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Real-time characteristics of Switched Ethernet for "1553B"-Embedded Applications: Simulation and Analysis

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Abstract—In our previous work [1], Full Duplex Switched Ethernet was put forward as an attractive candidate to replace the MIL-STD 1553B data bus, in next generation "1553B"-embedded applications. An analytic study was conducted, using the Network Calculus formalism, to evaluate the deterministic guarantees offered by our proposal. Obtained results showed the effectiveness of traffic shaping techniques, combined with priority handling mechanisms on Full Duplex Switched Ethernet in order to satisfy 1553B-like real-time constraints.

In this paper, we extend this work by the use of simulation. This gives the possibility to capture additional characteristics of the proposed architecture with respect to the analytical study, which was basically used to evaluate worst cases and deterministic guarantees. Hence, to assess the real-time characteristics of our proposed interconnection technology, the results yielded by simulation are discussed and average latencies distributions are considered.

I. INTRODUCTION

Over the last thirty years, the MIL-STD 1553B data bus has been used in many embedded systems, like aircrafts, ships, missiles and satellites. It is a 1 Mbps serial asynchronous data bus with a centralized system control [2]. The Medium Access Control (MAC) mechanism is described as command / response time division multiplexing: the Bus Controller (BC) sends command messages at predetermined times to Remote Terminals (RT), to give them access to the bus (see figure 1). The BC follows the instructions stored in its transaction table to control communication and to monitor message requests. Thus, BC's operation is well ordered and pre-established. The polling cycle time must be carefully chosen since it must efficiently transfer all data to prevent any RT from being polled either too often or too little. This data bus can support different types of messages: periodic and sporadic with strict deadlines that must be respected in transmission. To fulfill these real-time constraints, a major frame is often defined to transfer all periodic messages at least once and it shall be no smaller than the biggest message period. Every major frame consists of a finite number of minor frames to meet the requirements of the higher update rate messages. Hence, MIL-STD 1553B is suitable for applications where generation and transfer of data

are pre-established and precise timeliness is required.

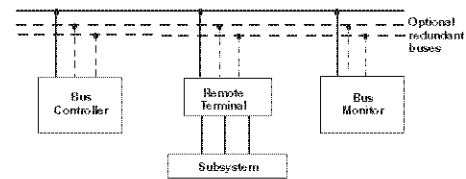


Fig. 1. MIL-STD 1553 Architecture

However, this traditional data bus is no longer effective in meeting the communication demands imposed by the new "1553B"-embedded applications. In fact, with this bus approach, communications are closely coupled to the bus controller, which limits system modularity and reconfigurability. Another limitation is its inability to handle the heavy throughput demands caused by the increasing subsystems' complexity. Therefore, a new interconnection system is needed to overcome the limitations of the MIL-STD 1553B data bus. Among several high speed networks, Switched Ethernet presents significant interests thanks to its reduced costs, its flexibility and its expandability. In fact, after the successful civil experience with the Airbus A380 ([3], [4], [5], [6]), Standard Full Duplex Switched Ethernet was put forward in our previous works [7] as a future interconnection technology to replace MIL-STD 1553B. However, the key argument against Switched Ethernet lies in its non-deterministic behavior that makes it inadequate to deliver hard time-constrained communications.

Various real-time communication solutions were offered for the CSMA/CD Ethernet ([8], [9], [10]). In our previous work [7], these solutions were described and their adaptation and their applicability over Switched Ethernet were discussed. After a comparative study of their ability to handle real-time constraints, the choice of a traffic shaping approach was justified and first experiments were conducted. Then, we

extended these works in [1] by giving a general analytical study, using the *Network Calculus* formalism, to characterize "1553B"-embedded applications and to evaluate the deterministic guarantees offered by our bus when it replaces the MIL-STD 1553B data bus.

However, even in cases where analytical models exist, simulation is still used to evaluate the real-time features of data buses. This is due to the fact that analytical models are often restricted to a particular level of abstraction. In our case, analytical models were used to capture worst cases (rare events) to obtain the highest possible delay of a data packet (deterministic guarantees). Hence, towards this paper, simulations will be useful to address the average real-time behavior of the proposed architecture. The main objective of this paper is to assess the real-time characteristics of the traffic shaping combined with priority handling over Switched Ethernet for "1553B"-embedded applications by analyzing the obtained average latencies distributions.

This paper is organized as follows. Our case study, used through simulations, is presented in section 2 and an overview of our previous established works is given in section 3. Section 4 shows our simulation models and the results yielded by this method are discussed and average latencies distributions are considered. Section 6 concludes the paper.

II. CASE STUDY

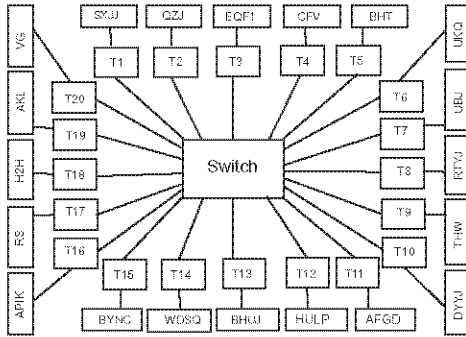


Fig. 2. General model based on a real case of a 1553B network

Our case study is a representative real-time traffic on a MIL-STD 1553B data bus in a modern French military aircraft. The selected data bus is the busiest one among those aboard this aircraft. Hence, we estimate that it is the most representative one of the MIL-STD 1553B behavior and its real-time requirements. For these reasons, this single case study is considered in this paper. In our selected "1553B"-embedded application, there are four important messages categories identified by their periodicity and their temporal deadlines:

- Urgent sporadic messages sent by the BC and that have to be received under a predefined small bounded time, like alarms.
- Periodic messages that depend on the time cycles defined by the BC and that are also hardly time-constrained, like

sensor data.

- Sporadic messages that have known deadlines to respect but without any urgency.
- Sporadic messages that do not have to respect strict time constraints, like file transfers.

The traffic is circulating between twenty subsystems connected to their associated terminals. Real-time flows are described in tables I and II. So, one can see that for periodic messages, the largest period is 160 ms and the most frequent value is 20 ms; and for sporadic messages, there are different response time bounds and the most urgent one is about 3 ms. As a result, the major frame has a duration of 160 ms and minor frames 20 ms, in order to meet the requirements of the higher update rate messages. Four parameters are defined for each message:

- the period T : for a periodic message, it is the period and for a sporadic flow, it is low bounded as its minimal inter-arrival time. In our case, we suppose that a subsystem can generate at most one sporadic message of each type once every minor frame (20 ms);
- the temporal local deadline D : (the message life duration) it is the period for a periodic message and the maximal response time for a sporadic message;
- the maximal length of a message L ;
- the priority P : we attribute a priority level for each message category: urgent sporadic messages with a requested maximal time of 3 ms will be tagged with the highest priority (4), then periodic traffic the medium priority (3), priority 2 for sporadic messages with a requested maximal response time ranging from 20 ms to 160 ms and finally priority 1 for sporadic messages with a maximal response time bigger than 160 ms.

TABLE I
PERIODIC FLOW DESCRIPTION

Period (ms)	Number of flows	L_{max} (bytes)
20	40	110
40	10	76
80	15	120
160	100	116

TABLE II
SPORADIC FLOW DESCRIPTION

Response time (ms)	Number of flows	L_{max} (bytes)
3	1	72
20	80	120
160	90	120
infinity	20	120

Therefore, the hardest real-time constraint to respect is the maximal response time for the most urgent sporadic messages (3 ms). In order to integrate the above traffic in a simple manner when replacing the MIL-STD 1553B data bus with a Full Duplex Switched Ethernet network, a MAC address

is attributed to each terminal and the different terminals are connected to one switch. Every 1553 message generated by a 1553 terminal is encapsulated in an Ethernet frame that respects the minimal frame size (64 bytes) and contains the source and destination addresses. Then, this frame is carried over the Switched Ethernet network. Figure 2 depicts our general model: a switch in the middle is connected to twenty terminals that transmit periodic and sporadic messages with determined characteristics.

III. ESTABLISHED RESULTS

In this section, we describe briefly our previous results concerning our proposed architecture to overcome the MIL-STD 1553B data bus limitations. First, our proposed approach to achieve an accepted QoS (Quality of Service) level offered by Switched Ethernet to support diverse "1553B"-based applications requirements is explained. Then, the delay bound analysis conducted to investigate the validity of our proposal and obtained results for our case study previously described in section II are provided.

A. Proposed approach

In order to use Full Duplex Switched Ethernet for "1553B"-based applications, the key of our solution was the use of traffic shapers at data sources to control traffic and an adequate choice of switch service policy to guarantee the real-time constraints of these critical applications.

Traffic Shaping approach has been initiated by Kweon and Shin [11] and then developed by Loeser and Haertig [12] to achieve real-time communication over Switched Ethernet. The latter approach provides transmission with low packet loss while the former provides statistical guarantees. Clearly, these guarantees are not sufficient for hard real-time systems like the "1553B"-embedded applications. These previous works present a similarity with our suggested approach, which consists in the use of traffic shapers at data sources to control traffic and to guarantee the integrity of the "1553B"-embedded applications. However, we added a priority handling method in data sources and in the switch to assure a good isolation level for urgent messages with hard deadline constraints. Then, an adequate choice of service policy in the switch was needed to guarantee low bounded delays.

Traffic shapers integration was as follows: inside each terminal, there is one traffic shaper for each transmitted stream to regulate its packets' arrivals, in accordance with their periodicity and their maximal size by using the leaky bucket concept. Then, obtained streams at the traffic shapers' outputs are multiplexed inside the terminal before being sent on the data bus. In the switch, incoming packets are processed according to the store and forward technique for safety reasons. Then, each packet is relayed to its destination port to be multiplexed with other received packets according to the switch scheduling policy. We have focused on the three

most widely implemented policies: First Come First Served (FCFS), Static Priority (SP) and Weighted Fair Queuing (WFQ). The latter is a fair policy which bridges the gap between the simplest policy FCFS, that serves packets without taking into account their temporal characteristics; and the SP policy that makes a strict segregation between priority levels by selecting the higher priority to be served.

B. Delay bounds analysis and obtained results

The main metric that has been chosen to validate our model was the maximal end to end delay bounds that were compared to temporal deadlines of each traffic class. To achieve this aim, an analytical study, using the Network Calculus theory introduced by Cruz [13] and developed by Leboudec [14], was conducted. In fact, this theory is well adapted to controlled traffic sources and provides deterministic end to end delay bounds. For this, traffic arriving at each switch input port was described by the so called arrival curve and the availability of the switch by a service curve. Then, the delay bound is given by the horizontal distance between the two curves. For our model, thanks to the use of traffic shapers, the traffic arrival curve at each switch input port is $\alpha(t) = b + rt$ with b the maximal burst and r the rate. The service curve offered by the switch depends on its scheduling policy, but has a common form $\beta(t) = \max(0, C * (t - T))$ with C its output capacity and T its imposed delay related to the forwarding process and buffered packets in output ports. Hence, the delay bound in the general case is $\frac{b}{C} + T$.

In our case study, given the important number of streams and the existence of multicast and broadcast transmission mode, it was more convenient to give a maximal end to end delay bound related to each destination subsystem rather than to each individual steam. Then, maximal delay bounds were determined in a global manner for each priority class and obtained results are described in table III. One can see that deadline constraints are violated with FCFS policy and respected with SP and WFQ policies. Hence, our first conclusion was that, as opposed to some received ideas, increasing the offered bandwidth is not sufficient to have a real-time behavior with switched Ethernet. Then, priority handling method combined with traffic shaping approach may be a good mean to improve the Switched Ethernet reliability and to achieve the QoS level required by "1553B"-based applications.

TABLE III
MAXIMAL END TO END DELAY BOUNDS

Priority	Hardest Deadline (ms)	D_{EED} (ms)		
		FCFS	SP	WFQ
4	3	21,8	0,63	1,9
3	20	21,8	9,8	18,6
2	20	21,8	19,7	19
1	infinity	21,8	38,8	37,8

IV. SIMULATION MODELS

A representative set of simulations has been conducted using the network simulation tool OPNET Modeler (Release 11.5). This tool allows network systems to be modeled at the lowest level of detail, and hence it is ideal for investigating the average end-to-end delay of each stream. OPNET Modeler contains many models of existing hardware for Switched Ethernet, however these models do not satisfy our application conditions. In fact, the existing Ethernet station is mono-source with a packet generator module based on a stochastic or uniform distribution, however in our case, we need a multi-source station with known static traffic. In addition, the existing switch model implements only the FCFS policy and in our model we rather need SP and WFQ policies.

Hence, standard models for data sources had to be modified to integrate our initial "1553B" traffic characteristics; and switches and MAC layer were extended to incorporate the priority paradigm to have different scheduling policies like SP and WFQ. In this section, we briefly describe the terminal and the switch models used in simulations.

A. Terminal model

To develop the "1553B" terminal model, the standard Ethernet station model was extended. The most important modified components are: the packet generator (SRC), the MAC process (MAC) and finally the packet receiver (SINK) (see figure 3).

- Transmission part: the SRC will generate appropriate packets that respect the integrity of the "1553B" traffic characteristics (length, period, source, destination) defined in an input file. This file depends on the scheduling policy used in the switch: for SP policy every packet is identified by a static priority, while for WFQ policy every packet has a given service weight. For each transmitted stream, a traffic shaper is implicitly integrated: packets departures events are generated and scheduled according to the respective minimal inter-arrival time. Then, the MAC module will process these generated packets according to their priorities thanks to the incorporation of SP policy instead of FCFS policy. This mechanism will be explained in a more detailed way in the switch model. Finally, the transmission controller (Tm) transmit these packets on the data bus.
- Reception part: packets are received from the data bus thanks to the reception controller (Rv). Then, arriving to the MAC process, their integrity is controlled and corrupted packets are dropped. Correct packets are finally received by the SINK part where defined statistics are calculated. In our case, we are interested on the end to end delay for each packet.

B. Switch model

Our developed switch model is based on the standard Ethernet switch model with thirty-two ports, but some modifications were necessary to incorporate the priority paradigm and different scheduling policies like SP and WFQ. As shown

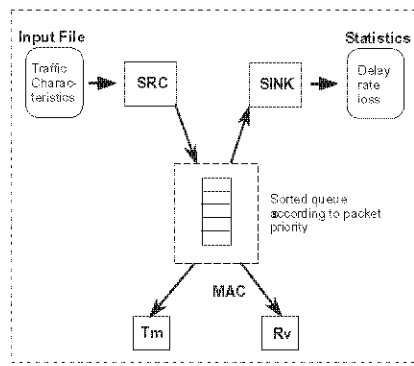


Fig. 3. Terminal Model

in the figure 4, there are thirty-two input/ output ports to transmit/ receive packets on/ from the data bus, where only twenty ports are used to connect the twenty terminals of our case study. Then, there is the MAC process which assures the connection between the switch ports and the filtering and relaying process. If multiple packets have the same destination port, they will be queued in the modified MAC port which incorporates the priority paradigm. It selects the appropriate packet to transmit according to the scheduling policy in the switch. OPNET provides a mechanism for inserting a packet into a subqueue based on a position index argument that allows a flexibility in determining where the specified packet should be inserted; it can be a concrete numeric position or a position determined by the packets priority property relative to other packets.

- With SP policy, the packet priority is allocated in a static manner according to our priority model defined in section II. Hence, higher priority packets (urgent packets) are inserted closer to the head of the subqueue than lower priority ones in order to be transmitted first.
- With WFQ policy, a more fair service is guaranteed to each priority packet. In fact, the virtual finish time is calculated for each packet which depends on its service share weight and its length. Unfortunately, the virtual finish time calculus is not easy to implement due to the complexity of the virtual function. So, our proposed solution to overcome this difficulty is to implement the Virtual Clock (VC) service discipline [15] instead of WFQ policy. In fact, for leaky bucket constrained sources, the obtained upper delay bounds are the same as the ones given by WFQ. Moreover, the VC virtual function is easier to implement and to analyze. Hence, the inverse of this obtained virtual finish time is tagged into the packet and the scheduler selects the higher priority packet which has the earliest virtual finish time.

V. REAL-TIME EVALUATION

A. Scenarios and metrics

To evaluate the real-time features of our simulation network, the main metric that has been chosen is the average end to end delay. OPNET offers the possibility to calculate this value in

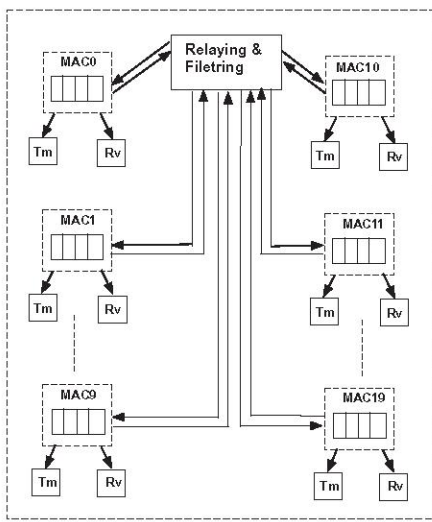


Fig. 4. Switch Model

a global manner: the average over all packets in an individual flow is first computed and from these the average over all flows is calculated. Average latencies distribution will be considered to analyze the average behavior of our proposed network.

Like the metrics choice, the simulation scenarios choice is considered as a critical factor to improve the credibility of simulation results. A network scenario may be defined by two elements: the network topology and the circulating traffic between the different network subsystems.

- *Network topology*: our network topology consists of twenty terminals connected to one central switch with Full Duplex links. Three parameters are used to define the switch: its output capacity (fixed at 10Mbps for all scenarios), its relaying technique (Store and Forward) and finally its scheduling policy which is the variable parameter (SP, WFQ). In fact, two different OPNET projects are created according to the used scheduling policy in the switch (SP, WFQ).
- *Traffic*: the traffic is defined a priori where each flow is characterized by a length, a period, a deadline, a priority, a service weight in the case of WFQ policy and two addresses (source and destination). However, the variable parameter in this case is the arrival distribution of packets on data bus. To create a realistic traffic generator, three parameters were introduced: seed, maximal jitter and what we called Initial Window.
 - Seed: it is an important parameter for a random generator. In fact, if many simulations are conducted with the same seed value, they will use the same "random" numbers in exactly the same order. This fact will necessarily decrease the coverage of simulations. Hence, it is important to run multiple, independent replications of the same simulation model by varying the seed value to improve the credibility of our obtained results. In our case, we

have chosen twenty different values of seeds which have been used to calculate confidence intervals for each researched average latency.

- Jitter: this parameter is introduced to increase the variation of the traffic generation and to avoid the very periodic behavior.
- Initial Window: This parameter is used in our packet generator to produce the packets' transmission instants belonging to this Initial Window at the beginning of each simulation. This parameter was fixed to 1ms which is low compared to the smallest packet period (20ms) to increase the congestion probability in the switch.

The variable scenarios' parameters are recapitulated in table IV. Hence, there is $6 \times 20 = 120$ scenarios for each scheduling policy and the run time for each simulation is 3mn which represents approximately 10^3 major frames of 160ms.

TABLE IV
SCENARIOS PARAMETERS

Scheduling Policy	SP, WFQ
Seeds	20 different values
Jitter	0ms, 2ms, 4ms, 6ms, 8ms, 10ms

B. Simulation results

Jitter Influence and Confidence Interval

Many network simulation studies conclude with a single simulation run to obtain results. This fact increases the probability of obtaining erroneous results due to the use of random packet distribution which depends on the seed parameter. Figure 5 illustrates how the average latency metric can vary considerably for the same jitter value between statistically independent simulation runs with different seed values. Hence, it is important to lead multiple replications of the same simulation model to increase the credibility of obtained results.

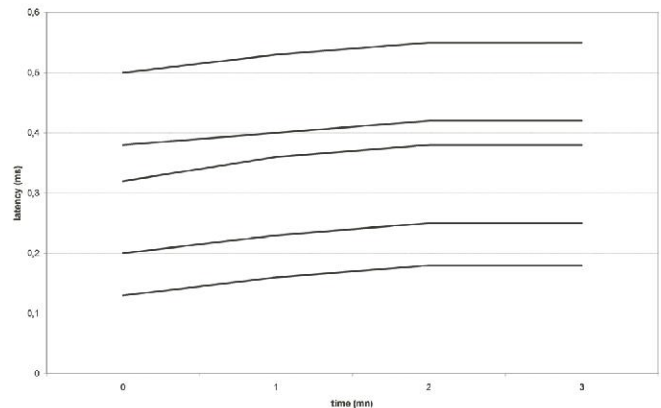


Fig. 5. Evolution of average latency over simulated time for 5 different replications (WFQ policy, jitter = 0ms, Priority 4)

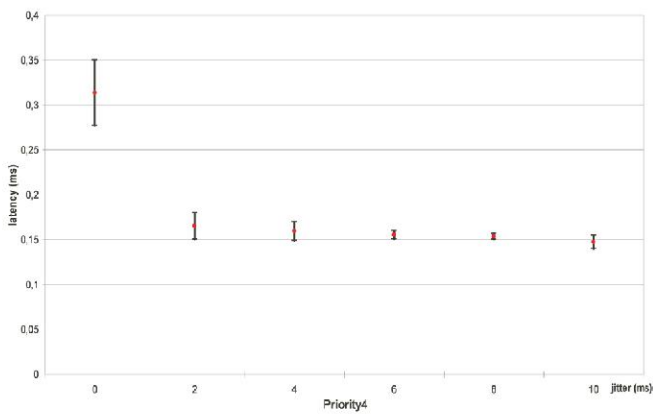


Fig. 6. Obtained Confidence Intervals for Priority 4 with WFQ policy

In our case, $n = 20$ independent simulation runs were conducted for each model by varying the seed value. Obtained average latencies are used to calculate an estimated mean latency with a confidence level $\alpha = 95\%$; and a confidence interval $\delta(n, \alpha)$ for this mean can be found:

$$\delta(n, \alpha) = \bar{X}(n) \pm t_{n-1, \alpha} \frac{S(n)}{\sqrt{n}}$$

Where $\bar{X}(n)$ is the estimated mean, $S(n)$ is the standard deviation and $t_{n-1, \alpha}$ is a parameter from the Student T-distribution, which is equal to 1.96 in our case. This distribution is based on the normal distribution and determines confidence interval for the researched value (mean latency) given the observed values (obtained average latencies). Figure 6 shows an illustrative example of obtained confidence intervals for each jitter value.

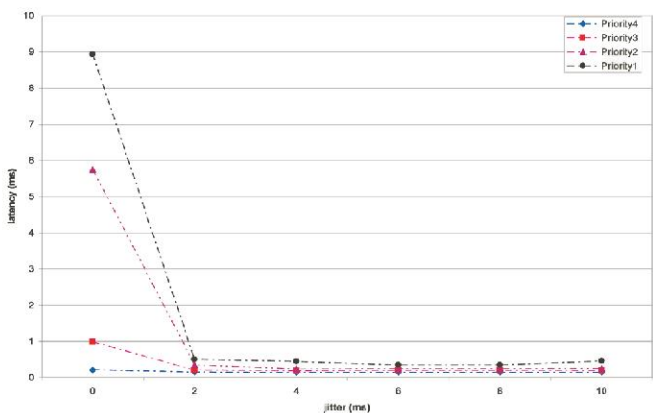


Fig. 7. Mean values and jitter influence with SP policy

Figures 7 and 8 show the variation of mean values of obtained average latencies with jitter for each traffic priority with SP and WFQ policies. It was more convenient to show mean values of average latencies for each traffic priority rather than confidence intervals to obtain clear curves. One can see that the obtained latencies are coherent with the priority paradigm: the higher the priority of a traffic class, the lower its latency. Moreover, with the Weighted Fair Queuing

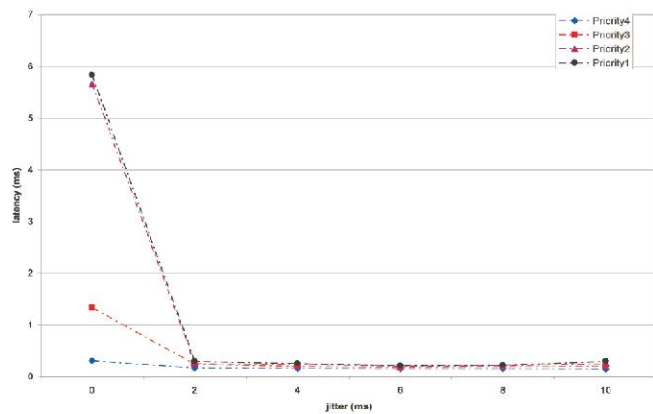


Fig. 8. Mean values and jitter influence with WFQ policy

policy, a more fair service is offered to all classes with a noticeable amelioration of low priorities latencies compared to the Static Priority policy, with little degradation for high priorities latencies. These results are compliant with our analytical results shown in III-B. It is worth to note that the obtained mean latency is low when jitter is non-null and it is the case for each priority traffic with the two considered scheduling policies. This is essentially due to the flows phasing degree which is widely dependent on jitter and the Initial Window. In fact, when jitter is non-null, the probability of having simultaneous packets is low and consequently the queue sizes are small.

Average Latencies Distributions

To better assess the real-time characteristics of our proposed interconnection topology, histogram and density of average latencies are considered for each traffic priority with SP and WFQ policies (120 values respectively obtained for 120 scenarios). These distributions will help us to analyze the average behavior of our bus. In fact, figures 9 and 10 reveal an important concentration of average latencies in a small interval. Table V shows an interval of average latencies for each traffic class with SP and WFQ policies, where the probability is 90%.

TABLE V
INTERVAL OF AVERAGE LATENCIES WITH HIGH DENSITY

Priority	4	3	2	1
SP	90% in [0.14, 0.16]	90% in [0.17, 0.18]	90% in [0.2, 0.4]	90% in [0.3, 0.8]
WFQ	90% in [0.14, 0.2]	90% in [0.15, 0.3]	90% in [0.2, 0.4]	90% in [0.2, 0.4]

One can see that the density of average latencies associated to each histogram is given in the same figures. These latter are obtained thanks to the use of Expectation Maximization (EM) algorithm [16]. This algorithm is used in statistics to find the better estimation of probabilistic observed parameters (in our case the obtained average latencies), where the model depends

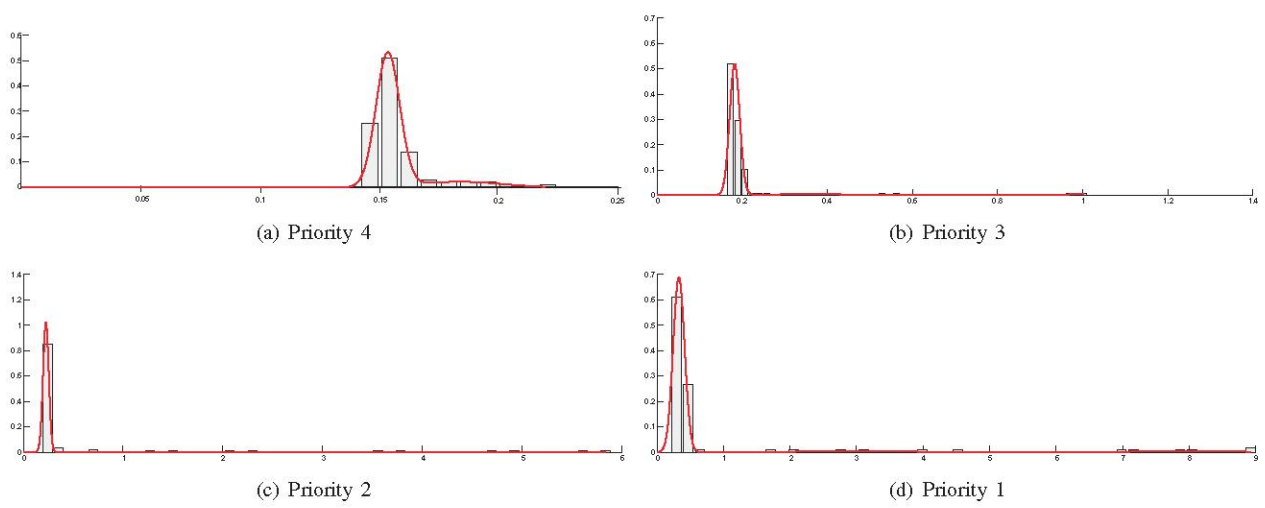


Fig. 9. Histogram and density of Average latencies with SP policy

on unobserved variables. The density f of average latencies is a Gaussian mixture with:

$$f(x) = \sum_{i=1..N} \alpha_i N(x, \mu_i, \sigma_i)$$

where for each Gaussian, there are three parameters to determine with EM algorithm: the weight α_i , the mean μ_i and the variance σ_i . To obtain these parameters, EM alternates between performing an expectation (E) step, which computes an expectation of the likelihood of observed average latencies, and a maximization (M) step, which computes the maximum likelihood found on the E step. The parameters found on the M step are then used to begin another E step, and the process is repeated.

In our case, we used the Matlab environment using an appropriate package to integrate the EM algorithm. Given the observed values and the chosen number of Gaussian in the input, this tool gives the researched three parameters for each Gaussian and the respective density curves. To choose the number of Gaussian, we took the same observed number of important peaks from histograms. In fact, these peaks correspond to the most frequent observed latencies. As one can see, for priorities 2 and 1 with WFQ policy, the densities of average latency are not considered given the important value of the principal peak. Table VI shows the parameters of Gaussian mixture for each priority class with SP and WFQ policies.

It is worth to note that the analytically determined latencies (see section III-B) are 4 (priority 4 with SP policy) to 100 (priority 1 with WFQ policy) times greater than the average latencies obtained from the respective histograms and density distributions. The main reason for these deviations is that the occurrence of worst cases is difficult to capture when using simulation. In fact, the used analytical study assumes that on all links, a burst can be generated at the same time in

order to obtain the highest possible delay of a data packet and thus deterministic bounds. However with simulation, such simultaneous conditions are extremely rare, difficult to generate and observe, and thus do not appear in the latency distributions. Hence, the analytical study and simulations are complementary to evaluate the real-time features of our proposed interconnection technology to replace the MIL-STD 1553B for future embedded applications. The former evaluates deterministic guarantees, whereas the latter determines the average behavior that can be expected from the real application case.

TABLE VI
GAUSSIAN MIXTURE PARAMETERS FOR EACH PRIORITY TRAFFIC WITH SP AND WFQ POLICIES

	priority	N	means	variances	weights
SP	4	2	0.1539,	0.00002,	0.8861,
			0.1852	0.00034	0.1139
	3	3	0.1827,	0.0001,	0.918,
			0.36,	0.017,	0.0635,
		0.99	0.0004	0.0185	
2	2	2.6933,	3.781,	0.1298,	
		0.227	0.0008	0.8702	
1	3	3.0014,	1.0035,	0.0561,	
		7.9801,	0.6332,	0.0555,	
		0.3297	0.0074	0.8884	
WFQ	4	2	0.1547,	0.00002,	0.8678,
			0.2069	0.0037	0.1322
	3	2	0.6004,	0.1416,	0.1349,
0.1848			0.0001	0.8651	

VI. CONCLUSION

In this paper, a detailed simulation study was described to evaluate the real-time characteristics of traffic shaping combined with priority handling, when applied to a 1553B-embedded application ported to Switched Ethernet. We have a high confidence in the simulation results, thanks to multiple

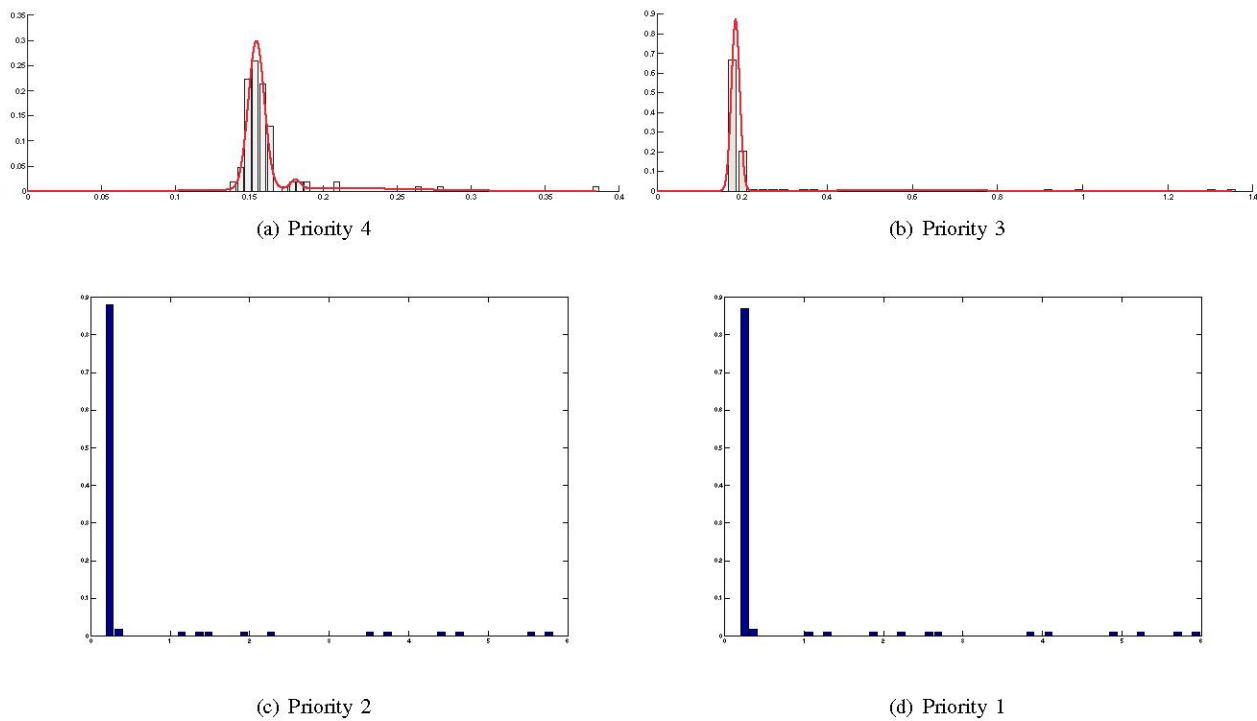


Fig. 10. Histogram and density of Average latencies with WFQ policy

replications of each simulation model and the use of average latencies distributions instead of mean values. Depending on the flow priorities and the switch policy (SP, WFQ), a ratio ranging from 4 to 100 was observed between the average end-to-end delays and the deterministic analytical bounds. The smallest ratio is obtained with the flows of the highest priority, which makes us conclude that the hardest real-time constraints bring a nice side-effect on the predictability of traffic, by reducing the overall range of possible end-to-end delays, and thus giving the best knowledge of end-to-end delay distributions, greatly complementing the deterministic bounds obtained by our previous analytical studies.

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