Work In Progress Paper: Pessimism analysis of Network Calculus approach on AFDX networks

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***Abstract*—Worst-case delay analysis of real-time networks is mandatory, since distributed real-time applications require bounded end-to-end delays. Switched Ethernet technologies have become popular solutions in the context of real-time systems. Several approaches, based on Network Calculus, trajectories, ..., have been proposed for the worst-case analysis of such technologies. They compute pessimistic upper bounds of end-to-end delays. Since this pessimism leads to an over-dimensioning of the network, it is important to quantify the pessimism of the computed upper bounds. In this paper, we propose such a pessimism analysis, based on Network Calculus. In a first step we focus on avionics switched Ethernet network (AFDX) with Fixed Priority/First In First Out (FP/FIFO) scheduling.**

I. Introduction

Real-time distributed applications have to respect timing constraints such as bounded end-to-end latency and jitter. It means that communication delays between tasks running on different nodes have to be upper bounded. Thus the communication technologies used for node interconnection have to provide such guarantees on delays.

Switched Ethernet technologies, such as AFDX, TTEthernet, Ethernet-AVB and TSN, have become popular solutions for this interconnection. Indeed, they provide high bandwidth. However, switched Ethernet is not deterministic, since, in the general case, contention on output ports can lead to unpredictable delays and/or buffer overflow. Therefore, features are added in order to master the delay. For instance, each flow transmitted on an AFDX network has an upper bounded bandwidth, thanks to the concept of virtual link.

Based on such assumptions, a lot of work has been devoted to the worst-case delay analysis of switched Ethernet. Computing the exact worst-case delay is most of the time impossible for realistic network configurations with hundreds of flows. Therefore approaches such as Network Calculus (NC) or Trajectories have been proposed. They compute a sure, but often pessimistic upper bound for the delay of each flow. This pessimism leads to an over-dimensioning of the network architecture, since those pessimistic upper bounds have to be smaller than the maximum allowed latencies. Thus evaluating to what extent those sure upper bounds are pessimistic is an important problem.

This kind of evaluation has been addressed in the literature. For instance, in [1], the pessimism of both NC and Trajectories is upper bounded in the context of industrial AFDX configurations, thanks to the simulation of unfavorable scenarios. Those existing pessimism evaluation are specific to a given service discipline and/or an applicative context (FIFO scheduling of avionic flows in [1]).

Thus our goal is to propose a generic approach for pessimism evaluation of worst-case delay analysis of real-time switched Ethernet networks.

This paper is a first step towards this goal. We consider AFDX network implementing FP/FIFO scheduling. The starting point is the well-know NC approach which is used to upper-bound end-to-end delays on typical aircrafts, such as A380 or A350. We illustrate the sources of pessimism of this NC approach. Then, we propose a modified "Network Calculus like" computation which removes all the pessimism, but might introduce some optimism. Thus this computation gives an under-estimation of the worst-case delay. The difference between this under-estimation and the over-estimation computed by the NC approach gives an over-estimation of the pessimism of the NC approach.

II. Network and flow model

Avionics Full DupleX Switched Ethernet (AFDX) standard defines the electrical and protocol specifications (IEEE 802.3 and ARINC 664, Part 7) [2] for the exchange of data between Avionics Subsystems. It provides a higher bandwidth, typically 100 $Mbits/s$, as compared to field buses like ARINC 429 and it has become the de facto standard for avionics communications. An AFDX network architecture is composed of end systems interconnected by AFDX switches through full-duplex links. Flows are defined as virtual links (VL) with a minimum inter-frame duration a.k.a. bandwidth allocation gap (BAG) and a maximum frame size (Smax). Altogether it determines the maximum bandwidth allocated to each VL. The AFDX switch uses static routing configurable table and store-and-forward mechanism. Each output port of a switch or an end system has a set of buffers supporting a scheduling policy. Two scheduling policies are considered for AFDX networks: First-In-First-Out (FIFO) which serves frames based on their arrival times as well as Fixed Priority/First-In-First-Out (FP/FIFO) which serves frames based, first on priorities, second on arrival times for frames with the same priority. In commercial AFDX switches, two priority levels are available: high (H) and low (L). In this work, we consider the FP/FIFO scheduling. FIFO scheduling can be considered as a special case of FP/FIFO scheduling when all VLs have the same priority.

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An example AFDX configuration is shown in Figure 1. Three AFDX switches interconnect seven AFDX end systems via full duplex links. Five VLs are transmitted.

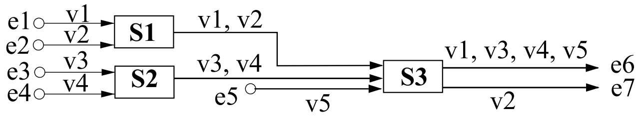

Fig. 1. AFDX Configuration

III. Pessimistic Network Calculus computation

The Network Calculus (NC) theory is based on the (min, +) algebra. It has been proposed for worst-case backlog and delay analysis in networks and it has been applied to avionics networks [3], wireless sensor networks [4], networks on chip [5] and server on Internet [6]. The general idea is to over-approximate flows by arrival curves and to under-approximate network elements by service curves. Worst-case delays and backlogs are obtained by applying convolution and deconvolution operators on these curves. We now illustrate NC modelling and computation on the AFDX configuration in Figure 1.

Figure 2 (a) shows the actual arrival data bits of VL v_1 at its source end system (red solid line). x-axis represents time while y-axis is the number of bits to be transmitted. First frame is released at $t = 0$, leading to a burst of 4000 bits (v_1 frame size). Then, the number of bits to be transmitted doesn't increase till v_1 BAG (4 ms), when a second v_1 frame is released, leading to 4000 more bits. In NC, such an arrival process is modelled by an arrival curve $\alpha_i^{e_x}(t) = rt + b$ for $t > 0$ and 0 otherwise. The source end system e_x sends a frame of a VL v_i of $b = Smax_i$ bits at once with a maximum transmission rate of $r = \frac{Smax_i}{BAG_i}\ Mbits/s$. This curve is shown with dotted line in the Figure 2 (a). Such a model over-estimates the number of arrived bits, except at the instants when a frame is released.

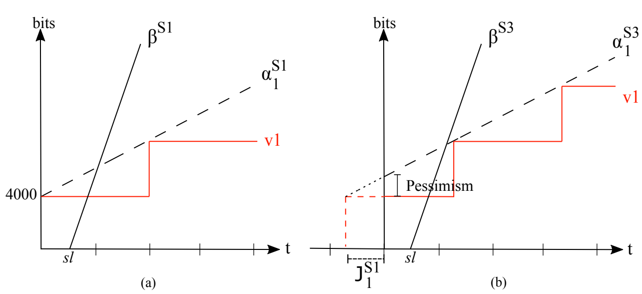

Fig. 2. Illustration of jitter integrated in arrival curve

According to [7], the service provided at a switch output port h with a transmission rate of R $(bits/s)$ is defined by $\beta^h(t) = R[t - sl]^+$, where sl is the switching latency of the switch. Such a curve is depicted in Figure 2. Frames wait sl before being ready for transmission. Then, they are transmitted at the speed of the link. When FP/FIFO scheduling is considered, the available service is shared by the different priority levels. Let's assume two levels (the AFDX case). The service curve for higher-priority VLs is $\beta_H^h(t) = \beta^h(t) - L$ where L is the size in bit of the largest lower-priority frame sharing this output port. The only impact of lower priority VLs on higher priority ones is due to non preemption. The service curve for lower-priority VLs is $\beta_L^h(t) = \beta^h(t) - \alpha_H^h(t)$ where $\alpha_H^h(t)$ is the sum of arrival curves of all higher-priority VLs at the output port h. It models the fact that lower priority frames are delayed by all pending higher priority frames.

Based on the arrival curves of VLs at their source end systems and the service curves of network elements, arrival curves of VLs at following hops in their path are computed. They are obtained by integrating the jitter experienced by VLs in each network element. This jitter is the difference between the worst-case delay and the best-case one. The best-case delay is classically obtained by considering that there is no waiting time in buffers.

The worst-case delay experienced by a VL of a given priority in a given output port is obtained by computing the maximum horizontal difference between the cumulative curve $\alpha(t)$ of traffic with same priority level crossing this output port (sum of arrival curves) and the service curve $\beta(t)$ offered by the output port to this priority level:

$$h(\alpha, \beta) = \sup_{s \geq 0}(\inf\{\tau \geq 0 | \alpha(s) \leq \beta(s + \tau)\})$$

Jitter introduction in arrival curves is illustrated in Figure 2. Highest possible jitter impact on actual arrival curve is obtained when first frame (at $t = 0$) experiences worst-case delay while following frames experience best-case delay. It comes to consider that the two first frames are as close as possible (smallest possible first step). Network calculus models such an arrival process by shifting the initial arrival curve to the left, as depicted in Figure 2 (b). It introduces pessimism, since the burst at time 0 is increased, leading to a larger horizontal difference between arrival and service curves.

An improvement was proposed in [3] by considering the fact that frames transmitted from the same input link are serialized and they cannot arrive at the output port at the same time. This physical constraint is called frame serialization. Consider the example in Figure 1, frames of VLs v_3 and v_4 are serialized at the output port of switch S_2 and then they cannot arrive at the output port of switch S_3 at the same time. Thus summing their arrival curves leads to a burst with two frames (one from v_3, one from v_4), which is impossible. Therefore [3] builds the overall arrival curve by considering that the burst is the largest frame between v_3 and v_4 and the other frame is received at the speed of the input link. Readers can refer to [3] for more details.

IV. Network Calculus pessimism analysis

A. Pessimism in NC approach

As explained in previous section, arrival curves as built by network calculus introduce pessimism for two reasons. First, at source node, the number of arrived bits is most of the time over-estimated. Second, jitter modelling at following nodes increases burst.

Pessimistic arrival curves have an impact on service curves. Indeed, arrival curves of higher priority VLs are removed from the service offered to lower priority VLs. As soon as arrival curves are over-estimated, the service for lower priority VLs is underestimated.

Let's illustrate the pessimism using the example in Figure 1. VL parameters are summarized in Table I. Both FIFO and FP/FIFO scheduling are considered. Link rate is $R = 100\ Mbits/s$ and switching latency is $sl = 16$ µs.

TABLE I
VL PARAMETERS OF THE NETWORK EXAMPLE IN FIGURE 1

VL	BAG (µs)	Smax ($bits$)	Priority	
			FIFO	FP/FIFO
v_1	4000	4000	-	L
v_2	4000	4000	-	L
v_3	4000	4000	-	H
v_4	4000	4000	-	H
v_5	4000	4000	-	L

We focus on VL v_1. According to the NC approach, the end-to-end delay upper bound of v_1 is computed as 273.6 μs under FIFO scheduling and 316.5 μs under FP/FIFO scheduling. Exact worst-case end-to-end delays of v_1 can be calculated by model checking approach (small configuration)[8]. They are 272 μs under FIFO and 312 μs under FP/FIFO. The small difference between the delay upper bound and the exact one indicates the pessimism introduced by NC approach. For the purpose of illustration, we detail the computation of delay at the output port of S_3 in Figure 3.

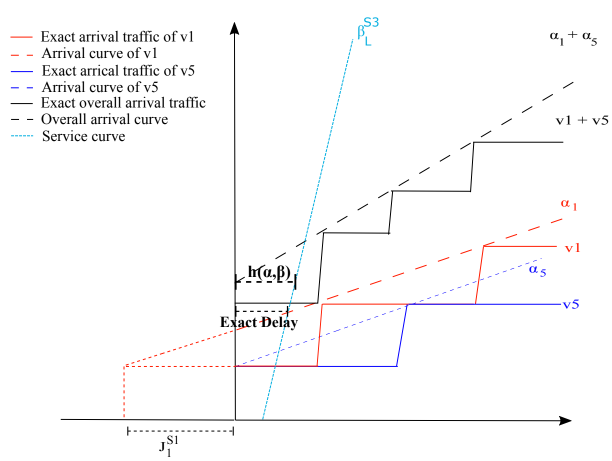

Fig. 3. Illustration on pessimistic delay computation of NC approach

As shown in Figure 3, v_1 and v_5 are lower-priority VLs and served by the service curve $\beta_L^{S_3}$ at the output port S_3. Since v_1 experienced a jitter $J_1^{S_1}$ at the output port S_1 which introduces pessimism as illustrated in Figure 2, the overall arrival curve of v_1 and v_5 becomes pessimistic compared to the actual arrival traffic of these two VLs as shown in Figure 3.

As previously mentioned, pessimism evaluation is important since pessimism means over-dimensioning of the network. One way to evaluate the pessimism is to compute a reachable end-to-end delay and upper bound the pessimism by the difference between the reachable delay and the delay upper bound. In the following paragraphs, an optimistic NC approach is proposed for calculating reachable delays.

B. An optimistic approach based on Network Calculus

A reachable delay can be obtained by replacing pessimistic assumptions by optimistic ones in the network calculus approach. Thus we consider the following optimistic assumptions:

The first optimistic assumption considers that Each VL emits one frame (only one step in the actual arrival curve). It is valid since VLs are defined as sporadic flows. It corresponds to a scenario where the inter-arrival interval of each VL is large enough so that a frame can only be delayed at most by one frame of every other VL traversing at least one shared output port. This assumption leads to the slope of arrival curve to be zero.

The second assumption considers no jitter in output ports. Actually, the only impact of jitter is to potentially increase the number of frames of a given VL which delays the VL under study. Since, based on the first optimistic assumption, we consider that at most one frame of each VL can delay the VL under study, integrating jitter in arrival curves is useless.

The third assumption removes pessimism from service curves by ignoring priorities when calculating the delay of lower-priority VLs. Under FP/FIFO scheduling, a higher-priority VL can delay a lower-priority VL in several output ports along the studied path, while under FIFO scheduling, a VL delays another VL only at their first shared output port. In that case, considering that the higher-priority VLs have the same priority as the studied lower-priority VL is an optimistic scenario. Then the whole service curve $\beta^h(t)$ is used to serve these same-priority VLs sharing the output port h.

C. Upper bound on pessimism

The difference between the exact worst-case end-to-end delay and the upper bound computed by network calculus gives the pessimism in this upper bound. Since the exact worst-case end-to-end delay is unknown, we calculate a reachable delay using the proposed optimistic NC approach. As depicted in Figure 4 the difference between the reachable delay and the sure upper bound gives an upper bound on the pessimism of the NC approach: $UBP = E2E_{NC} - E2E_{NCO}$.

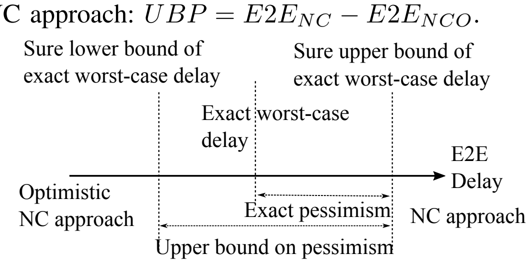

Fig. 4. Upper bound on pessimism

V. Evaluation

In this section, a case study is first given and then a comparative analysis is carried out on an industrial AFDX configuration. End-to-end delays are computed with the different NC approaches discussed above. Then, the upper bound on pessimism introduced by NC approach is analyzed.

A. Case Study in Figure 1

A tool has been developed in C++ to implement both NC approach discussed in previous sections. Table II compares the end-to-end delay calculated using the NC approach and the model checking approach [8]. The column NC shows the delays calculated using Network Calculus, while EWC shows the exact worst-case delays calculated using model checking. The results obtained by the proposed optimistic NC approach are given in the column NC_O. Results show that our optimistic approach introduces some optimism for the FP/FIFO case.

TABLE II
Comparisons on end-to-end delays with FIFO and FP/FIFO scheduling policies

VL	FIFO				FP/FIFO			
	NC	EWC	NC_O	pess (%)	NC	EWC	NC_O	pess (%)
v_1	273.6	272	272	0.58	316.5	312	272	14.06
v_2	192.4	192	192	0.2	192.4	192	192	0.2
v_3	273.6	272	272	0.58	232.4	232	232	0.17
v_4	273.6	272	272	0.58	232.4	232	232	0.17
v_5	177.6	176	176	0.9	220.5	216	176	20.18

B. Industrial configuration

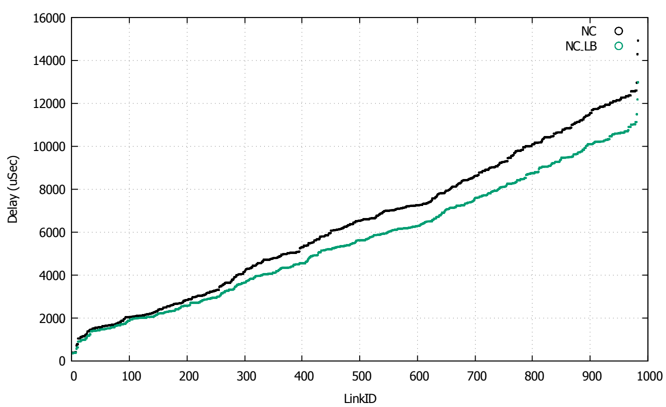

Fig. 5. End-to-end delay in an industrial configuration with FIFO

Figure 5 shows the analysis made on an AFDX industrial configuration to compute upper bound of pessimism. This configuration includes 96 end systems, 8 switches, 984 Virtual Links, and 6412 VL paths (due to VL multi-cast characteristics). Results for FIFO and FP/FIFO are presented in Figures 5 and 6, where the paths are sorted by increasing order of E2E Delay values. The average upper bound of pessimism computed for the given approach is 11.69% for FIFO and 10.97% for FP/FIFO.

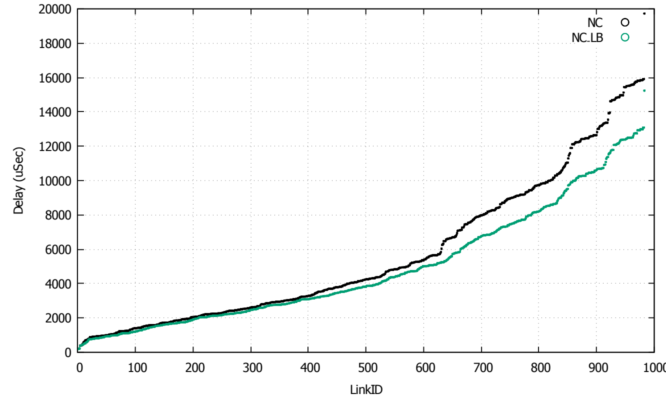

Fig. 6. End-to-end delay in an industrial configuration with FP/FIFO

VI. Conclusion

Industrial switched Ethernet networks like AFDX need to guarantee real-time performance. Deterministic approaches are chosen to evaluate real-time performance by calculating end-to-end delay upper bounds of flows transmitted through the network, and therefore introducing pessimism in the computation. The evaluation of the introduced pessimism is important in order to make upper bounds convincing. In this work, we focus on the network calculus (NC) which has been used for aircraft certification. We propose an optimistic NC approach which leads to reachable end-to-end delays. The difference between the reachable delays and upper bounds gives an over-estimation of the pessimism. An evaluation based on an industrial AFDX configuration is carried out and the results show that the NC approach introduces pessimism of about 10%.

Work presented in this paper is a first step towards a generic approach for pessimism evaluation of worst-case delay analysis of real-time switched Ethernet networks.

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