreemptionLoss} = Y < 64 < 147 = f_i.\text{MixedLoss}$.
- When $64 \leqslant Y$, $f_i.\text{OptPreemptionLoss} = 24 < 143 = f_i.\text{MixedLoss}$.

4) When $124 \leqslant X, 60 \leqslant Y$ and $X - Y < 64$, $f_i.\text{MixedLoss} = 123 - (X - Y) = (Y - X) + 123 \geqslant 60$.

- When $60 \leqslant Y < 64$, $f_i.\text{OptPreemptionLoss} = Y > Y + (123 - X) = f_i.\text{MixedLoss}$. We discuss different values of Y as below.

a) If $Y = 61$, and $124 \leqslant X < 125$, then when $X = 124$, $f_i.\text{MixedLoss} = 60$, $f_i.\text{OptPreemptionLoss} = 61$

b) If $Y = 62$, and $124 \leqslant X < 126$, then when $X = 124$, we have $f_i.\text{MixedLoss} = 61$, $f_i.\text{OptPreemptionLoss} = 62$, when $X =$

125, we have f_i.MixedLoss = 60, f_i.OptPreemptionLoss = 62

c) If $Y = 63$, and $124 \leqslant X < 127$, then

when $X = 124$, we have f_i.MixedLoss = 62, f_i. OptPreemptionLoss = 63;

when $X = 125$, f_i.MixedLoss = 61, f_i.OptPreemptionLoss = 63;

when 126, we have f_i.MixedLoss = 60, f_i.OptPreemptionLoss = 63.

• When $64 \leqslant Y$ and $60 \leqslant X - Y < 64$, f_i.OptPreemptionLoss $= 24 < -64 + 123 < (Y - X) + 123 =$ f_i.MixedLoss.

• When $64 \leqslant Y$ and $X - Y < 60$, f_i.OptPreemptionLoss $= (Y - X) + 88 < (Y - X) + 123 =$ f_i.MixedLoss.

Above all, only when Y =61, 62, or 63, the mixed strategy saves bandwidth of no more than 3 bytes than that of the optimal preemption strategy. Since the variable Y represents the random bit position of a preempted BE frame at the specific time point of a TT frame, Y is not equal to 61, 62, or 63 with a high probability, and the bandwidth loss of the optimal preemption strategy is significantly less than that of the mixed strategy when Y is not equal to 61, 62, or 63. So, the optimal preemption strategy is better than the mixed strategy in the sense of probability.

5 Results and Analysis

This section conducts experimental tests to compare the proposed predictive mixed transmission mechanism with the previous mechanisms by simulating their probability models.

5.1 Experimental Setup

The experiments set X bursty flows to obey uniform distribution, binomial distribution, poisson distribution, and normal distribution within the range of length [64, 1 518]. Y is the uniform distribution number of the transmitted bytes of BE frames at the sending time points of TT frames. We use MATLAB programming to implement the bandwidth-loss probability models of all strategies.

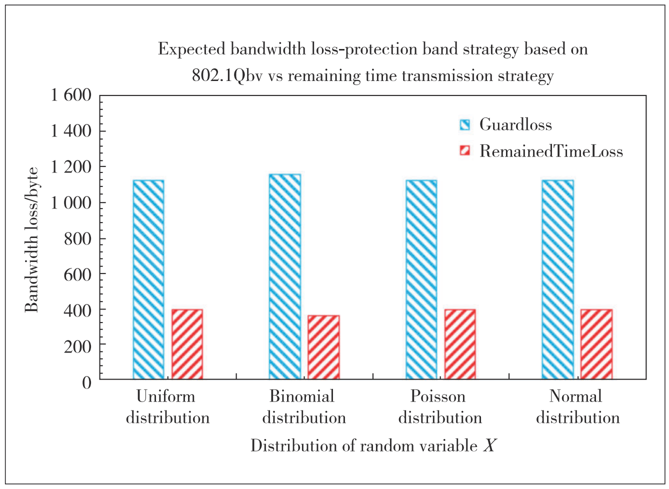
5.2 Experimental Results

First, we evaluate the expected bandwidth loss under the proposed remaining time transmission strategy and the guard band strategy, respectively. As illustrated in Table 1 and Fig. 6, the expected bandwidth loss of the remaining time transmission strategy is less than 400 bytes while the expected bandwidth loss of the guard band strategy is more than 1 100 bytes in all X distributions. As a result, the expected bandwidth loss of the remaining time transmission strategy is about one third of the expected bandwidth loss of the guard band strategy. And then, we evaluate the expected bandwidth loss under the proposed optimal preemption strategy and the mixed strategy of guard band and frame preemption, respectively. Table 2 and Fig. 7 are the expected bandwidth loss comparison of the optimal preemption strategy and the mixed strategy when X obeys uniform distribution, binomial distribution, Poisson distribution, and normal distribution. In all distributions, the expected bandwidth loss of the optimal strategy is less than 30 bytes while the expected bandwidth loss of the mixed strategy is more than 130 bytes. As a result, we achieve a 79.48% reduction of the expected bandwidth loss on average from the mixed strategy to the optimal preemption strategy. And different probabilistic distributions have a little effect on the expected bandwidth loss, which demonstrates that the proposed strategy has the consistent advantage of saving bandwidth.

Furthermore, Tables 3, 4, 5 and 6 illustrate the detailed comparison of different ranges of X and Y in uniform distribution, binomial distribution, Poisson distribution, and normal distribution, respectively. For all different ranges of X and Y, the optimal preemption strategy saves bandwidth better than

▼Table 1. Expected bandwidth loss: the remaining time transmission strategy (RemainedTimeLoss) vs the guard band strategy (Guardloss) of 802.1QBV

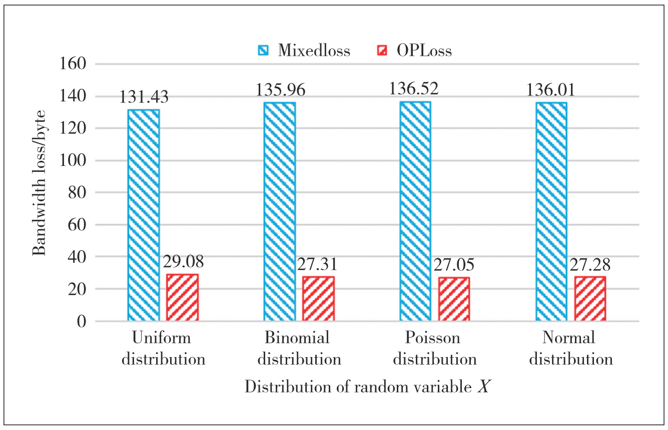
X Distribution Within the Range of Length [64, 1 518]	RemainedTimeLoss/byte	Guardloss/byte
Uniform distribution	395.5	1 122.5
Binomial distribution	363.75	1 154.2
Poisson distribution	395.5	1 122.5
Normal distribution	395.75	1 122.3



▲Figure 6. Comparison of the expected bandwidth loss between the remaining time transmission strategy and the guard band strategy of 802.1Qbv

▼Table 2. Expected bandwidth loss: the optimal preemption strategy (OPLoss) vs the mixed strategy (MixedLoss) of the guard band and the frame preemption

X Distribution Within the Range of Length [64, 1 518]	OPLoss/byte	MixedLoss/byte	Reduced Rate/byte
Uniform distribution	29.08	131.43	77.87%
Binomial distribution	27.31	135.96	79.91%
Poisson distribution	27.05	136.52	80.19%
Normal distribution	27.28	136.01	79.94%



▲ **Figure 7. Comparison of the expected bandwidth loss between the optimal preemption strategy (OPLoss) and the mixed strategy (MixedLoss) of the guard band and the frame preemption**

▼ **Table 3. Expected bandwidth loss of each part: the optimal preemption strategy (OPLoss) vs the mixed strategy (MixedLoss) in Uniform distribution**

Uniform Distribution Within the Range of Length [64, 1 518]	OPLoss/byte	MixedLoss/byte
$X < 124$	1.93	3.14
$X \geq 124$, $Y < 60$	3.04	11.61
$X \geq 124$, $Y \geq 60$, $X - Y \geq 64$	17.89	106.61
$X \geq 124$, $Y \geq 60$, $X - Y < 64$	6.22	10.07

▼ **Table 4. Expected bandwidth loss of each part: the optimal preemption strategy (OPLoss) vs the mixed strategy (MixedLoss) in Binomial distribution**

Binomial Distribution (p=0.5) Within the Range of Length [64, 1 518]	OPLoss/byte	MixedLoss/byte
$X < 124$	0	0
$X \geq 124$, $Y < 60$	2.43	9.27
$X \geq 124$, $Y \geq 60$, $X - Y \geq 64$	19.91	118.64
$X \geq 124$, $Y \geq 60$, $X - Y < 64$	4.97	8.04

▼ **Table 5. Expected bandwidth loss of each part: the optimal preemption strategy (OPLoss) vs the mixed strategy (MixedLoss) in poisson distribution**

Poisson Distribution Within the Range of Length [64, 1 518]	OPLoss/byte	MixedLoss/byte
$X < 124$	0	0
$X \geq 124$, $Y < 60$	2.24	8.53
$X \geq 124$, $Y \geq 60$, $X - Y \geq 64$	20.24	120.58
$X \geq 124$, $Y \geq 60$, $X - Y < 64$	4.57	7.4

that of the mixed strategy.

6 Conclusions

We first analyze the mixed transmission strategies of bursty flows and periodic flows in TSN, and point out that the mixed strategies of 802.1Qbv-based guard band strategy and 802.1Qbu-based frame preemption strategy can be improved.

▼ **Table 6. Expected bandwidth loss of each part: the optimal preemption strategy (OPLoss) vs the mixed strategy (MixedLoss) in normal distribution**

Normal distribution within the range of length [64, 1 518]	OPLoss/byte	MixedLoss/byte
$X < 124$	0.016	0.028 9
$X \geq 124$, $Y < 60$	2.41	9.18
$X \geq 124$, $Y \geq 60$, $X - Y \geq 64$	19.94	118.83
$X \geq 124$, $Y \geq 60$, $X - Y < 64$	4.92	7.96

Then, we propose the predictive mixed transmission mechanism based on the prediction of time-triggered transmission. The proposed mechanism consists of the remaining time transmission strategy and the optimal preemption strategy. We present the probability models and algorithms of the proposed mechanism, and prove its advantages in terms of reducing bandwidth loss. Finally, we simulate the proposed mechanism by its probability model. Compared with the mixed strategy of guard band and frame preemption, we achieve a 79.48% reduction of the expected bandwidth loss of different probability distributions on average.

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