

Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping

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Abstract—We compute bounds on end-to-end worst-case latency and on nodal backlog size for a per-class deterministic network that implements Credit Based Shaper (CBS) and Asynchronous Traffic Shaping (ATS), as proposed by the Time-Sensitive Networking (TSN) standardization group. ATS is an implementation of the Interleaved Regulator, which reshapes traffic in the network before admitting it into a CBS buffer, thus avoiding burstiness cascades. Due to the interleaved regulator, traffic is reshaped at every switch, which allows for the computation of explicit delay and backlog bounds. Furthermore, we obtain a novel, tight per-flow bound for the response time of CBS, when the input is regulated, which is smaller than existing network calculus bounds. We also compute a per-flow bound on the response time of the interleaved regulator. Based on all the above results, we compute bounds on the per-class backlogs. Then, we use the newly computed delay bounds along with recent results on interleaved regulators from literature to derive tight end-to-end latency bounds and show that these are less than the sums of per-switch delay bounds.

I. INTRODUCTION

Time-Sensitive Networking (TSN) is an emerging IEEE standard of the 802.1 Working Group which defines mechanisms for bounded end-to-end latency and zero packet loss [1]. It specifies a number of per-class queuing, scheduling and shaping mechanisms. Because the mechanisms are per-class, one key issue in this context is how to deal with the burstiness cascade: individual flows that share a resource dedicated to a class may see their burstiness increase, which may in turn cause increased burstiness to other flows downstream of this resource. Computing latency upper bounds for per-class networks is difficult, unless flows are reshaped at every hop [2]–[5]. This is why a TSN proposal is to reshape flows at every hop, using the concept of interleaved regulator introduced in [6] and analyzed in [7] (called “Asynchronous Traffic Shaping”, ATS, within TSN). An interleaved regulator reshapes individual flows without per-flow queuing.

In [6], an end-to-end delay bound is computed for a network of FIFO constant rate servers with aggregate multiplexing that uses interleaved regulators to avoid the burstiness cascade. However, this does not account for the multi-class nature of a TSN network and for a representative combination of queuing and scheduling mechanisms proposed by TSN, specifically for the scheme called Credit Based Shaper (CBS). The first goal of this paper is to extend these calculations to a more generic TSN network. However, the calculations in [6] are

very complex; extending them seems to be intractable unless some higher level of abstraction is used, as described below. The second goal of this paper is to provide backlog bounds, which can be used to dimension buffers.

To address these goals, we use classic network calculus concepts such as a service-curve characterization of CBS and extend the results in [8] to include high-priority control-data traffic (CDT). We combine this with the max-plus representation of interleaved regulators proposed in [7]. Further, we use the result of [7] that the upper bound on the delay in the combination of an interleaved regulator following a FIFO system is no greater than the upper bound on the delay of the FIFO system. Overall, in this paper we compute delay upper bounds for the CBS, the interleaved regulator and end-to-end delay bounds along with backlog bounds for the first two. Our main contributions are listed below.

i) We obtain a service curve for every AVB (Audio-Video Bridging) class at a CBS system, extending a similar result in [8] by accounting for the presence of CDT (Theorem III.1). The service curves are used to decouple the interleaved regulator from CBS and are essential to obtain the other results mentioned below.

ii) We obtain a novel, tight bound for the *response* time at a CBS subsystem when the input traffic is reshaped by an interleaved regulator (Theorem III.2).

iii) Using this bound and that an interleaved regulator does not increase the delay bound of a FIFO system [7], we obtain a delay bound for the interleaved regulator (Theorem III.3).

iv) We use the delay bound of the interleaved regulator to derive a service curve for the interleaved regulator and hence a backlog bound at the interleaved regulator.

v) We are the first to compute a tight end-to-end latency bound for a TSN network of this kind. We show that the end-to-end latency bound obtained is less than the sum of delay bounds computed at every switch along the path of a flow. Ignoring this, as is often done, leads to a gross overestimation of the worst-case end-to-end latency.

Section II describes the system model. Section III provides: a service curve for the CBS subsystem; a novel tight bound on the response time in the CBS subsystem; a delay bound for the interleaved regulator; and a tight end-to-end delay bound. Section IV uses these results to derive backlog bounds. Section V provides case studies, shows the tightness of the bounds and

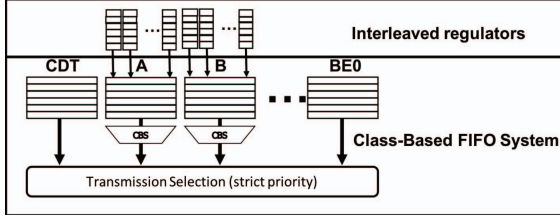


Fig. 1: Architecture of one TSN node output port.

the sub-additivity of the end-to-end delay bound. Section VI concludes the paper.

II. SYSTEM MODEL

We consider a network with a set \mathcal{S} of nodes (switches and hosts) along with a set of flows, F , between hosts. Hosts are sources or destinations of flows. There are four types of flows, namely, control-data traffic (CDT), class A, class B, and best effort (BE) [9] in decreasing order of priority. Flows of classes A and B are together referred to as AVB flows [8], [10]. We focus on delay and backlog bounds for AVB traffic. We assume a subset of TSN functions as described next.

A. Architecture of a TSN node

We assume that contention occurs only at the output port of a TSN node. Each node output port performs per-class scheduling with eight classes: one for CDT, one for class A traffic, one for class B traffic, and five for BE traffic denoted as BE₀–BE₄ (TSN standard [1]). In addition each node output port also performs per-flow regulation for AVB flows using an interleaved regulator. Thus, at each output port of a node, there is one interleaved regulator per-input port and per-class [6], [7]. The detailed picture of scheduling and regulation at a node output port is given by Fig. 1. The packets received at a node input port for a given class are enqueued in the respective interleaved regulator at the output port. Then, the packets from all the flows, including CDT and BE flows, are enqueued in a class based FIFO system (CBFS).

The CBFS includes two CBS subsystems [11], one for each class A and B. As defined in [1], [11], the CBS serves a packet from a class according to the available credit for that class. The credit for class x increases based on the idle slope, I_x , and decreases based on the send slope, S_x , both of which are parameters of the CBS [12]. The CDT and BE₀–BE₄ flows in the CBFS are served by separate FIFO subsystems. Then, packets from all flows are served by a transmission selection subsystem that serves packets from each class based on its priority. All subsystems are non-preemptive.

Guarantees for AVB traffic can be provided only if CDT traffic is bounded; we assume that the CDT traffic from node i to node j has an affine arrival curve $r_{ij}t + b_{ij}$. How to derive such arrival curves involves other TSN mechanisms and is outside the scope of this paper.

Fig. 2 shows a part of a TSN network with three switches serving four flows of class A. In switches SW_1 and SW_2 two flows are coming from two different input ports, thus, they use different interleaved regulators. The flows entering switch

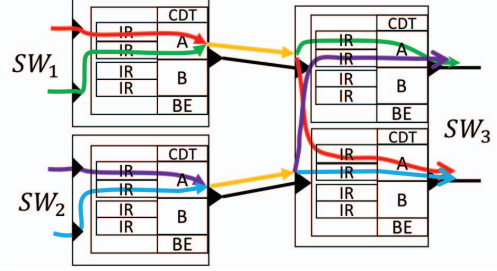


Fig. 2: Illustration of the queuing policy in interleaved regulators (IR) by TSN switches for four flows of class A.

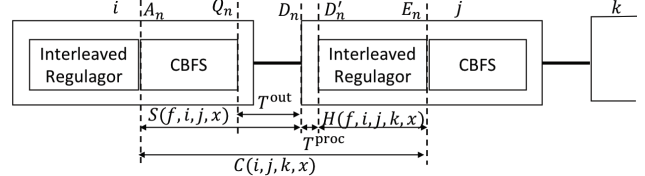


Fig. 3: Timing Model in TSN

SW_3 from switch SW_1 are going to different output ports, and use different interleaved regulators.

B. Flow Regulation

Following [6], we assume that flows are regulated at their source, according to either leaky bucket (LB) or length rate quotient (LRQ). The LB-type regulation forces flow f to conform to the arrival curve $r_f t + b_f$. The LRQ-type regulation with rate r_f ensures that the time separation between two consecutive packets of sizes l_n and l_{n+1} is at least l_n/r_f . Note that if flow f is LRQ-regulated, it satisfies the arrival curve constraint $r_f t + L_f$ where L_f is its maximum packet size (but the converse may not hold). For an LRQ regulated flow we set $b_f = L_f$. We also call M_f the minimum packet size of flow f . We assume that, at the source hosts, the traffic satisfies its regulation constraint, i.e. we can ignore the delay due to interleaved regulator at hosts.

According to [7], at each switch implementing an interleaved regulator, packets of multiple flows are processed in one FIFO queue; the packet at the head of the queue is regulated based on its regulation constraints; it is released at the earliest time at which this is possible without violating the constraint. The regulation type and parameters for a flow are the same at its source and at all switches along its path.

C. Other Notations and Definitions

The indices for nodes, e.g., i, j, k lie in $[1, |\mathcal{S}|]$. A directed link from node i to j is denoted by (i, j) with a capacity of c_{ij} . Also, $n \in \mathbb{N} \setminus 0$ is used as an index for packets, $f \in F$ is used as an index for flows, and $x \in \{A, B, E\}$ is used as an index for AVB classes A and B, and BE flows, respectively. The set of packets belonging to flow f is N_f . The set of flows of class x going from node i to node j is denoted by F_{ij}^x and those that continue to node k , by F_{ijk}^x . The maximum packet size of flows in F_{ij}^x is defined as L_{ij}^x . The flows in F_{ijk}^x use the same CBFS in node i and interleaved regulator in node

j . As mentioned in Section II-A, for each output port, there is a per-class per-input port interleaved regulator. Thereby, the interleaved regulator in node j connected to link (j, k) indicates an output port of node j connected to node k .

Fig. 3 shows the various delays of a packet n of a flow in F_{ijk}^x . We see five important time instants: (1) A_n is the arrival time of packet n in CBFS, (2) Q_n is the time that packet n starts transmission from CBFS, (3) D_n is the time that packet n is received at a node, (4) D'_n is the time that packet n is enqueued in the interleaved regulator, and (5) E_n is the time that packet n leaves the interleaved regulator.

$(D'_n - D_n)$ is the processing time at node j , which is defined as the delay from the reception of the last bit of a packet, coming from node i , to the time the packet is enqueued at the interleaved regulator. We assume that $D'_n - D_n \in [T_{ij}^{\text{proc}, \min}, T_{ij}^{\text{proc}, \max}]$. $(D_n - Q_n)$ is the output delay for packet n traversing from node i to node j , which is defined as the time required from the selection of a packet for transmission from a CBFS queue of node i to the reception of the last bit of the packet by the node j . Also, $D_n - Q_n = l_n/c_{ij} + T_{ij}^{\text{var}, n}$, where l_n is the length of packet n and $T_{ij}^{\text{var}, n}$ is in $[T_{ij}^{\text{var}, \min}, T_{ij}^{\text{var}, \max}]$.

We compute the following bounds for packets of AVB flows belonging to class x going from node i to j (see Fig. 3):

- $S(f, i, j, x)$: upper bound on the response time for flow f in CBFS, i.e. on $(D_n - A_n)$;
- $H(f, i, j, k, x)$: upper bound on the response time for flow f in the interleaved regulator at node j 's output port for link (j, k) , i.e. a bound on $(E_n - D'_n)$;
- $C(i, j, k, x)$: upper bound for all flows on the response time in the combination of the CBFS at node i and the interleaved regulator at node j for link (j, k) , i.e. a bound on $(E_n - A_n)$ for all flows.

III. DELAY BOUNDS IN TSN

The aim of this section is the computation of bounds on the delays an AVB flow experiences due to CBFS, $S(f, i, j, x)$, and interleaved regulator at a node, $H(f, i, j, k, x)$. To do so, in Section III-A, we first derive a service curve of CBFS for an AVB flow, in presence of CDT with an LB arrival curve. Then, in Section III-B, we use this service curve to compute a bound on the response time for an AVB flow in the CBFS of a node, i.e., $S(f, i, j, x)$. Using $S(f, i, j, x)$, we compute $C(i, j, k, x)$. Consequently, we can compute a bound on the response time of an interleaved regulator, $H(f, i, j, k, x)$ in Section III-C, and therefore we have all the elements to compute a bound on the delay of a single TSN node. We also compute a tight end-to-end delay bound for an AVB flow in Section III-D.

A. Service Curve Offered by CBFS to AVB flows

The following theorem provides service curves offered by a CBFS at a TSN node, for AVB flows in presence of CDT flows with LB arrival curve. In [8], the authors compute service curves for AVB flows according to the IEEE AVB standard [10], i.e., in absence of CDT. Note that service curves for AVB flows in TSN are proposed in [12]; however in their proof credit reset is not considered, and we show in Section

V that it leads to incorrect response time bound for CBFS. We obtain different service curves than [12] and we use them to obtain tight delay bounds.

Theorem III.1. *Assume a node i and a link (i, j) , where the CDT has an LB arrival curve with parameters (r_{ij}, b_{ij}) and the line rate is c_{ij} . Then, the CBFS offers to class A flows a rate-latency service curve with parameters,*

$$T_{ij}^A = \frac{1}{c_{ij} - r_{ij}} \left(\bar{L}_{ij}^A + b_{ij} + \frac{r_{ij} \bar{L}_{ij}}{c_{ij}} \right), \quad (1)$$

$$R_{ij}^A = \frac{I_i^A (c_{ij} - r_{ij})}{I_{ij}^A - S_{ij}^A}, \quad (2)$$

where I_{ij}^A and S_{ij}^A are the idle slope and send slope, correspondingly, of the CBS for class A and link (i, j) , $\bar{L}_{ij}^A = \max(L_{ij}^B, L_{ij}^E)$, and $\bar{L}_{ij} = \max(L_{ij}^A, L_{ij}^B, L_{ij}^E)$. Similarly for class B flows, CBFS offers a rate-latency service curve with parameters,

$$T_{ij}^B = \frac{1}{c_{ij} - r_{ij}} \left(L_{ij}^E + L_{ij}^A - \frac{\bar{L}_{ij}^A I_{ij}^A}{S_{ij}^A} + b_{ij} + \frac{r_{ij} \bar{L}_{ij}}{c_{ij}} \right), \quad (3)$$

$$R_{ij}^B = \frac{I_{ij}^B (c_{ij} - r_{ij})}{I_{ij}^B - S_{ij}^B}, \quad (4)$$

where I_{ij}^B and S_{ij}^B are the idle slope and send slope, correspondingly, of the CBS for class B and link (i, j) .

The proof is available in the technical report [13].

B. Upper Bound on the Response Time in CBFS

The rate-latency service curve offered by CBFS at node i for link (i, j) to class $x \in \{A, B\}$ has parameters R_{ij}^x, T_{ij}^x , as calculated in Theorem III.1. Also, let $b_{ij}^{\text{tot}, x} = \sum_{f \in F_{ij}^x} b_f$. Then, the following theorem gives an upper bound on the response time for a flow f at a CBFS of node i .

Theorem III.2. *A tight upper bound on the response time in the CBFS of node i (following the interleaved regulator) for flow f of class $x \in \{A, B\}$, going from node i to j , is:*

$$S(f, i, j, x) = T_{ij}^x + \frac{b_{ij}^{\text{tot}, x} - \psi_f}{R_{ij}^x} + \frac{\psi_f}{c_{ij}} + T_{ij}^{\text{var}, \max}, \quad (5)$$

where the parameter ψ_f depends on the flow f and the type of regulator, namely, for LRQ: $\psi_f = L_f$ and for LB: $\psi_f = M_f$.

The proof is given in the technical report [13].

Remark. Importantly, we should note that the bound on the response time in the CBFS given by Eq. (5) improves the corresponding bound obtained by using the classical network calculus approach (see [14], Theorem 1.4.2 and Section 1.4.3). Specifically, the latter bound is not a per-flow bound and is equal to $T_{ij}^x + \frac{b_{ij}^{\text{tot}, x}}{R_{ij}^x} + T_{ij}^{\text{var}, \max}$, which is always larger than $S(f, i, j, x)$ (Eq. (5)) since $\frac{-\psi_f}{R_{ij}^x} + \frac{\psi_f}{c_{ij}} < 0$. We reached this improved bound by combining the min-plus representation of service curve and max-plus representation of regulation [7].

It is known from [7] that for all flows belonging to class x sharing the same CBFS queue at node i and interleaved regulator at node j (e.g., for link (j, k)),

$$C(i, j, k, x) = \sup_{f' \in F_{ijk}^x} S(f', i, j, x) + T_{ij}^{\text{proc, max}}. \quad (6)$$

Therefore, the following Corollary is a direct result.

Corollary III.2.1. *Assume flows of class $x \in \{A, B\}$, going from node i to j , and enqueued in the interleaved regulator at node j for link (j, k) . An upper bound, for each flow, of the combination of the response time in CBFS of node i (following the interleaved regulator of i) and the interleaved regulator at node j for link (j, k) is given by:*

$$C(i, j, k, x) = T_{ij}^x + \frac{b_{ij}^{\text{tot}, x}}{R_{ij}^x} + T_{ij}^{\text{var, max}} + \sup_{f' \in F_{ijk}^x} \left(\frac{\psi_{f'}}{c_{ij}} - \frac{\psi_{f'}}{R_{ij}^x} \right) + T_{ij}^{\text{proc, max}}, \quad (7)$$

where for LRQ: $\psi_f = L_f$ and for LB: $\psi_f = M_f$.

C. Bound on the Response Time in the Interleaved Regulator

The following theorem proves an upper bound on the response time in the interleaved regulator, $H(f, i, j, x)$.

Theorem III.3. *An upper bound on the response time for flow f of class $x \in \{A, B\}$ in the interleaved regulator at node j for link (j, k) that follows the CBFS of node i is:*

$$H(f, i, j, k, x) = C(i, j, k, x) - \frac{M_f}{c_{ij}} - T_{ij}^{\text{var, min}} - T_{ij}^{\text{proc, min}}. \quad (8)$$

The proof is given in the technical report [13].

Remark. It is shown numerically in Section V, that H is tight for the flow f that achieves the maximum response time at the CBFS, i.e., for which $S(f, i, j, x) = C(i, j, k, x)$.

D. Upper Bound on the End-to-End Delay

Assume an AVB flow f routed through the nodes (i_1, \dots, i_k) , where the source is i_1 and destination is i_k . It is assumed that the arrival curves of the generated flows in source conform to the flows' regulation policies, and thus the flows do not experience delay at the interleaved regulators of the source nodes. An upper bound on the end-to-end delay for flow f of class x , namely, D_f^x , is,

$$D_f^x = \sum_{j=1}^{k-2} C(i_j, i_{j+1}, i_{j+2}, x) + S(f, i_{k-1}, i_k, x). \quad (9)$$

D_f^x can be easily computed by using Eqs. (5), (7). In Section V-E, we show numerically that this bound is tight, in the sense that we exhibit an example that it achieves this bound.

IV. BACKLOG BOUNDS

In this section, we determine an upper bound on the backlog for each AVB class of interleaved regulator and CBFS.

A. Backlog Bound on Interleaved Regulator

In network calculus, computing upper bounds on the backlog requires information on arrival and service curves [14].

1) Service Curve Offered by Interleaved Regulator: It is known that a service curve offered by a FIFO system which guarantees a maximum delay D , is equal to the ‘‘impulse’’ function $\delta_D(t)$ ¹ [7]. The interleaved regulator is a FIFO system, for which a delay upper bound is computed in Section III-C. Therefore, a service curve offered by the interleaved regulator for class x , at node j for link (j, k) , that follows a CBFS of node i is $\delta_{D(i, j, k, x)}(t)$, where $D(i, j, k, x) = \sup_{f' \in F_{ijk}^x} H(f', i, j, l, x)$ is computed using Theorem III.3.

2) Arrival Curve of Interleaved Regulator Input: The output flows of the upstream CBFS (node i) may not share the same interleaved regulator. Let us consider the interleaved regulator of node j for link (j, k) that follows the CBFS of node i . Suppose that r_s and b_s are the sum of rates and bursts of the flows $f' \in F_{ijk}^x$ for $x \in \{A, B\}$. In addition, r_w and b_w are the sum of rates and bursts of the flows that do not use the same interleaved regulator in downstream node with the previous flows. The CBFS offers a rate-latency service curve with parameters (R_{ij}^x, T_{ij}^x) to the class $x \in \{A, B\}$ (Theorem III.1). Then, according to [14], the output arrival curve of the former flows is an LB one, $r_s t + b_{out}$ with $b_{out} = b_s + r_s(T_{ij}^x + \frac{b_w}{R_{ij}^x})$.

On the other hand, the upstream line has constant rate, c_{ij} . Therefore, it also enforces an arrival curve to the input of the interleaved regulator equal to $c_{ij}t + \sup_{f' \in F_{ijk}^x} L_{f'}$.

As the CBFS follows the interleaved regulator, the input arrival curve of the interleaved regulator is,

$$\alpha(t) = \min \left(c_{ij}t + \sup_{f' \in F_{ijk}^x} \{L_{f'}\}, r_s t + b_s + r_s \left(T_{ij}^x + \frac{b_w}{R_{ij}^x} \right) \right). \quad (10)$$

3) Backlog Bound on Interleaved Regulator: The backlog bound is calculated as $\sup_{s \geq 0} \alpha(s) - \beta(s)$ [14], where $\alpha(t)$ is the arrival curve and $\beta(t)$, the service curve. By replacing the arrival and service curves obtained in the two previous subsections, we obtain the backlog bound of the interleaved regulator for class $x \in \{A, B\}$ at node j for link (j, k) that follows the CBFS of node i , denoted as $B_{ijk}^{\text{IR}, x}$ and given:

$$B_{ijk}^{\text{IR}, x} = \min \left(c_{ij}D(i, j, k, x) + \sup_{f' \in F_{ijk}^x} \{L_{f'}\}, r_s D(i, j, k, x) + b_s + r_s \left(T_{ij}^x + \frac{b_w}{R_{ij}^x} \right) \right), \quad (11)$$

where T_{ij}^x, R_{ij}^x are computed in Theorem III.1.

B. Backlog Bound on Class-Based FIFO System

Consider all flows $f \in F_{ij}^x$. The input of the CBFS for class x has an arrival curve equal to the sum of all α_f . Using Theorem III.1 and following a process similar to the one followed for the interleaved regulator, the backlog bound of the CBFS at node i for link (i, j) and class x , denoted as $B_{i,j}^{\text{CBFS}, x}$ is

$$B_{i,j}^{\text{CBFS}, x} = \sum_{f' \in F_{ij}^x} b_{f'} + \sum_{f' \in F_{ij}^x} r_{f'} T_{ij}^x. \quad (12)$$

¹defined as $\delta_D(t) = 0, 0 \leq t \leq D$, else $\delta_D(t) = +\infty$.

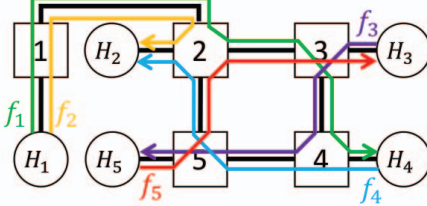


Fig. 4: Practical TSN network used for the case study.

V. CASE STUDY

In this section, we apply the results obtained in the previous sections to practical TSN networks (Fig. 4, 6). We highlight the tightness of the delay bounds obtained and the sub-additivity property of the end-to-end delay bound.

A. TSN Network Setup and Flows

We use the network shown in Fig. 4. It consists of five switches labeled 1-5, and five hosts (as sources and destinations of flows), namely H_1 - H_5 , with five class A flows f_1 - f_5 . Flow f_1 is LRQ regulated with rate $r_{f_1} = 20 \text{ Mbps}$ and has maximum packet length $L_{f_1} = 1 \text{ Kb}$. Flows f_2 - f_5 are LRQ regulated with rate 20 Mbps and maximum packet length 2 Kb . It is assumed that on each output port there is a CDT flow with an LB arrival curve ($20 \text{ Mbps}, 4 \text{ Kb}$), and a BE flow with maximum packet length of 2 Kb . As is shown in the Fig. 4, the network introduces circular dependency among the flows, in which case obtaining end-to-end latency bounds for the flows without the use of interleaved regulators is difficult.

For ease of presentation, we assume that the CBFS has only three classes: CDT, class A, and one BE. Moreover, $T_{ij}^{\text{var,max}}$ and $T_{ij}^{\text{proc,max}}$ are zero in all switches i , links (i, j) and all packets of a same flow have the same size. The line rate is equal to 100 Mbps . The parameters of CBS are $I_{ij}^A = 50 \text{ Mbps}$ and $S_{ij}^A = -50 \text{ Mbps}, \forall i, j, H_1 - H_5$. We are interested in studying the worst case response time of flow f_1 in CBFS of host H_1 and its corresponding interleaved regulator in switch 1. Also, we compute the theoretical end-to-end delay bound of this flow and show its sub-additivity property.

B. Computation of Theoretical Bounds

We compute the obtained upper bounds for the response time in CBFS and interleaved regulator for flow f_1 , and the backlog bounds for the host H_1 and switch 1. According to Theorem III.2, the bound on the CBFS response time for flow f_1 in the host H_1 is $S(f_1, H_1, 1, A) = 140 \mu\text{s}$. Also, from Theorem III.3, the bound on the response time in interleaved regulator for flow f_1 , enqueued in the output port for link (1, 2) on switch 1 is $H(f_1, H_1, 1, 2, A) = 130 \mu\text{s}$. Also, the backlog bound for the same interleaved regulator (Eq. (11)) is 11.4 Kb . The backlog bound for CBFS of class A in host H_1 is 6.2 Kb (Eq. (12)). To compute the end-to-end delay, we use Eq. (9). Using Eq. (7), we find that $C(H_1, 1, 2, A) = C(1, 2, 3, A) = C(2, 3, 4, A) = C(3, 4, H_4, A) = 140 \mu\text{s}$, and $S(f_1, 4, H_4, A) = 140 \mu\text{s}$. Thus, for flow f_1 of class A we have the upper bound on delay $D_{f_1}^A = 700 \mu\text{s}$.

C. Numerical Example of Tightness

Next, we show how these bounds are tight by presenting a particular series of packet arrivals as shown in Fig. 5. This figure shows the input and output curves related to f_1 , f_2 , CDT and BE flows in host H_1 and switch 1. A step in the input curve indicates the time of reception of the entire packet. According to Fig. 5a, at time $0 \mu\text{s}$, a packet of BE arrives and starts being transmitted. At time $0^+ \mu\text{s}$, a burst of CDT traffic arrives and then for time $t \geq 0^+$, CDT traffic continues to arrive with rate 20 Mbps up to the time $75 \mu\text{s}$. The transmission of CDT traffic at time 0^+ is blocked by the transmission of the BE packet as all switches are non-preemptive. At time $20 \mu\text{s}$, CDT traffic has accumulated a backlog and starts its transmission.

From Fig. 5b, we see that time $20 \mu\text{s}$ is the start of the backlog period of class A since a packet of flow f_2 and a packet of f_1 arrive, with first of the two being the former. The first packet of flow f_2 reaches at time $95 \mu\text{s}$ the interleaved regulator in switch 1 for link (1, 2) that implies a response time of $75 \mu\text{s}$ for flow f_2 in the CBFS of host H_1 . The first packet of flow f_1 finishes its transmission at time $160 \mu\text{s}$ from CBFS in H_1 , due to its earlier blockage by the CDT and f_2 traffic. This implies a response time of $140 \mu\text{s}$ for flow f_1 in CBFS of H_1 , i.e., equal to the bound in Section V-B.

Remark. Using the service curve computed in Theorem 1 of [12], gives a bound equals to $135 \mu\text{s}$ for the response time of CBFS for f_1 . In the described scenario, flow f_1 faced a response time of $140 \mu\text{s}$ that is higher than $135 \mu\text{s}$.

From Fig. 5c, we notice that the worst-case response time in the interleaved regulator for flow f_1 at switch 1 is for the packet that arrives at time $230 \mu\text{s}$. This packet is declared eligible by the interleaved regulator at time $360 \mu\text{s}$. This implies the response time of $130 \mu\text{s}$ in the interleaved regulator that is the upper bound for flow f_1 as computed in Section V-B. The maximum response time seen in Fig. 5c for flow f_2 is for its packet that arrives at time $260 \mu\text{s}$ at the interleaved regulator at switch 1 and is equal to $100 \mu\text{s}$.

Note that this packet of flow f_2 could have been declared eligible by the interleaved regulator already at $260 \mu\text{s}$ but is blocked by preceding packets of flow f_1 that were not yet eligible at that time. Based on Fig. 5b and 5c, we observe that packets of flow f_1 experience a maximum delay of $140 \mu\text{s}$ from the time being enqueued in the CBFS of H_1 to the time being declared eligible by the interleaved regulator at switch 1 (equal to $C(H_1, 1, 2, A)$, computed in Section V-B).

The maximum observed backlog for class A used in the CBFS at the output port of H_1 is equal to 4 Kb during times $70 \mu\text{s}$ to $75 \mu\text{s}$, which is 65% of the computed bound. Furthermore, the maximum backlog observed in the interleaved regulator at output port of switch 1 is equal to 5 Kb during times $230 \mu\text{s}$ to $260 \mu\text{s}$, which is 43% of the computed bound.

D. Sub-additivity of End-to-End Delay Bound

In TSN, the common way of computing the end-to-end delay bound is by adding the delay bounds of each switch in the path of a flow. However, Eq. (9) provides a much better

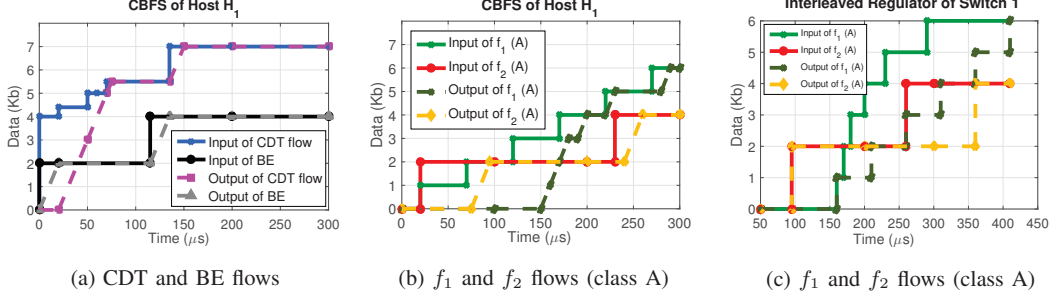


Fig. 5: Cumulative data input and output curves for the CBFS of H_1 and interleaved regulator of switch 1, with respect to Fig. (4). Figures (a) and (b) show the data arrival and departures from the CBFS of H_1 , and the figure (c) shows the arrival and departure of data from the interleaved regulator for flows f_1 and f_2 in switch 1.

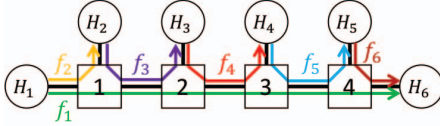


Fig. 6: TSN network for tightness of end-to-end delay bound.

upper bound. To show this, we first compute the delay upper bound for switch i following switch j and followed by switch k in the path of a flow f of class x , is given by,

$$d_{j,i,k}^{x,f} = H(f, j, i, k, x) + S(f, i, k, x) + T_i^{\text{proc,max}}, \quad (13)$$

where for i being a source, $H(f, j, i, k, A)$ is equal to zero. Considering $T_i^{\text{proc,max}}$ equal to zero in this case, an end-to-end delay bound for flow f_1 over the path $(H_1, 1), (1, 2), (2, 3), (3, 4), (4, H_4)$ can be computed as $(0 + 140) + 4 \times (130 + 140) = 1220 \mu\text{s}$.

From Section V-C, we know that an upper bound on the end-to-end delay for flow f_1 is $700 \mu\text{s}$ which is 57% of $1220 \mu\text{s}$, obtained using Eq. 13.

E. Tightness of End-to-End Delay Bound

Consider the network shown in Fig. 6, having four switches labeled 1 - 4, and six hosts, namely $H_1 - H_6$, with six class A flows $f_1 - f_6$. The assumptions on $f_1 - f_5$, CDT and BE traffic are as in Section V-A and f_6 is similar to $f_2 - f_5$.

To show the tightness of end-to-end delay bound of Eq. (9), we claim that each pair of f_1, f_3 at switch 1, f_1, f_4 at switch 2, f_1, f_5 at switch 3, and f_1, f_6 at switch 4 experience the same input/output curves as the pair of flows f_1, f_2 in Fig. 5 but appropriately shifted in time, so that they take place sequentially. Thus, flow f_1 has a delay of $140 \mu\text{s}$ from the time being enqueued in the CBFS of H_1 to the time declared eligible from the interleaved regulator at 1. The same delay is experienced by flow f_1 at the rest pairs of switches in its path. Similar to Section V-C, the response time of f_1 at CBFS of switch 4 is equal to $140 \mu\text{s}$. Therefore, the end-to-end delay for f_1 is equal to $4 \times 140 + 140 = 700 \mu\text{s}$, which is equal to the bound computed from Eq. (9).

VI. CONCLUSION

We have provided a set of formulas for computing bounds on end-to-end delay and backlog for class A and class B

traffic in a TSN network that uses CBS and ATS. The bounds are rigorously proven, while we provide a representative case study that highlights the tightness of the delay bounds provided and shows the sub-additivity of the end-to-end delay bound. Future work will address other mechanisms in TSN.

REFERENCES

- [1] Time-sensitive networking (TSN) task group. [Online]. Available: <https://1.ieee802.org/tsn/>, (Accessed:14/03/2018).
- [2] A. Charny and J.-Y. Le Boudec, "Delay bounds in a network with aggregate scheduling," in *Quality of Future Internet Services*. Springer, 2000, pp. 1–13.
- [3] J. C. Bennett, K. Benson, A. Charny, W. F. Courtney, and J.-Y. Le Boudec, "Delay jitter bounds and packet scale rate guarantee for expedited forwarding," *IEEE/ACM Transactions on Networking (TON)*, vol. 10, no. 4, pp. 529–540, 2002.
- [4] M. Boyer and C. Fraboul, "Tightening end to end delay upper bound for afdx network calculus with rate latency fifo servers using network calculus," in *IEEE Int'l Workshop on Factory Communication Systems (WFCS)*, 2008, pp. 11–20.
- [5] A. Bouillard and G. Stea, "Exact worst-case delay for fifo-multiplexing tandems," in *the 6th Int'l Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS)*, 2012, pp. 158–167.
- [6] J. Specht and S. Samii, "Urgency-Based Scheduler for Time-Sensitive Switched Ethernet Networks," in *the 28th Euromicro Conference on Real-Time Systems (ECRTS)*, Jul. 2016, pp. 75–85.
- [7] J.-Y. Le Boudec, "A Theory of Traffic Regulators for Deterministic Networks with Application to Interleaved Regulators," *arXiv:1801.08477 [cs]*, Jan. 2018. [Online]. Available: <http://arxiv.org/abs/1801.08477/>, (Accessed:09/02/2018).
- [8] J. A. R. De Azua and M. Boyer, "Complete modelling of avb in network calculus framework," in *the 22nd ACM Int'l Conf. on Real-Time Networks and Systems (RTNS)*, NY, USA, 2014, pp. 55–64.
- [9] S. Thangamuthu, N. Concer, P. J. L. Cuijpers, and J. J. Lukkien, "Analysis of ethernet-switch traffic shapers for in-vehicle networking applications," in *Design, Automation & Test in Europe Conf. & Exhibition (DATE)*, 2015, pp. 55–60.
- [10] "IEEE standard for local and metropolitan area networks—audio video bridging (AVB) systems," pp. 1–45.
- [11] IEEE 802.1: 802.1qbv - enhancements for scheduled traffic- draft 0.0. [Online]. Available: <http://www.ieee802.org/1/pages/802.1bv.html>, (Accessed:29/03/2018)
- [12] L. Zhao, P. Pop, Z. Zheng, and Q. Li, "Timing analysis of avb traffic in tsn networks using network calculus," in *Real-Time and Embedded Technology and App. Symp.*, ser. RTAS '18. IEEE, 2018, pp. 25–36.
- [13] E. Mohammadpour, E. Stai, M. Mohiuddin, and J.-Y. Le Boudec, "End-to-end Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping," *arXiv:1804.10608 [cs.NI]*, 2018. [Online]. Available: <https://arxiv.org/abs/1804.10608/>
- [14] J.-Y. Le Boudec and P. Thiran, *Network Calculus: A Theory of Deterministic Queuing Systems for the Internet*. Springer Science & Business Media, 2001, vol. 2050.