Using network calculus on worst-case latency analysis for TTEthernet in preemption transmission mode

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***Abstract*—Time-Triggered Ethernet (TTEthernet) improved from Avionics Full Duplex Switched Ethernet (AFDX) is supposed to enhance the determination by introducing time-triggered mechanism, while indeterminacy problem still exists in rate-constrained (RC) flows thus requiring worst-case latency analysis. Traditional network calculus model used for AFDX is not suitable for TTEthernet due to time-triggered (TT) flow mandatory competition for network resource. In this paper, we derive formula of traffic delay for RC flows in TTEthernet with intensive TT-schedule schema under the condition of preemption transmission mode, expand performance analysis scope to support multi-priority flows through assuming TT flow as the highest-priority RC flow when considering the pessimism of scheduling and verify the practicability of modified model by calculating its algorithmic complexity. Experiments show that our model gives effective latency upper bound which is slightly beyond exact value but no more than 16.7% and sustains rapid calculation for a real complicated network configuration within 3 seconds compared with other existing models.**

Keywords—TTE; worst-case latency; network calculus; priority scheduling; AFDX.

I. INTRODUCTION

Avionics Full Duplex Switched Ethernet (AFDX) is a communication network defined in ARINC644, Part 7 standard [1]. It eliminates access control indeterminacy of traditional Ethernet by using full-duplex Ethernet links, but causes delay indeterminism due to resource competition of asynchronous traffic flows at switch output ports [13]. In order to strengthen real-time performance guarantee, AFDX introduces concept of virtual links (VL) to realize logic isolation for traffic flows and statically configured switches of the network are capable of enhancing the forwarding assurance [9].

Furthermore, AFDX improves network resource utilization through traffic prioritization which is defined in configuration of VLs and provides scheduling support for flows with different quality of service (QoS) [5], [17]. However, it is difficult to realize collision free of transmission on AFDX because of event-triggered communication essence. Time-triggered communication minimizes such problem via synchronized time base and off-line designed schedule table. Consequently it can guarantee the determinacy of time-triggered messages and is suitable for applications with high criticality requirements [7], [20].

In order to support applications with different requirements and fully utilize network resource, Time-Triggered Ethernet (TTEthernet) classifies traffic flows into three traffic classes including time-triggered (TT) traffic, rate-constrained (RC) traffic as well as best-effort (BE) traffic [21], and can pre-configure static slots for TT traffic while using residue bandwidth between two TT frames for RC traffic. Moreover, RC traffic in TTEthernet inherits VL in AFDX thus needing end-to-end communication delay which is described as the sum of transmission delays on links and latencies in switches to achieve certification [4].

Network calculus theory has been successfully used for computing a safe upper bound of this end-to-end delay in AFDX [14], [22] thanks to the pioneering work of R. L. Cruz [15], [16]. Nevertheless, it is not appropriate for TTEthernet because of the instruction of TT traffic. Current models available for worst-case latency analysis in TTEthernet [11], [24] mainly focus on the porosity characteristic of TT-schedule without premeditating changes in transmission mode when meeting contentions and priority discrimination among the RC flows based on prioritization mechanism of switches in the network. Simultaneously, they are not suitable for real complicated configurations due to the combinatorial explosion problem existed in derivation of TT arrival curve.

The aim of this paper is to build appropriate models for multi-priority RC traffic by assuming TT traffic as highest-priority RC traffic which is proved reasonable with intensive TT-schedule under the condition of preemption transmission mode. Furthermore, we construct an illustrative small configuration to analyze the pessimism of the upper bound obtained in our models in comparison with current model results [12] which can be considered as exact computation. In addition, a large realistic configuration comparably sized with B787 [3] is designed to demonstrate the arithmetic capability and computation speed of modified models.

This paper is organized as follows. Section II presents background of study which contains AFDX, TTEthernet and network calculus theory. In section III and IV, we elaborate our modified worst-case latency analysis models under different

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RC priorities and then provide verification by experimental results in section V. Section VI comes to conclusion.

II. Background of Study

A. AFDX

AFDX is a switched Ethernet tailored for avionics requirements [13]. An example configuration of AFDX is depicted in Fig. 1. It is composed of eleven end systems (ES1 to ES 11) which are the inputs or outputs of the network and three switches (Sw1 to Sw3) interconnected by full-duplex links. Furthermore, each switch has no input buffer on input ports and one FIFO buffer for asynchronous flows on each output port. Each end system is connected to one switch port and each switch port is connected to at most one end system or another switch input port [1].

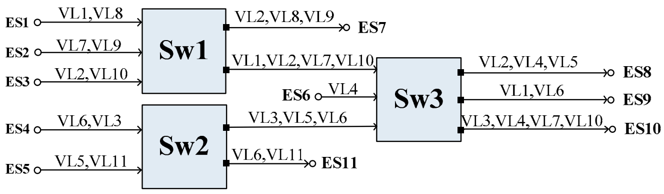

Fig. 1. An example configuration of AFDX

End systems exchange frames through Virtual Links (VL) which is statically defined from one source end system through several switches to one or more destination end systems. For example, VL2 is a multicast VL with path {ES3-Sw1-ES7} and {ES3-Sw1-Sw3-ES8}, while VL1 is a unicast VL with path {ES1-Sw1-Sw3-ES9} [4]. VL definition also includes Bandwidth Allocation Gap (*BAG*) which is the minimum interval between two consecutive frames of the VL, as well as the minimum and the maximum frame length.

To strengthen resource utilization and timeliness, AFDX introduces traffic prioritization mechanism, i.e. high-priority frame should be transmitted preferentially in the waiting queue, but its arrival will not preempt low-priority frame which is already in the process of transmission. Corresponding to this mechanism, switches in AFDX are capable of policing traffic flows based on two priority levels defined in configuration table of VL [1].

As an avionic network, AFDX has to be certified, which means it is mandatory to prove that end-to-end delay of each flow transmitted in the network is upper-bounded and guarantee that no frame will be lost because of buffer overflow [17].

B. TTEthernet

TTEthernet is an improved time-critical network developed from AFDX and can support applications with different requirements by classifying traffic flows into three traffic classes including TT flows, RC flows and BE flows, in which RC flows inherit VL in AFDX [18]. Fig. 2 shows an example configuration of TTEthernet.

TTEthernet uses remaining bandwidth between two statically pre-configured TT frame slots for asynchronous RC traffic flows and can be segmented into sparse network and intensive network according to the density of TT slots as shown in Fig. 3.

Fig. 2. An example configuration of TTEthernet

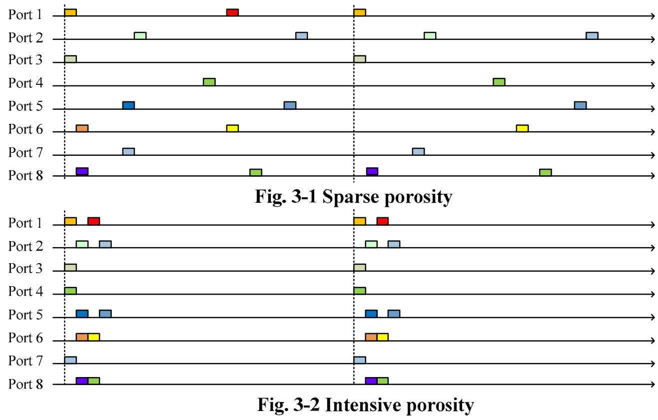

Fig. 3. Porosity of TT-schedule

Due to the introduction of synchronous clock and porosity concept, there exists competition in TTEthernet when a RC frame is already for transmission while encountering fixed slot of a TT frame, thus influencing the end-to-end latency for RC traffic flows. Three transmission modes [21], i.e. preemption, timely block and shuffling, are designed to describe this competition mechanism and illustrated in Fig. 4. Preemption means the RC frame can be preempted and relayed after the transmission of TT. In timely-block mode, even if the RC frame arrives before the next adjacent TT frame, it is constrained to wait as long as the idle time is insufficient for its transmission. Shuffling is the mode in which TT frame will be delayed until the transmission for RC is finished.

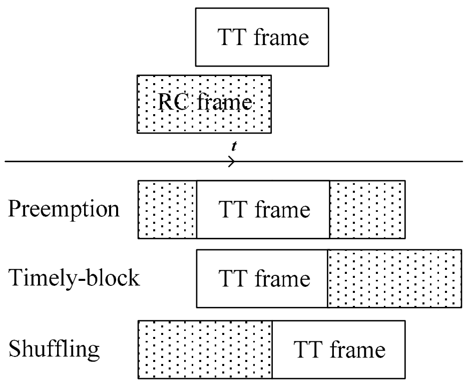

Fig. 4. Transmission modes between TT traffic and RC traffic

In this paper, we derive the upper bound of end-to-end latency for RC flows by considering TT traffic as highest-priority RC traffic, which means shifting the focus from the influence of TT schedule to traffic prioritization mechanism and practical engineering application, and use analysis results on an illustrative small TTEthernet in the intensive TT-schedule under the condition of preemption transmission mode as a reference for exact worst-case calculation.

C. Network Calculus Theory

Network calculus is a mature theory used for computation of delay upper bounds and buffer size in AFDX to achieve certification. The application of network calculus theory is based on arrival curve and service curve defined by means of min-plus convolution [10].

For a given flow compliant with input cumulative function $R(t)$ which represents the total data bits that arrived in the network element in time interval $[0, t]$, it is constrained by arrival curve $\alpha(t)$ if

$$R(t) \leq inf_{0\leq s\leq t}\{R(s) + \alpha(t-s)\} = (R\otimes\alpha)(t) \qquad (1)$$

where $\otimes$ is the notation of min-plus convolution. There are two archetypal arrival curve models, including affine arrival curve

$$\alpha_{\sigma,\rho}(t) = \begin{cases} \sigma + \rho t & t > 0 \\ 0 & t < 0 \end{cases} \qquad (2)$$

which allows a source end system to send σ *bits* at once but no more than ρ $bits/s$ over the long run, and stair arrival curve

$$\alpha_{T,\tau}(t) = \begin{cases} k \cdot \left\lceil \frac{t+\tau}{T} \right\rceil & t > 0 \\ 0 & t < 0 \end{cases} \qquad (3)$$

which is suitable for a periodic flow with period *T*, packet size *k* and one-point cell delay variation τ.

For a network element through which a flow transmits with input cumulative function $R(t)$ and output cumulative function $R^*(t)$, service curve $\beta(t)$ can be used to describe its processing capability of available resource, if

$$R^*(t) \geq inf_{0\leq s\leq t}\{R(s) + \beta(t-s)\} = (R\otimes\beta)(t). \qquad (4)$$

A typical service curve is rate-latency function given by

$$\beta_{R,T}(t) = R[t-T]^+ \qquad (5)$$

where parameter R, T represent service rate and service latency. Notably the notation $[x]^+$ is equal to x if $x \geq 0$ and 0 otherwise.

The latency experienced by the flow which is constrained by arrival curve $\alpha(t)$ traversing the network capable of offering service curve $\beta(t)$ is upper bounded by the maximum horizontal deviation between $\alpha(t)$ and $\beta(t)$ [5], and can be formulated as

$$D = sup_{s\geq 0}\{inf\{\tau \geq 0 | \alpha(s) \leq \beta(s+\tau)\}\}. \qquad (6)$$

III. Relationship between Preemption and Priority Transmission Modes

In AFDX, traffic flows are divided into two priority classes and transmitted compliance with priority transmission mode in which the service for high-priority flow can be delayed by low-priority flow that arrived shortly before it. As derivation in [10], the service curves for high-priority RC flow and low-priority RC flow are separately given by

$$\beta_H(t) = [Ct - l_{max}^L]^+ \qquad (7)$$

$$\beta_L(t) = [Ct - \alpha_H(t)]^+ \qquad (8)$$

where C equals physical link rate, l_{max}^L represents the maximum frame length of low-priority flow and $\alpha_H(t)$ is arrival curve for high-priority RC flows.

Nevertheless, priority transmission mode is not suitable for TTEthernet which integrates flows of three traffic classes (TT, RC and BE) onto a single physical network and complies with three different methods when there exists contention, which means a RC flow is already in transmission while a TT flow gets ready. These methods have been fully explained in section II part B and in this paper we mainly focus on preemption transmission mode which has corresponding technology support [19] since it is capable of improving network bandwidth utilization and reducing end-to-end delay for RC flows.

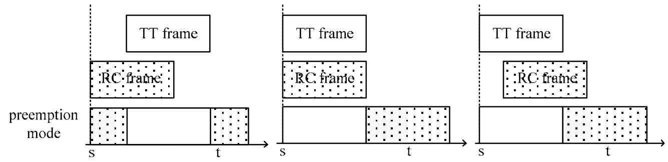

Fig. 5. Circumstances of preemption transmission mode

Different from priority mode, in preemption mode the RC frame can be preempted and relayed by TT flows even if it is already in transmission at node port *h* and the residue RC frame has to wait until the service for TT flow is finished. Fig. 5 illustrates three elementary contention circumstances that probably occur in TTEthernet under the condition of preemption transmission mode and they all submit to the following analysis. Using *s* to present the beginning of the server busy period, then all traffic flows arrived before *s* have been served completely and the backlogs for both TT flows and RC flows are empty at *s*, meaning

$$R_{RC}^*(s) = R_{RC}(s) \qquad (9)$$

$$R_{TT}^*(s) = R_{TT}(s) \qquad (10)$$

where $R_{TT}(s)$ and $R_{TT}^*(s)$ indicate input and output cumulative functions of TT flows, so as $R_{RC}(s)$ and $R_{RC}^*(s)$ for RC flows. Over an arbitrary interval $(s, t]$,

$$R_{RC}^*(t) - R_{RC}^*(s) = C(t-s) - [R_{TT}^*(t) - R_{TT}^*(s)]. \qquad (11)$$

Considering

$$0 \leq R_{TT}^*(t) - R_{TT}^*(s) = R_{TT}^*(t) - R_{TT}(s)$$
$$\leq R_{TT}(t) - R_{TT}(s) \leq \alpha_{TT}(t-s) \qquad (12)$$

then

$$R_{RC}^*(t) - R_{RC}(s) = R_{RC}^*(t) - R_{RC}^*(s)$$
$$\geq C(t-s) - \alpha_{TT}(t-s). \qquad (13)$$

Generally, there are more than one TT traffic flow traversing the node port *h* in accordance with their respective cycles, and Fig. 6 gives an intensive TT-schedule example using the arrival time of τ_{TT_1} as time basis point. Asynchronous RC flow may arrive at an arbitrary time and we only need to consider it in a hyper-period of all TT flows.

Cases 1-5 in Fig.6 are just combination of elementary contention circumstances, while case 6 needs separate theoretical analysis. Using s' to present the beginning of the last busy period for RC flow up to time *t*, and in time interval $(s', t]$, the RC flows can occupy all resources, then

$$\mathrm{R}^*_{\mathrm{RC}}(\mathrm{t}) - \mathrm{R}^*_{\mathrm{RC}}(\mathrm{s}) \geq \mathrm{C}(\mathrm{t}-\mathrm{s}) \geq \mathrm{C}(\mathrm{t}-\mathrm{s}) - \alpha_{\mathrm{TT}}(\mathrm{t}-\mathrm{s}). \quad (14)$$

Similar to the above derivation, we can get

$$\begin{aligned} R^*_{RC}(t) - R_{RC}(s) &= R^*_{RC}(t) - R^*_{RC}(s) \\ &\geq C(t-s) - \alpha_{TT}(t-s). \end{aligned} \quad (15)$$

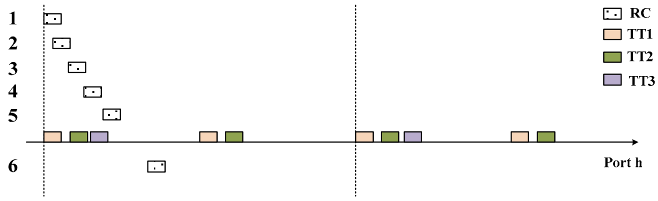

Fig. 6. An intensive TT-schedule example

As $[Ct - \alpha_{TT}(t)]^+$ is widely-increasing, it can be used as service curve for RC flows in TTEthernet under the condition of preemption transmission mode, and due to its compatibility with service curve for low-priority traffic flows in priority transmission mode, we can assume TT traffic flow as high-priority RC flow to analyze its impact on latency upper bounds for RC flows in TTEthernet. Obviously this assumption is pessimistic especially for TTEthernet with sparse TT-schedule or few RC flows, since there exists a condition that RC frame can be fully transmitted in the interval between two TT frames without encountering the next adjacent TT frame as shown in Fig. 7-1 while latency analysis based on the above assumption is conducted as Fig. 7-2, but this pessimism will be substantially reduced or even negligible with intensive TT-schedule which is the focal point of this paper.

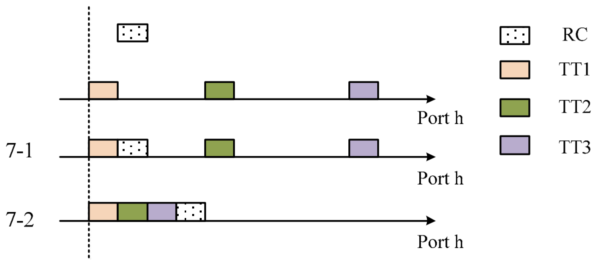

Fig. 7. A sparse TT-schedule or few RC flows example

IV. WORST-CASE LATENCY ANALYSIS FOR RC FLOWS

A. *Impact of aggregate TT flows*

Several worst-case latency analysis models based on network calculus theory have been successfully used to calculate upper bounds for end-to-end delay of traffic flows through VLs in the AFDX, and according to comparative analysis in section III, we can calculate upper bounds for RC flows in TTEthernet by assuming TT flows as highest-priority RC flows. In this section we will discuss the aggregate arrival curve of TT traffic to show its impact on the service of RC traffic.

TT traffic is appropriate for applications with high criticality requirements, and therefore needs to reserve enough time slots during the TT-schedule offline design. For an independent TT flow τ_{TT_i}, its frames are periodically transmitted through the network along its transmission path and the reserved segments are interval of the maximum TT frame length beginning from its maximum arrival times $\left(a_{l_{TT_i max}}\right)$ as shown in Fig. 8 [12].

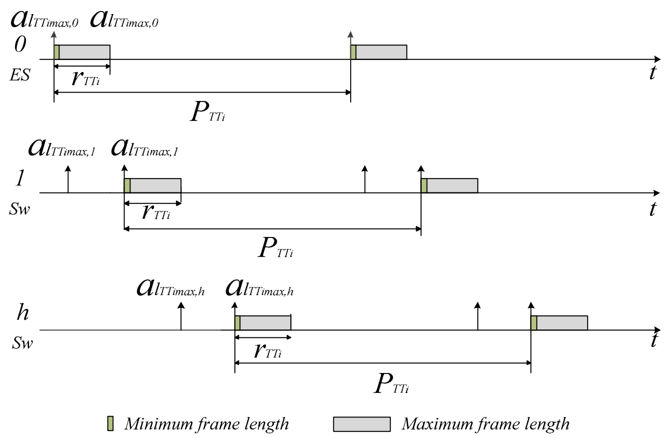

Fig. 8. Reserve form along TT transmission path

Since TT frames can only be served in reserved segments, the arrival curve of the independent TT flow τ_{TT_i} can be simplified as stair function

$$\alpha^{stair}_{TT_i,h}(t) = \begin{cases} l_{TT_i max} \cdot \left\lceil \frac{t}{p_{TT_i}} \right\rceil, & t > 0 \\ 0, & t \leq 0 \end{cases} \quad (16)$$

where *h* represents an arbitrary node port along its transmission path. In order to improve speed and efficiency of the analysis process for large realistic network, the arrival curve can be slightly loosened to piecewise linear function

$$\alpha^{linear}_{TT_i,h}(t) = \begin{cases} l_{TT_i max} + l_{TT_i max} \cdot \frac{t}{p_{TT_i}}, & t > 0 \\ 0, & t \leq 0 \end{cases} \quad (17)$$

as shown in Fig. 9.

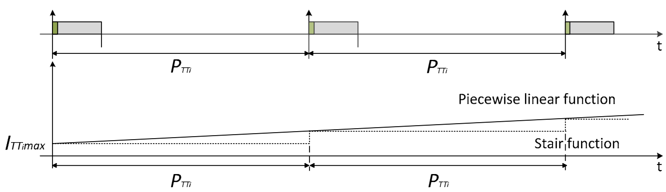

Fig. 9. Arrival curve of an independent TT flow

Proof:

The total frames of τ_{TT_i} traversing an arbitrary node port *h* during an arbitrary interval $(s, t]$ should not exceed

$$N_{TT_i,h} = \left\lceil \frac{t-s}{p_{TT_i}} \right\rceil. \quad (18)$$

Assuming $R_{TT_i,h}(t)$ represents the input cumulative function of τ_{TT_i} in node port *h*, we will have

$$R_{TT_i,h}(t) - R_{TT_i,h}(s) \le l_{TT_i max} \cdot N_{TT_i,h} = l_{TT_i max} \cdot \left\lceil \frac{t-s}{p_{TT_i}} \right\rceil$$
$$\le l_{TT_i max} + l_{TT_i max} \cdot \frac{t-s}{p_{TT_i}} = \alpha_{TT_i,h}(t-s) \qquad (19)$$

thus the piecewise linear function can be arrival curve for independent TT flow τ_{TT_i}.

This piecewise linear function is identical to the (σ, ρ) arrival curve for traffic flows transmitted through AFDX by setting parameter σ, ρ to $l_{TT_i max}, l_{TT_i max}/p_{TT_i}$, and from this perspective we could think of TT traffic as highest-priority RC traffic just sent in a collision-free way [21] while still different from ordinary RC flows since its burst tolerance remains along the transmission path which is inconsistent with traditional network calculus theory but beneficial to latency analysis for RC flows due to avoiding indeterminism of TT flows. On this basis, the arrival curve for aggregate TT flows through the same node port *h* is given by

$$\alpha_{TT,h}(t) = \sum_{\tau_{TT_i} \in h} \alpha^{\text{linear}}_{TT_i,h}(t)$$
$$= \sum_{\tau_{TT_i} \in h} l_{TT_i max} + \sum_{\tau_{TT_i} \in h} \frac{l_{TT_i max}}{p_{TT_i}} \cdot t \qquad (20)$$

for $t > 0$ and *0* otherwise. This simplification generates pessimism apparently due to ignorance of guaranteed temporal regularity in TTEthernet but will considerably expand computing scale and suit practical network configuration, which will be illustrated in section IV.

B. Worst-case latency analysis for RC flows

In this section, we will use network calculus theory to analyze worst-case latency for multi-priority RC flows [5]. Firstly, we calculate remaining service for aggregate RC flows in preemption transmission mode at the node output port *h*. Assume that *C* is physical link rate for the output port *h* and $\alpha_{TT,h}(t)$ is the aggregate TT flow arrival curve at *h*, and then the service curve for aggregate RC flows at *h* is given by

$$\beta_{RC,h}(t) = \left[Ct - \alpha_{TT,h}(t)\right]^+ \qquad (21)$$

which is proved in section III. Furthermore, RC flows are divided into different priority levels according to real-time requirements in TTEthernet which is similar to VLs in AFDX and also inherits prioritization mechanism of switches from AFDX, therefore the service curve for aggregate high-priority RC flows at *h* is given by

$$\beta^H_{RC,h}(t) = \left[\beta_{RC,h}(t) - \max_{\tau^L_{RC_i} \in h}\left\{l_{RC_i max}\right\}\right]^+ \qquad (22)$$

where $l_{RC_i max}$ represents maximum frame length of τ_{RC_i}, and the service curve for aggregate low-priority RC flows which are transmitted under the pressure of TT flows and high-priority RC flows is given by

$$\beta^L_{RC,h}(t) = \left[\beta_{RC,h}(t) - \alpha^H_{RC,h}(t)\right]^+ \qquad (23)$$

where $\alpha^H_{RC,h}(t)$ represents the arrival curve for aggregate high-priority RC flows.

Secondly, we calculate arrival curve for aggregate RC flows at node output port *h*. Since RC flow τ_{RC_i} whether high-priority or low-priority is limited at the source end system by its Bandwidth Allocation Gap (BAG_{RC_i}), which is the minimum delay between two consecutive frames of τ_{RC_i}, as well as the maximum frame length $l_{RC_i max}$, the arrival curve for τ_{RC_i} is

$$\alpha_{RC_i,0}(t) = l_{RC_i max} + \frac{l_{RC_i max}}{BAG_{RC_i}} \cdot t. \qquad (24)$$

At later node port h along its transmission in the network, the arrival curve $\alpha_{RC_i,h}(t)$ can be calculated from its prior arrival curve $\alpha_{RC_i,h-1}(t)$ in accordance with

$$\alpha_{RC_i,h}(t) = \alpha_{RC_i,h-1}\left(t + D_{RC_i,h-1}\right) \qquad (25)$$

where $D_{RC_i,h-1}$ represents its delay at node port $(h-1)$ [8]. Considering there are several RC flows with different priorities traversing h asynchronously, respective arrival curve for aggregate high-priority RC flows and low-priority flows are given by

$$\alpha^H_{RC,h}(t) = \sum_{\tau^H_{RC_i} \in h} \alpha^H_{RC_i,h}(t) \qquad (26)$$

$$\alpha^L_{RC,h}(t) = \sum_{\tau^L_{RC_i} \in h} \alpha^L_{RC_i,h}(t). \qquad (27)$$

Finally, according to network calculus theory the latency for τ_{RC_i} at an arbitrary port h is upper bounded by the maximum horizontal deviation between $\alpha(t)$ and $\beta(t)$, and can be formulated as

$$D_{RC_i,h} = \sup_{s \ge 0}\left\{\inf\{\tau \ge 0 | \alpha_{RC,h}(s) \le \beta_{RC,h}(s+\tau)\}\right\}. \qquad (28)$$

The worst-case end-to-end latency for τ_{RC_i} is the sum of delays from the source end system to destination end system along its transmission path, and is given by

$$D_{RC_i} = (n-1) \cdot t_{tech} + \sum_h D_{RC_i,h} \qquad (29)$$

Where n is the total number of node ports including end systems and switches τ_{RC_i} traverses through and t_{tech} is the technical delay in each switch [11].

V. EXPERIMENTAL EVALUATION AND ANALYSIS

In this section, we experiment to verify correctness and advantage of the modified model.

A. An illustrative small configuration

The topology used in this example is illustrated in Fig. 2, which includes 11 end systems, 3 switches, 11 RC flows and 15 TT flows. The transmission speed on all physical links is $100Mbps$ and the technical delay in each switch is upper-bounded by a definite value $16\mu s$. RC flows are divided into two priority classes and limited by the maximum frame length $\left(l_{RC_i max} = 1518\, bytes\right)$ and bandwidth allocation gap $\left(BAG_{RC_i}\right)$ as shown in TABLE I (a). TT flows are limited by transmission period $\left(p_{TT_i}\right)$ and the frame length $\left(l_{TT_i min} = 64\, bytes\ and\ l_{TT_i max} = 1518\, bytes\right)$ as shown in TABLE I (b). Since TT flows are transmitted with high periodicity, we only give the initial arrival time of different TT flows in source end systems as shown in TABLE I (c) from which the whole TT-schedule can be deduced.

We have developed a tool to automatically calculate the latencies for RC flows in the TTEthernet and obtain the analysis results of this example on the calculation tool. Since traditional models available for worst-case latency analysis in TTEthernet make no allowance for prioritization in RC flows, we firstly give the results by assuming that all RC flows are at the same priority, and compare our latency bounds with the experiment results proposed by [12] in intensive TT-schedule and preemption transmission mode which can be considered as a reference for exact worst-case calculation in TTEthernet, as shown in Fig. 10.

TABLE I

(a) Priorities and BAGs of RC flows

RC Label	1	2	3	4	5	6	7	8	9	10	11
Priority	H	L	L	L	H	H	L	L	H	H	L
BAG (ms)	2	32	2	16	8	4	32	4	4	8	2

(b) Periods of TT flows

Label	1	2	3	4	5	6	7	8
Period (ms)	8	8	4	16	8	4	2	6
Label	9	10	11	12	13	14	15	
Period (ms)	4	4	4	4	4	4	4	

(c) Arrival time of TT flows

Node port	ES1		ES2		ES3		
TT label	1	13	10	4	5	7	15
Time (ms)	0	121.44	121.44	242.88	0	242.88	364.32

Node port	ES4				ES5		ES6	
TT label	8	14	12	6	9	2	3	11
Time (ms)	0	121.44	242.88	364.32	121.44	242.88	0	242.88

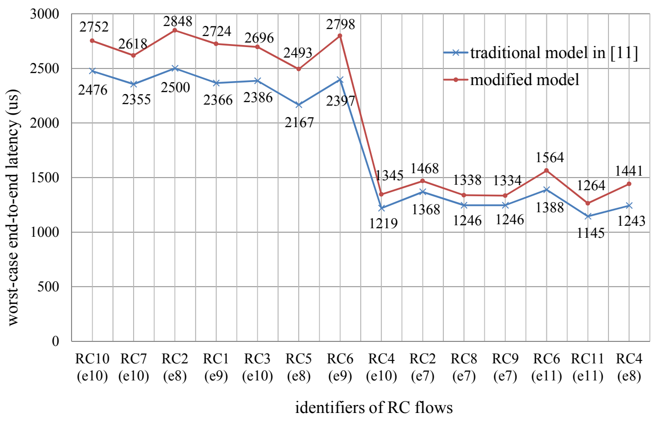

Fig. 10. Compared latency bounds of RC flows without prioritization mechanism respectively in traditional model [12] and modified model

In Fig.10, the maximum difference between two models is equal to 16.7% and all the exact results locate below results calculated from our modified model, meaning it provides efficient upper bounds for RC flows in TTEtherent which can illuminate the correctness of our results.

Then, taking into consideration the fact that RC flows are in different priorities, we can obtain analysis results and add it to the comparison figure as shown in Fig. 11. Since in prioritization mechanism high-priority RC flows get earliest opportunity to export at output ports, the end-to-end latency bounds for them are lower than those without prioritization at the expense of delay increase for low-priority RC flows which also reflect a balance of configuration for multi-priority RC flows. We can detect that experimental results correspond with theoretical investigation.

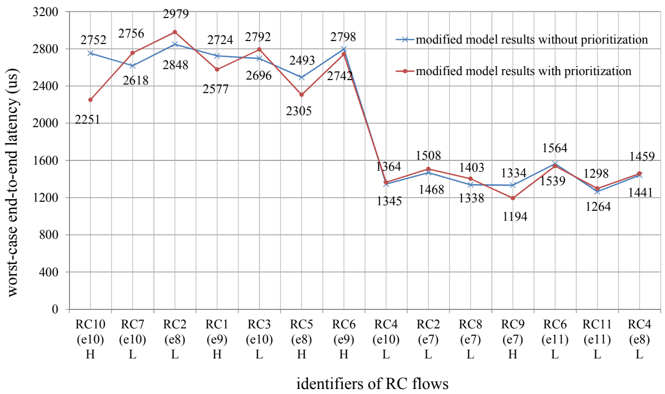

Fig. 11. Compared latency bounds of RC flows respectively in modified model

B. *A large realistic configuration*

Traditional model is able to compute the extremely accurate worst-case latency for RC flows but at a very high computational expense and only supports a limited number of traffic flows. As it pays much attention to porosity character in TT traffic flows and intends to calculate subtle arrival curve for TT flows, this algorithm costs $O\left(n_{Sw}\left(n_{TT}^2\, log_2\, n_{TT} + n_{RC}\right)\right)$ time which is relavant to the number of TT flows n_{TT}, RC flows n_{RC} and switches n_{Sw}, and consequently its algorithmic compexity inevitably increases sharply along with the increase of computing scale. In this perspective, it is not suitable for real industrial configurations with numerous traffic flows. However, modified algorithm only costs $O\left(n_{Sw}\left(n_{TT} + n_{RC}\right)\right)$ time, indicating that modified algorithm has lower complexity and higher speed and meets the actual needs of realistic applications which may include 1000 traffic flows or more.

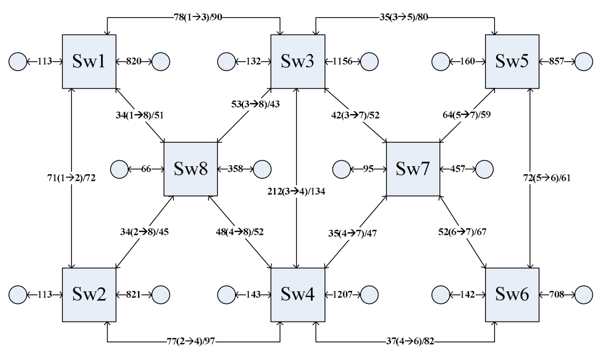

Fig. 12. Network topology in A380

It is obvious that our model is pessimistic meaning it can calculate a safe upper bound for RC flows, but yields unnecessary high upper bounds since time assurance mechanism in TTEthernet based on offline TT-schedule is not taken into account, thus the purpose of this example is not on the accuracy of our technique. Our objective is to highlight that our model is practicable to analysis the realistic systems illustrated by examples based on B787 network topology which includes 16 end systems and 8 switches [3].

We have analyzed this example and obtained calculation results within *3 seconds* on an I*ntel Core i5 CPU* at *3.20 GHz*. The end-to-end latency distribution of this example calculated from our prototype tool is shown as Fig. 13 in which horizontal coordinate axis represents possible end-to-end latency in terms of millisecond and vertical coordinate axis represents the percentage of RC flows whose latency is in the vicinity of corresponding value, and the result corresponds with theoretical analysis of transmission path and congestion for RC flows.

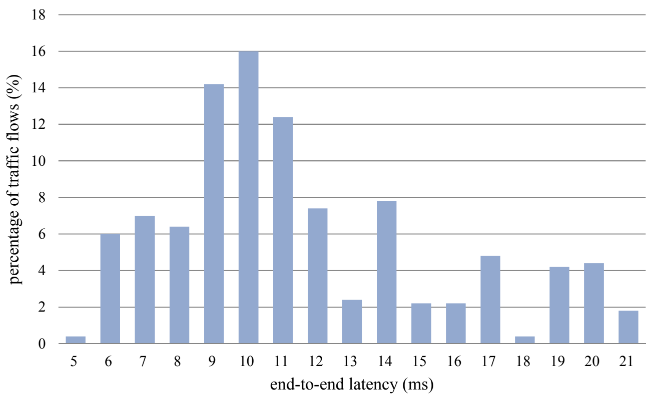

Fig. 13. End-to-end latency distribution

VI. CONCLUSION

In this paper, we present a modified model of worst-case latency analysis for RC flows in TTEthernet comprehensively considering the introduction of TT flows and prioritization mechanism in RC flows. Unlike current models which mainly focus on the influence of TT-schedule and porosity concept, our model pays more attention to preemption transmission mode in TTEthernet, traffic prioritization mechanism in RC flows and practical engineering application in realistic network. The main advantage of our model is that it gives rapid and efficient computation for enormous examples.

Prototype tool has been exploited to assist us in model checking and analysis results obtained by this tool for large network configuration can demonstrate the computation capacity, calculation correctness and actual scalability of the model.

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