AVB-aware Routing and Scheduling for Critical Traffic in Time-sensitive Networks with Preemption - Supplementary Material

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Abstract

In this supplementary material, we present two proofs, one related to the (min-plus) minimum service curve for an arbitrary AVB Class under preemption with HOLD/RELEASE, and the other one related to the impact of preemption overhead on the CBS credit behavior when comparing the preemptive and non-preemptive modes. The proofs build upon similar proofs from literature [9, 8], extending and adapting them for the preemptive mode with HOLD/RELEASE and non-frozen credit during the preemption overhead.

2012 ACM Subject Classification Computer systems organization → Dependable and fault-tolerant systems and networks

Keywords and phrases TSN, real-time, network calculus, scheduling.

1 Introduction and notations

We build upon the timing analysis results of the non-preemptive mode from [9, 2] and the results from [8], extending them with a timing analysis for an arbitrary number of AVB classes in the preemptive mode with HOLD/RELEASE (c.f. [4, 5], superseded by [5]) for non-frozen credit during the guard band interval in compliance with the standard. In time-sensitive networks (TSN) networks, we have three types of traffic, namely scheduled traffic (ST), also named time-triggered (TT) traffic, audio-video bridging (AVB), and best-effort (BE) traffic. Similar to [1, 8, 6], we assume that ST, AVB, and BE traffic types are isolated in their own queues and that the timed gates of IEEE 802.1Qbv [3] (superseeded by [5]) for two different queues are not open at the same time. Additionally, AVB and BE are configured as preemptable, while the ST queues are configured as express.

Any frame that has a size of $l_{\mathrm{nPr}}^{\max} = 123$ bytes or smaller cannot be preempted since, as defined in [4, 5] the minimum frame size that can be preempted is $l_{\mathrm{Pr}}^{\min} = 124$ bytes. The guard band window required before an ST open gate event in preemptive mode is equal to $L_{\mathrm{GB}} = (l_{\mathrm{nPr}}^{\max} + l_{\mathrm{IFG}}^{+})/C = (123 + 20)/C$, including the fragmentation overhead and the inter-frame gap (IFG). During the guard band window, a frame can finish its transmission or be preempted [2] and the credit of the credit-based shaper (CBS) increases in this interval if the gate for AVB queues is open. This non-frozen credit behavior is specified in the 802.1Q [5] standard and has been addressed in [8]. The IEEE 802.1Q standard [5] also stipulates that a preemption overhead $l_{\mathrm{OH}} = 24$ bytes [7] will be added to each fragment of a preempted frame.

We summarize the notations used for the proofs in this supplementary material in Table 1.

2 Theorem 1 - Service Curve for AVB Traffic

A Network Calculus (NC)-based worst-case response-time (WCRT) analysis for two AVB classes in the TSN/TAS+CBS architecture has been introduced in [9] which only looks at the preemptive and non-preemptive behavior without HOLD/RELEASE and assumes that the CBS credit is frozen during the guard band of the non-preemptive mode. A timing analysis for an arbitrary number of AVB classes that considers both frozen and non-frozen credit during the guard band of the non-preemptive mode has been presented in [8]. Neither of the papers discussed the performance analysis in the preemptive with HOLD/RELEASE mode. Although the preemptive mode with HOLD/RELEASE has been discussed in [2], the authors consider the overhead and ST window together, which introduces pessimism since the credit of the AVB traffic class will be reduced/increased rather than frozen during the preemption overhead segment. In this section, we derive the service curve for multiple AVB classes M_i ($i \in [1, n^{\mathrm{h}}_{\mathrm{CBS}}]$), extended from [8] for the preemptive mode with HOLD/RELEASE.

▶ **Theorem 1.** *The (min-plus) minimum service curve for an AVB Class M_i ($i \in [1, n^{h}_{CBS}]$) in egress port h under preemption with HOLD/RELEASE is*

$$\beta^{h,[PrH/R]}_{M_i}(t) = idSl_{M_i}\left[t - \frac{\alpha^{h}_{ST}(t)}{C} - \frac{\alpha^{h,M_i}_{OH}(t) + c^{\max}_{M_i}}{idSl_{M_i}}\right]^{+}_{\uparrow}. \tag{1}$$

where $\alpha^{h}_{ST}(t)$(c.f. [9, 8, 2]) is the arrival curve of ST traffic scheduled according to the pre-defined GCLs, $\alpha^{h,M_i}_{OH}(t)$ is the arrival curve with respect to the extra overheads due to the preemption mode, and $c^{\max}_{M_i}$ given by Lemma 2 is the maximum credit bound of Class M_i with non-frozen credit during GB, which is compliant with the standard hypothesis.

2.1 Proof of Theorem 1

Proof: The proof builds closely upon the proof of Theorem 1 in [9] on the service curve for AVB traffic. We define $R^{\mathrm{h}}_{\mathrm{M}_i}(t)$ and $R^{*\mathrm{h}}_{\mathrm{M}_i}(t)$ as the cumulative arrival and departure functions of AVB streams of Class M_i in egress port h. Similarly, $R^{\mathrm{h}}_{\mathrm{ST}}(t)$, $R^{\mathrm{h}}_{\mathrm{GB}}(t)$, $R^{\mathrm{h}}_{\mathrm{OH}}(t)$ and $R^{*\mathrm{h}}_{\mathrm{ST}}(t)$, $R^{*\mathrm{h}}_{\mathrm{GB}}(t)$, $R^{*\mathrm{h}}_{\mathrm{OH}}(t)$, represent the cumulative arrival and departure functions of ST streams, guard bands, and overheads in egress port h. Let $t \in \mathbb{R}^+$ be a time point when the queue Q_{M_i} of AVB Class M_i is backlogged, i.e., $R^{*\mathrm{h}}_{\mathrm{M}_i}(t) < R^{\mathrm{h}}_{\mathrm{M}_i}(t)$. We define $s = \sup\{u \leq t \,|\, c_{\mathrm{M}_i}(u) = 0, R^{*\mathrm{h}}_{\mathrm{M}_i}(u) = R^{\mathrm{h}}_{\mathrm{M}_i}(u), R^{*\mathrm{h}}_{\mathrm{ST}}(u) = R^{\mathrm{h}}_{\mathrm{ST}}(u), R^{*\mathrm{h}}_{\mathrm{GB}}(u) = R^{\mathrm{h}}_{\mathrm{GB}}(u), R^{*\mathrm{h}}_{\mathrm{OH}}(u) = R^{\mathrm{h}}_{\mathrm{OH}}(u)\}$. This implies that $\forall u \in (s, t]$, the queue Q_{M_i} is non-empty or $c_{\mathrm{M}_i}(u) < 0$. Otherwise, we can always find another $s < s' \leq t$ that satisfies $c_{\mathrm{M}_i}(s') = 0$ and $R^{*\mathrm{h}}_{\mathrm{M}_i}(s') = R^{\mathrm{h}}_{\mathrm{M}_i}(s')$. Moreover, it also implies that s is outside of ST window, guard bands, overheads duration. We define the duration $(s, t]$ the busy period of AVB Class M_i.

Similar to [9], the interval $\Delta t = t - s$ can be decomposed by

$$\Delta t = \Delta t^{-} + \Delta t^{+} + \Delta t^{0},$$

Table 1 Summary of notation.

Symbol	Meaning
C	Physical link rate
$l_{\mathrm{nPr}}^{\mathrm{max}}$	The maximum non-preemptable frame size (123 bytes)
$l_{\mathrm{Pr}}^{\mathrm{min}}$	The minimum preemptable frame size (124 bytes)
L_{GB}	Guard band size with HOLD/RELEASE (143 bytes/C)
l_{IFG}^{+}	Preemption overhead (20 bytes)
l_{FCS}^{+}	MAC DA, MAC SA, FCS frame overhead (22 bytes)
l_{FCS}	Overhead of FCS for a frame (4 bytes)
$l_{\mathrm{payload}}^{\mathrm{F,min}}$	Min payload (42 bytes) of the first fragment of a frame
$l_{\mathrm{payload}}^{\mathrm{NF,min}}$	Min payload (60 bytes) for the subsequent fragments
l_{OH}	Overhead (24 bytes) due to preemption
h	Output port of a node
M_i	Priority/Class of AVB traffic
Q_{M_i}	Queue for AVB Class M_i
$Q_{\mathrm{AVB}}^{\leq i}$	AVB queues with priority higher than or equal to M_i
$n_{\mathrm{CBS}}^{\mathrm{h}}$	The number of priorities for AVB traffic
$\beta_{\mathrm{M}_i}^{\mathrm{h,[PrH/R]}}(t)$	Min-plus minimum service curve for AVB Class M_i under preemption with HOLD/RELEASE
$\mathrm{idSl}_{\mathrm{M}_i}, \mathrm{sdSl}_{\mathrm{M}_i}$	Idle and send slopes of the AVB class M_i
$c_{\mathrm{M}_i}^{\mathrm{max}}, c_{\mathrm{M}_i}^{\mathrm{min}}$	Upper and lower bounds of credit for AVB Class M_i
$\alpha_{\mathrm{ST}}^{\mathrm{h}}(t)$	Arrival curve for ST traffic
$o_i^{\mathrm{h}}, L_{\mathrm{ST},i}^{\mathrm{h}}$	Starting time and duration of i^{th} ST window on h
$o_{j,i}^{\mathrm{h}}$	Relative offset i^{th} and j^{th} ST windows on h, i.e., $o_j^{\mathrm{h}} - o_i^{\mathrm{h}}$
$p_{\mathrm{GCL}}^{\mathrm{h}}$	GCL period on h
$N_{\mathrm{ST}}^{\mathrm{h}}$	Number of ST windows within the GCL period
$\alpha_{\mathrm{OH}}^{\mathrm{h,M}_i}(t)$	Arrival curve with respect to preemption overheads
$l_{\mathrm{M}_i}^{\mathrm{h,max}}$	The maximum frame of AVB Class M_i on h
$l_{\mathrm{M}_i,\mathrm{payload}}^{\mathrm{h,max}}$	The payload of the frame $l_{\mathrm{M}_i}^{\mathrm{h,max}}$
$\bar{l}_{\mathrm{M}_i,\mathrm{payload}}^{\mathrm{h,max}}$	Leftover payload that has not been transmitted
$l_{\leq i}^{\mathrm{h,max}}, l_{\leq i}^{\mathrm{h,min}}$	Max and min AVB frame size with priority $\geq \mathrm{M}_i$ on h
$l_{>i}^{\mathrm{h,max}}$	Max AVB frame size with priority lower than M_i on h
$l_{\mathrm{OH},j}^{\mathrm{h,M}_i}$	Preemption overhead after j^{th} ST window on h
$n_{\mathrm{Pr}}^{\mathrm{h,M}_i}$	The max preemption times of a frame of AVB Class M_i
$L_{\mathrm{GB},j}^{\mathrm{h,M}_i}$	Guard band duration before j^{th} ST window on h
$\sigma_{\mathrm{GB}}^{\mathrm{h,M}_i}, \rho_{\mathrm{GB}}^{\mathrm{h,M}_i}$	Burst and rate of linear arrival curve of guard band duration
Δt_{M_i}	Transmission duration of frames with priority M_i
$\Delta t_{\mathrm{AVB}}^{<i}$	Duration of higher priority frames from $Q_{\mathrm{AVB}}^{<i}$
Δt_{LP}	Duration of a lower priority frame from $Q_{\mathrm{AVB}}^{>i}$ or Q_{BE}
Δt_{GB}	Guard band duration
$\Delta t_{\mathrm{OH}}^{<i}$	Overhead duration due to higher priority preempted frames
$\Delta t_{\mathrm{OH}}^{\mathrm{M}_i}$	Overhead duration due to preempted frames of M_i
Δt_{ST}	time slots reserved for ST traffic

where Δt^-, Δt^+, and Δt^0 are the accrued length of all periods where the credit is decreasing, increasing, and frozen, respectively. For the preemption mode with HOLD/RELEASE, $\Delta t^- = \Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}$ represents the transmission duration of AVB Class M_i and the extra overhead transmission time when frames of Class M_i traffic are preempted by ST (express) traffic, $\Delta t^0 = \Delta t_{\mathrm{ST}}$ is caused by ST traffic windows. Then we have

$$\Delta t^+ = \Delta t - \Delta t_{\mathrm{M}_i} - \Delta t_{\mathrm{OH}}^{\mathrm{M}_i} - \Delta t_{\mathrm{ST}}. \tag{2}$$

The service curve for AVB traffic is defined by the CBS mechanism [8]. Similar to [8], the credit $c_{\mathrm{M}_i}(t)$ of AVB Class M_i increases with slope $\mathrm{idSl}_{\mathrm{M}_i}$ when there is a frame waiting in queue Q_{M_i} (during Δt^+ when high-priority frames in $Q_{\mathrm{M}_j} \in Q_{\mathrm{AVB}}^{<i}$ are transmitted, or guard band blocking due to preemption with HOLD/RELEASE etc.), and decreases at rate $\mathrm{sdSl}_{\mathrm{M}_i} = \mathrm{idSl}_{\mathrm{M}_i} - \mathrm{C}$ when the frame in the queue Q_{M_i} is being sent (during $\Delta t^- = \Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}$). The credit $c_{\mathrm{M}_i}(t)$ of AVB Class M_i remains frozen when the gate of Q_{M_i} is closed during ST traffic transmission. Due to the definition of s, for $\forall u \in (s, t]$, the queue Q_{M_i} cannot be temporarily empty when $c_{\mathrm{M}_i}(u) > 0$. Thus, there is no case in which the credit of AVB Class M_i can be reduced from some positive value P to 0 due to resets. Then the variation of credit for AVB Class M_i during the time interval $\Delta t = t - s$ can be given by,

$$c_{\mathrm{M}_i}(t) - c_{\mathrm{M}_i}(s) = (\Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}) \cdot \mathrm{sdSl}_{\mathrm{M}_i} - (t - s - \Delta t_{\mathrm{M}_i} - \Delta t_{\mathrm{OH}}^{\mathrm{M}_i} - \Delta t_{\mathrm{ST}}) \cdot \mathrm{idSl}_{\mathrm{M}_i},$$

Thus, for the preemption mode with HOLD/RELEASE, the relation of service times for AVB Class M_i, ST traffic windows occupancy, guard bands and preemption overheads in any interval Δt is

$$\Delta t_{\mathrm{M}_i} = \big[(t - s - \Delta t_{\mathrm{ST}})\mathrm{idSl}_{\mathrm{M}_i} - C \cdot \Delta t_{\mathrm{OH}}^{\mathrm{M}_i} - c_{\mathrm{M}_i}(t) + c_{\mathrm{M}_i}(s)\big]/C. \tag{3}$$

Moreover, the output of ST traffic during $\Delta t = t - s$ is,

$$\begin{aligned} R_{\mathrm{ST}}^{*\mathrm{h}}(t) - R_{\mathrm{ST}}^{*\mathrm{h}}(s) = R_{\mathrm{ST}}^{*\mathrm{h}}(t) - R_{\mathrm{ST}}^{\mathrm{h}}(s) = C \cdot \Delta t_{\mathrm{ST}} \\ \le R_{\mathrm{ST}}^{\mathrm{h}}(t) - R_{\mathrm{ST}}^{\mathrm{h}}(s) \le \alpha_{\mathrm{ST}}^{\mathrm{h}}(t - s), \end{aligned}$$

where $\alpha_{\mathrm{ST}}^{\mathrm{h}}(t)$ (see main paper) is the arrival curve of ST traffic scheduled according to GCL. Thus,

$$\Delta t_{\mathrm{ST}} \le \alpha_{\mathrm{ST}}^{\mathrm{h}}(t - s)/C. \tag{4}$$

Similar to [9], we can obtain

$$\Delta t_{\mathrm{OH}}^{\mathrm{M}_i} \le \alpha_{\mathrm{OH}}^{\mathrm{h},\mathrm{M}_i}(t - s)/C, \tag{5}$$

where $\alpha_{\mathrm{OH}}^{\mathrm{h},\mathrm{M}_i}(t)$ (see main paper) is the arrival curve of overheads due to the preemption mode.

The service could only be supplied for AVB traffic of class M_i during Δt_{M_i} in the time Δt^- when the credit is decreasing. Then, similar to [9], over the interval $(s, t]$, considering $c_{\mathrm{M}_i}(t) \le c_{\mathrm{M}_i}^{\max}$, $c_{\mathrm{M}_i}(s) = 0$, and Eqs. (3), (4), (5), we have

$$\begin{aligned} R_{\mathrm{M}_i}^{*\mathrm{h}}(t) - R_{\mathrm{M}_i}^{*\mathrm{h}}(s) = C \cdot \Delta t_{\mathrm{M}_i} \ge \\ \mathrm{idSl}_{\mathrm{M}_i} \left(t - s - \frac{\alpha_{\mathrm{ST}}^{\mathrm{h}}(t - s)}{C} - \frac{\alpha_{\mathrm{OH}}^{\mathrm{h},\mathrm{M}_i}(t - s) + c_{\mathrm{M}_i}^{\max}}{\mathrm{idSl}_{\mathrm{M}_i}} \right) \end{aligned}$$

Since we have also $R^{*h}_{M_i}(t) - R^{*h}_{M_i}(s) = R^{*h}_{M_i}(t) - R^{h}_{M_i}(s) \geq 0$ and $R^{*h}_{M_i}(t)$ is a wide-sense increasing function, from which we derive

$$R^{*h}_{M_i}(t) \geq R^{h}_{M_i}(s) + \mathrm{idSl}_{M_i}\left[t - s - \frac{\alpha^{h}_{ST}(t-s)}{C} - \frac{\alpha^{h,M_i}_{OH}(t-s) + c^{\max}_{M_i}}{\mathrm{idSl}_{M_i}}\right]^{+}_{\uparrow}$$
$$\geq \inf_{0\leq s\leq t}\left\{R^{h}_{M_i}(s) + \mathrm{idSl}_{M_i}\left[t - s - \frac{\alpha^{h}_{ST}(t-s)}{C} - \frac{\alpha^{h,M_i}_{OH}(t-s) + c^{\max}_{M_i}}{\mathrm{idSl}_{M_i}}\right]^{+}_{\uparrow}\right\}.$$

Therefore, for the preemption with HOLD/RELEASE, the service curve $\beta^{h,[PrH/R]}_{M_i}(t)$ for AVB Class M_i is,

$$\beta^{h,[PrH/R]}_{M_i}(t) = \mathrm{idSl}_{M_i}\left[t - \frac{\alpha^{h}_{ST}(t)}{C} - \frac{\alpha^{h,M_i}_{OH}(t) + c^{\max}_{M_i}}{\mathrm{idSl}_{M_i}}\right]^{+}_{\uparrow}.$$

■

3 Lemma 2 - Impact of overhead on the CBS credit

▶ **Lemma 2.** *For the preemption with HOLD/RELEASE mode, the impact of overhead is also reflected in the lower bound of credit compared with the non-preemption mode,*

$$c^{\min}_{M_i} = sdSl_{M_i}\cdot\frac{l^{h,\max}_{M_i}}{C} + n^{h,M_i}_{\mathrm{Pr}}\cdot\left(sdSl_{M_i}\cdot\frac{l_{OH}}{C} + idSl_{M_i}\cdot\frac{l^{\max}_{nPr}}{C}\right)\cdot\mathbb{1}_{\{idSl_{M_i}\cdot l^{\max}_{nPr} < -sdSl_{M_i}\cdot l_{OH}\}},\tag{6}$$

where n^{h,M_i}_{Pr} is the maximum number of preemptions for a single frame of Class M_i. The upper bound on the credit with non-frozen state during guard band is computed using the expression for the non-preemption mode proposed in [8],

$$c^{\max}_{M_i} = idSl_{M_i}\cdot\frac{\sum_{j=1}^{i-1} c^{\min}_{M_j} - l^{h,\max}_{>i} - \sigma^{h,M_i}_{GB}}{\sum_{j=1}^{i-1} idSl_{M_j} + \rho^{h,M_i}_{GB} - C}.\tag{7}$$

by replacing $c^{\min}_{M_j}$ with Eq. (6), and the guard band duration with $L^{h,M_i}_{GB,j}$ in Eq. (8) below for constructing the linear arrival curve of the guard band duration with the burst σ^{h,M_i}_{GB} and the rate ρ^{h,M_i}_{GB} [8].

The actual maximum guard band length before each ST window j is also related to the maximum frame $l^{h,\max}_{\leq i}$ of AVB traffic with priority higher than or equal to M_i in the current node port, and the idle interval time between two adjacent ST windows $o^{h}_{j,i} - o^{h}_{j-1,i} - L^{h}_{ST,j-1}$.

$$L^{h,M_i}_{GB,j} = \min\left\{L_{GB}, L_{GB} - \frac{l^{h,\min}_{\leq i}\cdot\mathbb{1}_{\{l^{h,\max}_{\leq i}\leq l^{\max}_{nPr}\}}}{C}, o^{h}_{j,i} - o^{h}_{j-1,i} - L^{h}_{ST,j-1}\right\}.\tag{8}$$

3.1 Proof of Lemma 2

Proof: The proof is very similar to the proof in [8] that assumes the non-frozen credit during guard bands, except that the additional overhead duration needs to be considered.

[Lower bound] The credit of AVB class M_i will be decremented only when the frame of Class M_i is being sent and during the overhead after the frame of Class M_i is preempted. Please note that when the frame is preempted, there will be a guard band with length L_{GB} reserved, and the credit of all AVB classes will be increased with the corresponding idleSlope. Therefore, the condition for reaching the minimum credit depends on the maximum frame size $l^{\mathrm{h,max}}_{\mathrm{M}_i}$ of Class M_i, the relation between the idleSlope and sendSlope, and the maximum number of times that a frame of Class M_i can be preempted.

The credit increases by $\mathrm{idSl}_{\mathrm{M}_i} \cdot l^{\max}_{\mathrm{nPr}}/C$ in a GB duration, and decreases by $-sdSl_{\mathrm{M}_i} \cdot l_{\mathrm{OH}}/C$ during an overhead duration. If $\mathrm{idSl}_{\mathrm{M}_i} \cdot l^{\max}_{\mathrm{nPr}} \geq -sdSl_{\mathrm{M}_i} \cdot l_{\mathrm{OH}}$, it means that the minimum credit can only be reached at the end of the maximum frame transmission without being preempted, i.e., $c^{\min}_{\mathrm{M}_i} = l^{\mathrm{h,max}}_{\mathrm{M}_i} \cdot sdSl_{\mathrm{M}_i}/C$. Otherwise, if $\mathrm{idSl}_{\mathrm{M}_i} \cdot l^{\max}_{\mathrm{nPr}} < -sdSl_{\mathrm{M}_i} \cdot l_{\mathrm{OH}}$, the minimum credit is reached when a maximum frame of Class M_i is preempted the most number of times. The highest number of preemption $n^{\mathrm{h,M}_i}_{\mathrm{Pr}}$ are related to the ST windows, which can be calculated according to the GCL that has been computed offline (see main paper). In such a case, the minimum credit equals to $c^{\min}_{\mathrm{M}_i} = (l^{\mathrm{h,max}}_{\mathrm{M}_i} + n^{\mathrm{h,M}_i}_{\mathrm{Pr}} \cdot l_{\mathrm{OH}}) \cdot sdSl_{\mathrm{M}_i}/C + n^{\mathrm{h,M}_i}_{\mathrm{Pr}} \cdot l^{\max}_{\mathrm{nPr}} \cdot \mathrm{idSl}_{\mathrm{M}_i}/C$.

[Upper bound] Let $t \in \mathbb{R}^+$ be a time instant at which the timed-gates for AVB traffic classes open, and $c_{\mathrm{M}_i}(t) > 0$. Additionally, let $s = \sup\{u \leq t \mid \forall Q_{\mathrm{M}_j} \in Q^{\leq i}_{\mathrm{AVB}}, c_{\mathrm{M}_j}(u) \leq 0\}$. As explained in [8], this implies that $\forall u \in (s,t]$, $\exists Q_{\mathrm{M}_j} \in Q^{\leq i}_{\mathrm{AVB}}$, $c_{\mathrm{M}_j}(u) > 0$, *i.e.*, there exists always a non-empty queue in $Q^{\leq i}_{\mathrm{AVB}}$, since otherwise, there is always another $s < s' \leq t$ that satisfies $\forall Q_{\mathrm{M}_j} \in Q^{\leq i}_{\mathrm{AVB}}, c_{\mathrm{M}_j}(s') \leq 0$. Since there is always at least one queue in $Q^{\leq i}_{\mathrm{AVB}}$ that is non-empty we have one of 3 cases for the frame:

- it it sent in $Q_{\mathrm{M}_j} \in Q^{\leq i}_{\mathrm{AVB}}$)
- it is blocked due to ST traffic or due to guard band relating to the preemption with HOLD/RELEASE. It can also be blocked due to a non-preemptive frame from lower priority queues ($Q^{>i}_{\mathrm{AVB}}$, Q_{BE}) that is in transmission before s since preemptable traffic classes cannot preempt each other (note that the lower priority traffic cannot be preempted by other higher priority AVB traffic but can be preempted by ST traffic))
- it waits for the transmission of additional overheads due to the preemption.

Similar to [8], we look at the evolution of the credit value $c_{\mathrm{M}_i}(t)$ between s and t, which increases with a rate of $\mathrm{idSl}_{\mathrm{M}_i}$ when the frame in the queue Q_{M_i} is waiting (during $\Delta t^{<i}_{\mathrm{AVB}} + \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} + \Delta t^{<i}_{\mathrm{OH}}$). The credit decreases at rate $sdSl_{\mathrm{M}_i} = \mathrm{idSl}_{\mathrm{M}_i} - C$ when the frame in the queue Q_{M_i} or its extra overhead is in transmission (during $\Delta t_{\mathrm{M}_i} + \Delta^{\mathrm{M}_i}_{\mathrm{OH}}$). Finally, the credit remains unchanged when the gate of Q_{M_i} is closed during ST traffic transmission Δt_{ST}, and, similarly to [8], may be reduced from some positive value P_{M_i} to 0 due to resets. Thus the variation of $c_{\mathrm{M}_i}(t)$ during $(s,t]$ is similar to [8], with the addition of the preemption overhead considerations,

$$\begin{aligned} c_{\mathrm{M}_i}(t) - c_{\mathrm{M}_i}(s) = &\left(\Delta t_{\mathrm{M}_i} + \Delta t^{\mathrm{M}_i}_{\mathrm{OH}}\right) \cdot sdSl_{\mathrm{M}_i} \\ &+ \left(\Delta t^{<i}_{\mathrm{AVB}} + \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} + \Delta t^{<i}_{\mathrm{OH}}\right) \cdot \mathrm{idSl}_{\mathrm{M}_i} - P_{\mathrm{M}_i}. \end{aligned} \tag{9}$$

Since $\Delta t^{<i}_{\mathrm{AVB}} + \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} + \Delta t^{<i}_{\mathrm{OH}} = s - t - \Delta t_{\mathrm{M}_i} - \Delta t_{\mathrm{ST}} - \Delta t^{\mathrm{M}_i}_{\mathrm{OH}}$ and $P_{\mathrm{M}_i} \geq 0$, Eq. (9) is modified into,

$$c_{\mathrm{M}_i}(t) - c_{\mathrm{M}_i}(s) \leq -\Delta t_{\mathrm{M}_i} \cdot C - \Delta t^{\mathrm{M}_i}_{\mathrm{OH}} \cdot C + (t - s - \Delta t_{\mathrm{ST}}) \cdot \mathrm{idSl}_{\mathrm{M}_i}. \tag{10}$$

As in [8], we denote the sum of credits for AVB traffic with the priority higher than M_i with $c_{<i}(t) = \sum_{j=1}^{i-1} c_{\mathrm{M}_j}(t)$. At any instant between s and t, $c_{<i}(t)$ increases at most at a rate

given by $\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j}$ when, as described in [8], a frame of M_i uses the link (during Δt_{M_i}), a low priority frame blocks the link (during Δt_{LP}), or during GB Δt_{GB}. Additionally to [8], the credit sum can also increase during the overhead $\Delta t_{\mathrm{OH}}^{\mathrm{M}_i}$ for M_i traffic. Conversely, the credit sum $c_{<i}(t)$ decreases at least at a rate given by $\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} - C$ when higher-priority frames are sent (during $\Delta t_{\mathrm{AVB}}^{<i}$) or during overhead $\Delta t_{\mathrm{OH}}^{<i}$ for AVB class with higher priority than M_i. Finally, the credit sum $c_{<i}(t)$ is frozen during ST traffic transmission Δt_{ST} or is reduced from some positive value to 0 due to resets, which is the same case as the credit variation for the M_i traffic class. Then, similar to [8] but with the additional overhead considerations, the variation of $c_{<i}(t)$ between s and t is

$$\begin{aligned} &c_{<i}(t) - c_{<i}(s) \\ &\quad = \left(\Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}\right) \cdot \sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} \\ &\quad + \left(\Delta t_{\mathrm{AVB}}^{<i} + \Delta_{\mathrm{OH}}^{<i}\right) \cdot \left(\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} - C\right) + \sum_{j=1}^{i-1} P_{\mathrm{M}_j} \end{aligned} \tag{11}$$

Since $\Delta t_{\mathrm{AVB}}^{<i} + \Delta t_{\mathrm{OH}}^{<i} = s - t - \Delta t_{\mathrm{M}_i} - \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} - \Delta t_{\mathrm{OH}}^{\mathrm{M}_i} - \Delta t_{\mathrm{ST}}$ and $P_{\mathrm{M}_j} \geq 0$, Eq. (11) is modified into,

$$\begin{aligned} c_{<i}(t) - c_{<i}(s) \leq &\left(\Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{LP}} + \Delta t_{\mathrm{GB}} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}\right) \cdot C \\ &+ (t - s - \Delta t_{\mathrm{ST}}) \cdot \left(\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} - C\right). \end{aligned} \tag{12}$$

Moreover, as discussed in [8], $\Delta t_{\mathrm{LP}} \cdot C \leq \max_{j \in [i+1, n_{\mathrm{CBS}}^h]} \{l_{\mathrm{M}_j}^{\max}, l_{\mathrm{BE}}^{\max}\} = l_{>i}^{\max}$ and $\Delta t_{\mathrm{GB}} \cdot C \leq \sigma_{\mathrm{GB}}^{\mathrm{M}_i} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} \cdot (t - s - \Delta t_{\mathrm{ST}})$, where $\sigma_{\mathrm{GB}}^{\mathrm{M}_i}$ and $\rho_{\mathrm{GB}}^{\mathrm{M}_i}$ are the burst and rate of the linear arrival curve of the guard band duration, respectively, derived from Theorem 3 and Lemma 4 in [8] by considering $L_{\mathrm{GB},j}^{h,\mathrm{M}_i}$ in Eq. (8) instead. Meanwhile combining Eq. (12) we have,

$$t - s - \Delta t_{ST} \leq \frac{c_{<i}(t) - c_{<i}(s) - (\Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}) \cdot C - l_{>i}^{\max} - \sigma_{\mathrm{GB}}^{\mathrm{M}_i}}{\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C}. \tag{13}$$

By applying Eq. (13) into Eq. (10), it is obtained that

$$\begin{aligned} &c_{\mathrm{M}_i}(t) - c_{\mathrm{M}_i}(s) \leq \\ &\quad - \frac{\sum_{j=1}^{i} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C}{\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C} \cdot (\Delta t_{\mathrm{M}_i} + \Delta t_{\mathrm{OH}}^{\mathrm{M}_i}) \cdot C \\ &\quad + \frac{c_{<i}(t) - c_{<i}(s) - l_{>i}^{\max} - \sigma_{\mathrm{GB}}^{\mathrm{M}_i}}{\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C} \cdot \mathrm{idSl}_{\mathrm{M}_i} \\ &\quad \leq \frac{c_{<i}(t) - c_{<i}(s) - l_{>i}^{\max} - \sigma_{\mathrm{GB}}^{\mathrm{M}_i}}{\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C} \cdot \mathrm{idSl}_{\mathrm{M}_i}. \end{aligned} \tag{14}$$

Since $c_{<i}(s) \leq 0$, $c_{\mathrm{M}_i}(s) \leq 0$, $\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C < 0$, and $c_{<i}(t) \geq \sum_{j=1}^{i-1} c_{\mathrm{M}_j}^{\min}$, we find that the extra overhead due to preemption does not have an impact on the expression of the upper bound for the credit, which remains the same as in [8], namely

$$c_{\mathrm{M}_i}(t) \leq \mathrm{idSl}_{\mathrm{M}_i} \cdot \frac{\sum_{j=1}^{i-1} c_{\mathrm{M}_j}^{\min} - l_{>i}^{\max} - \sigma_{\mathrm{GB}}^{\mathrm{M}_i}}{\sum_{j=1}^{i-1} \mathrm{idSl}_{\mathrm{M}_j} + \rho_{\mathrm{GB}}^{\mathrm{M}_i} - C}.$$

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