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# Real-time guarantees on Full-Duplex Switched Ethernet for military applications

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**Abstract:** This paper is a proposal for a future method of avionics data communication in military aircrafts. The need for this proposal results from the increasing complexity of avionics systems that is pushing the MIL-STD-1553B well beyond the limits of its bandwidth. Among several high speed interconnection technologies, Full-Duplex Switched Ethernet is an attractive candidate to replace the MIL-STD-1553B for advanced military aircraft system interconnection but, unfortunately, it was not originally developed with the aim to deliver real-time communications. Therefore, we have to add new mechanisms over Switched Ethernet to achieve real-time behaviour with bounded delays.

In this paper, we describe the most important existent real-time transfer solutions for the classic Ethernet and discuss their possible applicability over Switched Ethernet. Then, we compare their performances and their capacities to handle real-time constraints required by the military applications. A special care is given to the traffic shaping approach which allows to limit the congestions in the switch and to guarantee low delays. We will show in experiments that with the traffic shaping approach with the priority handling, we can achieve deterministic transmission that respect the military application's requirements.

**Keywords:** Full-Duplex Switched Ethernet, real-time communication, Traffic Shaping, priority handling, delay bounds.

## 1. Introduction

The increasing complexity of avionics systems has been pushing the limits of the traditional communication buses in aircrafts. This rapid progress has opened up the possibility for implementing a new high speed standard AFDX (Avionics Full-Duplex Switched Ethernet) which is integrated for the civil next generation aircraft (A380). In contrast, military avionics communication systems are still kept at relatively low speed.

In fact, current military avionics data buses are MIL-STD 1553B which have been widely used in various military aircrafts for decades. These are 1Mbps command/response multiplexed data buses with a

centralized system control. Nowadays, the number of MIL-STD 1553B data buses used in military aircrafts has increased and integration of new data buses with higher data rates has been required. In fact, the STANAG 3910 bus, that is designed to improve the throughput whilst maintaining MIL-STD 1553B compatibility, and the SCI (Scalable Coherent Interface) operating at 1Gbps, are used to support the increasing amount of information exchanged between the equipments in current military aircrafts. Clearly, these different data buses increase the complexity of providing end to end real time constraints guarantee and a new homogeneous interconnection system is needed to achieve this aim.

Full-Duplex Switched Ethernet is a COTS network that has the potential to replace the MIL-STD 1553B and the other data buses used in the military aircrafts. This technology is not originally designed to deliver time-constrained communication, but some of its properties, such as its reduced cost, its flexibility and its expandability make it an attractive candidate. Full-Duplex Switched Ethernet LAN removes CSMA/CD arbitration since no collision can happen but, unfortunately, congestion may occur when simultaneous traffic data attempt to share network segments and messages can be lost if switch queues overflow. Thus, it is impossible to guarantee predictable delays in delivering packets to the end systems, in the general case. So, we have to add new mechanisms to avoid information loss and to guarantee hard real-time communication with low latency.

Various real-time transfer solutions exist for Ethernet; all of them add a transmission control to avoid possible collisions caused by the CSMA/CD arbitration. For example:

- TDMA where stations transmit messages at predetermined slots in a cyclic fashion with a precise clock synchronization.
- FTT-Ethernet where a central master periodically distributes a group of tokens that allows slaves to send data for a specific amount of time.

- *Token- Ring* approach where a circulating token represents the permission to transmit data during a bounded access time.
- *Traffic shaping* method that consists in applying traffic shapers to all transmitted data to achieve lower guaranteed delays and to avoid buffer overflow.

This paper deals with the applicability of these approaches over Switched Ethernet in real-time environments. The remainder of the paper is organized as follows: section 2 describes the MIL-STD 1553B protocol, defines the real-time constraints required by the military applications and then reviews the previous research to replace this data bus. In section 3, we describe the various approaches to achieve real-time communication over Ethernet and their possible adaptability to the Switched Ethernet; then, we compare their relative merits to support real-time constraints required by the military applications. A special care is given to the Traffic Shaping approach in sections 4 and 5. We start by describing the characteristics of the Switched Ethernet model under consideration in section 4. Then, we detail our experimental study of this approach in Section 5. We present our conclusions in the final section.

## 2. Background

In this section, we describe the MIL-STD 1553B data bus protocol to better understand the real-time constraints required by the military applications. Then, we present the previous proposals to replace this data bus and justify our choice of the Switched Ethernet technology.

### 2.1 An overview of MIL-STD 1553B

MIL-STD-1553B has been the data bus for military avionics systems for the last three decades. This bus still fulfils most data communication needs for command and control applications and its success is due to its simplicity, its high reliability and its real time properties [20, 21].

The MIL-STD-1553B data bus is a 1 Mbps serial data bus which provides an integrated centralized system control and a standard interface for all the connected equipments. With such a bus concept, the traffic on the data bus is accessible through a single connection for up to 32 equipments. The Medium Access Control (MAC) mechanism is described as command/response time division multiplexing (TDM): the bus controller polls remote terminals to allow them to access the bus and it is the responsible equipment for the sequencing and timing

of all information transfers. Several techniques have been developed to determine the sequence used called transaction table. Military applications require two types of traffic: periodic and sporadic, with strict deadlines that must be respected in transmission; the polling cycle time must be carefully chosen since it must efficiently transfer all data, thus preventing any remote terminal from being polled either too often or too little. It shall be no smaller than the biggest message period to fulfil real-time guarantees. A major frame is defined for the 1553B bus to transfer all periodic messages at least once; and minor frames are established to meet the requirements of the higher update rate messages. At the beginning of each new minor frame an interrupt occurs and the bus controller starts issuing the messages for that minor frame.

The MIL-STD 1553B is suitable for systems where the generation and transfer of data are regular and static in nature. It is a shared-media network that supports precise timeliness in a deterministic way but cannot address new needs of high-bandwidth data.

### 2.2 To replace MIL-STD 1553B

Our work complements the recent research in the study of future methods of avionics data communication for military aircrafts to replace the MIL-STD 1553B. The interconnect technologies available today which could meet the military requirements are Fiber Channel, ATM and Switched Ethernet. Such commercial off-the shelf (COTS) network products are expanding their application domain thanks to their maturity.

The FC-AE (Fiber Channel Avionics Environment) working group is developing an operational profile of the existing Fiber Channel standard for use in military avionics environments [1]. The working group is defining a set of real-time constructs to provide the deterministic latency and bandwidth needed by military aircraft systems.

Parish and Briggs [2] proposed a communication architecture based upon ATM as a future avionic interconnect system and they emulate the MIL-STD 1553B over ATM to allow the coexistence of the two protocols.

Although these high speed networks are available, Switched Ethernet has been drawing significant interests because of its extremely low price, maturity and expandability. In fact, this COTS network has been recently integrated into avionics applications: it is extensively used in civil aircraft A380 [3] and succeeds to maintain the integrity of the data and the network. Therefore, after this successful civil experience, we propose Full-duplex Switched Ethernet as a future technology for the military avionics data communication.

Despite its popularity and low cost, Switched Ethernet has a serious drawback when carrying real-time messages. Congestion might occur in a switch when several ports forward their traffic to the same output port and messages can be lost if a switch output port queue overflows. Military aircraft operate in a hostile and dynamic environment, so they are considered as critical systems where a failure might have a disastrous consequence on the operational mission or the aircraft itself. So, a message loss or a violated deadline is not allowed when replacing the MIL-STD 1553B. Thus, we have to add new mechanisms over Switched Ethernet to avoid information loss and to guarantee hard real-time communication with low latency.

### 3. Switched Ethernet and real-time

The use of the classic CSMA/CD protocol to control the access to the shared medium results in a non deterministic access delay. Hence, many techniques have been developed to guarantee predictability on Ethernet in order to use the Ethernet network for real-time systems. These proposed real-time transfer solutions decrease the collision probability and ensure an exclusive access to the network medium. The switching technology could make these proposals easier since Switched Ethernet provides a private collision domain to each of the ports of a switch, and when using Full-Duplex links on each of these ports, collisions do not exist. Clearly, by eliminating collisions, we have a better predictability of the protocol but it is still indeterministic because overflows might still occur in the switches and messages might be lost. So, the real problem when building real-time communication over Full-Duplex Switched Ethernet is to be able to guarantee the deadlines of time critical messages. The use of switches results in duplicating the time transmission when using a store and forward mode which is usually mandatory in safety conscious environments like embedded systems. In the rest of this section, we will only review the most interesting approaches used for the Ethernet that can be adapted to Full-Duplex Switched Ethernet to guarantee the real-time constraints and compare their relative merits.

#### TDMA

The simplest approach to have real-time guarantees on Ethernet is by using the TDMA (Time Division Multiple Access) approach [4, 5]: time is divided into slots often of equal size, each terminal transmits during its own period of time called slot. Bus master sends a frame synchronization signal before each round of messages to synchronize clocks. The slots repeat continuously giving each terminal periodic access to the channel. In this method, network size

is fixed during installation and slots are pre-allocated. H. Shin and J. Lee [9] worked on the TDMA implemented Ethernet which makes each terminal transmit its message on predefined slot time based on the globally synchronized clock. They developed a variable allocation scheme that is based on the traffic characteristics to achieve an efficient use of bandwidth and to schedule more real-time task sets than the static allocation scheme. This bandwidth reallocation scheme consists of reporting changes, calculating a new schedule and reliably broadcasting the schedule. Using this protocol, TDMA implemented Ethernet becomes suitable for distributed real-time systems where traffic characteristics change dynamically.

As we can see, with the general TDMA protocol, the slots time are determined to be a fixed value before the run time, so, the waste of the bandwidth is unavoidable since even nodes that do not have any packets to send, will still reserve the network for their allocated slot. As different from this approach, on the TDMA implemented Ethernet, the slot and frame time are determined considering the traffic characteristics in a dynamic way to achieve an efficient bandwidth use and guarantee to meet real-time constraints.

The use of this method could be efficient to have a real-time behaviour over Full-Duplex Switched Ethernet. However, we must take into account the fact that the frame has to go through the switch before reaching its destination. This mainly affects the synchronization process: the slaves receive the synchronization frame after at least twice the time required on the classic Ethernet (one transmission from the master to the switch and the other from the switch to slaves). In the other hand, the use of switches has no effect on the slot allocation scheme: the one used on TDMA- Ethernet will drive the traffic both on the input links of the switch and on the output links (the same traffic pattern will exit only shifted in time).

#### FTT-Ethernet

A mixed approach is presented by Pedreiras and Almeida in FTT-Ethernet [10], which uses a master-slave organization with TDMA protocol. It follows the Flexible Time Triggered paradigm and supports different types of traffic: event triggered, time triggered, real-time and non real-time. The traffic is organized in elementary cycles of fixed size. Each cycle is divided into a synchronous window for guaranteed traffic and an asynchronous window for non real-time traffic. At the beginning of the elementary cycle, the master station broadcasts a synchronization message that contains the list of identifiers of messages that must be transmitted in

the synchronous window of the cycle and the time at which the stations may transmit. The slave stations transmit then the data for a specific amount of time. After the synchronous window, the master polls some stations for possible asynchronous traffic. The master station plays the role of system coordinator and it is responsible for keeping the functionalities required for proper system operation. A traffic scheduler is implemented in the master to guarantee the real-time constraints on synchronous messages and a fair access for non real-time traffic. Slave stations execute the application software required by the user and produce messages according to their identifier tables. At the end of the elementary cycle, there is a guard window. As soon as it begins, stations are no longer allowed to transmit.

Despite having been originally designed for Ethernet, this protocol can also work over Switched Ethernet. The FTT-Ethernet protocol can take advantage of Switched Ethernet features: the use of the switch eliminates possible collisions and this can reduce the need for synchronization mechanism between the slave nodes. In this case, upon reception of the trigger message, the terminals only need to identify which messages they should produce within the elementary cycle and transmit them immediately. Conversely, the use of FTT-Ethernet may contribute to reduce the congestion problem in the switch since it performs the traffic control required to guarantee bounded delays. However, using FTT-Ethernet protocol over Switched Ethernet requires the addition of extra idle time in each elementary cycle to support the forwarding delays on the switch to guarantee that every transmitted message arrives to its destination within the same elementary cycle as perceived by the master. Otherwise, the variable delay introduced by the switch could make some frames overflow the current cycle which in turn could delay the synchronization message of the next cycle and disturb the synchronization mechanism. So, the applicability of this approach over Switched Ethernet requires some modifications in the master scheduler in order to provide an efficient use of the network and to guarantee the real-time constraints.

### **Token passing**

Token passing protocol was widely used to have a real-time transfer over Ethernet: a token is circulated among the stations and only the station that currently holds the token is allowed to transmit data during a bounded time. When it has exhausted its right, the station transfers the token to the next using a special message. The temporal properties of token-passing systems have been extensively studied [13, 14, 15]. This protocol is based on two parameters, the timed token rotation time (TTRT) and the synchronous bandwidths. TTRT is the time elapsed between two

consecutive receptions of the token at a given station. A fraction of TTRT is assigned as the synchronous bandwidth of an individual station. After a station receives a token, it will transmit its synchronous messages for a maximum period given by its synchronous bandwidth and then it can transmit its asynchronous messages only if it has received the token earlier than expected. Furthermore, it can transmit the asynchronous frames only for a period of time equal to the time by which the token has been early. These two parameters should be carefully calculated to ensure the protocol performance. In fact, the TTRT is very important: a smaller value limits network capacity and if TTRT is too large, the token may not arrive often enough at a station to meet message deadlines. In the other hand, the allocation of the synchronous bandwidths is critical; a too small value results in violating the deadline because the node has not enough network access time. Conversely, large value causes a long token rotation time and message deadlines might be missed.

The real-time network RETHER [11], developed by Venkatramani and Chiueh, is implemented for existing Ethernet to provide bandwidth guarantees. There is two operating modes: a regular CSMA/CD mode in absence of real-time traffic and a token passing mode for real-time operations. When there are no nodes with real-time messages to send, the RETHER operates in CSMA/CD mode like Standard Ethernet. As soon as a request for a real-time traffic arrives on a given terminal, this terminal initiates a transition to the token passing mode, all terminals have to acknowledge this transition and from this point the system operates according to the token passing protocol. In this later mode, terminals are divided in two groups: the RT group for terminals with real-time messages and NRT group for all the others. Access to the channel for both groups is regulated by a token. The RT group is given the priority to transmit messages. Each station of the RT group gets the token once every period and the station that do not have real-time traffic are visited as soon as all RT stations have been visited and there is still available time before the next token rotation period. The system goes back to CSMA/CD mode when the RT group becomes empty. The experimental results show that the system has important overheads in case of small packets because of switching between the two modes.

In our knowledge, there are no explicit proposals of using token passing protocol over Switched Ethernet. We think that the priority driven token ring protocol, which has been incorporated in the IEEE 802.5 standards [12], could be a good approach to have real-time communication over Switched Ethernet. In this protocol, the token contains a priority field which regulates station's access to the

ring and we could accord a high priority to the stations that have urgent messages to transmit. With this control access, we can avoid congestion in the switch and guarantee the real time constraints by respecting the deadlines. But, we should take into account the delays introduced by switches which add an overhead to the token passing operations because no station is allowed to transmit before it has received the token. The token passing operation requires twice the time needed in the Standard Ethernet (from the emitting station to the switch and from the switch to the receiving station).

### **Traffic Shaping**

Traffic Shaping is an interesting approach that has been initiated by Kweon and Shin [16] to achieve real-time communication over Ethernet. The idea is that a smooth traffic, in which messages arrive at a constant rate, suffers less from collisions than a bursty traffic. Specifically, a traffic smoother is installed in every station between the Ethernet MAC layer and the UDP or TCP/IP layer: first it gives real-time (RT) packets priority over non real-time (NRT) packets, second it smoothes the NRT-stream to reduce collision with RT-packets from the other nodes. The smoothing process uses the token bucket principle [6]: when a burst occurs, the messages are kept in a queue and sent one after the other at a rate which is lower than the arrival rate. The real-time traffic is not smoothed and is sent as soon as it arrives. The authors have shown that there is a significant reduction of RT packet deadline-miss ratio when both RT and NRT packets are transported over Ethernet with adaptive traffic smoothing. Traffic smoothing approach is efficient for soft real-time systems, but needs additional mechanisms to be applied to hard real-time systems. Despite its apparent attractiveness, traffic smoothing over Ethernet is less appealing because nowadays, the switched network architecture dominates future LAN environments and have less difficulty to transmit bursty traffics.

Based on the above experiences, Varadarajan and Chiueh [22] proposed a real-time Ethernet switch EtheReal that supports bandwidth guarantee over Switched Ethernet. EtheReal is based on a real-time connection setup algorithm that installs, per connection, bandwidth guarantee information along the network path from the source host to the destination host. It distinguishes two classes of traffic, best effort and real-time. When a station wants to transmit real-time traffic to another one, it sets a connection via its real-time communication daemon (RTCD). A connection request that contains the QoS parameters and the destination identifier is sent to the switch. If the switch accepts the QoS requirements, it returns an acknowledgment to the

initiating node. In that moment, the initiating station RTCD creates a proxy IP address that is used to send real-time packets. Best effort traffic will be forwarded in a usual way without special guarantees. Unlike this approach where switches implement the improvements, the Traffic Shaping approach developed by Loeser and Haertig [17] implements the improvements inside the stations. Their idea is: to guarantee some deterministic performances of the network, the incoming traffic has to be bounded. Therefore, traffic shaper is installed for each stream to regulate bursts and to make the stream as regular as possible in order to reduce the chances of congestions in the switch. The shaper uses the leaky bucket controller concept to model the arrival constraints representing each stream. A leaky bucket controller with leak rate  $r$  and bucket size  $b$  imposes that the traffic generation is bounded by an affine function  $f(t) = b + rt$ . This function represents the arrival curve of the traffic to the input of the switch. They show that, with the Traffic Shaping as node cooperation mean, reliable transmission with bounded delays could be guaranteed for the soft real time. In our case, we will analyze this approach over Full-Duplex Switched Ethernet used for a hard real time system interconnection and improve it by adding a priority handling method to guarantee the deadline constraint for the urgent messages.

### **Comparative Study**

As we can see, it is difficult to design a perfect approach over Switched Ethernet to have real-time communications. With TDMA, the waste of bandwidth is unavoidable and the system flexibility is reduced because a static schedule, built before run-time, is used. This limitation is not severe when having a static real-time system, but the real difficulty is the impact of the additional delays introduced by switches that should be taken into account when developing the allocation scheme and maintaining the distributed clock synchronization. Unlike this approach, Token passing offers a flexible allocation bandwidth and a better bus utilization when the protocol parameters (TTRT and synchronous bandwidth) are carefully chosen. But, it introduces an important overhead with the use of switches especially when only one station has traffic to transmit. In the other hand, the use of the Flexible Triggered Time approach is interesting because it can take advantage of Switched Ethernet features. For example, the use of switches can decrease the importance of the synchronization mechanism since stations can transmit their messages immediately within the elementary cycle. In the other hand, FTT approach can perform the traffic control on the Switched Ethernet to guarantee bounded delays by reducing the congestion occurrence in switches.

Unfortunately, the use of switches increases the complexity of the master scheduler which has to take into account the forwarding delays on the switches. The traffic shaping approach seems the easiest one to adapt over Switched Ethernet. In fact, we determine the adequate traffic shaper characteristics for each stream to have controlled bus utilization with bounded incoming traffic that reduces congestions in the switch. Thus, a good knowledge of our system input characteristics can help us to determine the adequate parameters of each traffic shaper to have a reliable transmission with bounded delays. A better performance comparison of these different approaches could be made by leading experimental analysis on a real traffic case. In this paper, we have started by analyzing the traffic Shaping approach and the detailed study is given in next sections.

#### 4. Traffic Shaping modelling

In this section, we explicit the characteristics of the circulating traffic that we should guarantee when replacing the MIL-STD 1553B data bus. Then, we describe a Full-Duplex Switched Ethernet model of the military system under consideration, which implements the Traffic Shaping approach to have real-time behaviour.

##### 4.1 Traffic model

In military applications, as we have explained, there are two kinds of communications between the different equipments. The first represents the periodic exchanges which are exactly known in terms of quantity and frequency. The second is the sporadic traffic characterized by a maximal response time and a maximal length.

There are  $n$  sets of streams, one set for each node:  $(S_1, S_2, \dots, S_n)$ . Every set  $S_i$  is formed by periodic and sporadic streams transmitted by the associated terminal  $i$ :

$$S_i = \{m_{i1}, m_{i2} \dots m_{iN}\}$$

- A periodic message  $m_{ij}$  is characterized by a period denoted by  $P_{ij}$  and a sporadic message  $m_{ik}$  by the minimal inter-arrival time  $P_{ik}$  (we suppose that a node generates at most one sporadic message of each type once every minor frame).
- The deadline of a periodic message is the end of the period in which it arrives; that is, if a message  $m_{ij}$  arrives at time  $t$ , then its deadline is  $D_{ij} = k * P_{ij}$  where  $(k-1) * P_{ij} \leq t < k * P_{ij}$ ; and the deadline of a sporadic message  $m_{ik}$  that arrives at time  $t$  is

$D_{ik} = t + R_{ik}$ , where  $R_{ik}$  is its requested maximal response time.

- The maximal length of each message  $m_{ij}$  in set  $S_i$  is  $L_{ij}$ .

##### 4.2 Network model

We consider the network topology as consisting of  $n$  Ethernet terminals connected with Full-Duplex links to a switch (these terminals represent the  $n$  existing equipments currently connected on the MIL-STD 1553B data bus that we compare to). In every terminal  $i$ , we associated a traffic shaper to each stream  $m_{ij}$  based on a leaky bucket, characterized by  $b_{ij} = L_{ij}$  its maximal size and  $r_{ij} = b_{ij} / P_{ij}$  its rate. A terminal is modelled by one multiplexer which sends the multiplexed flows to the central switch.

The Full-Duplex Switched Ethernet model depends on the behaviour of the switch. In our case, we consider a 10 Mbps switch in "store & forward" mode (waiting until the complete reception of the frame). Moreover, it is operating at wire speed, which means that all ports of a switch can simultaneously transmit or receive at their full bit rates. Thus we assume the switch is able to process a continuous flow of minimal-size Ethernet frames and we arbitrarily derive the technological switch relaying latency ( $\tau$ ) from this wire speed behaviour.

We give an example here of the network architecture with four terminals and four sets of streams of three messages each (Figure 1).

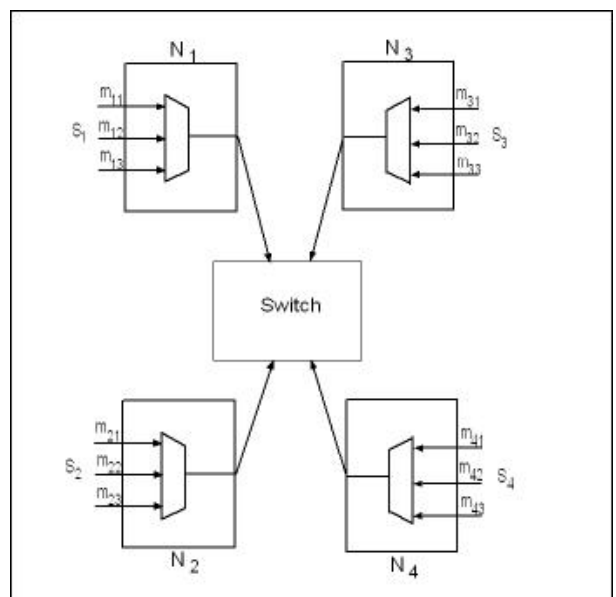


Figure 1: Terminal output port model

## 5. Traffic Shaping performance evaluation

### 5.1 Case study and metric definition

Our case study is a representative real time traffic circulating between 20 equipments connected on a MIL-STD 1553B data bus, like in the Rafale aircraft. The transaction table is statically defined in such a way that all time constraints are enforced. In fact, the biggest message period is about 160 ms, so a major frame of 160ms is defined on of the MIL-STD 1553B; and the smallest message period is about 20 ms, so minor frames have a duration of 20 ms. Moreover, the most urgent sporadic message has a response time of 3 ms. So, the deadline of this type of message represents the hardest real-time constraint to respect when using Full-Duplex Switched Ethernet.

To investigate the effectiveness of the Traffic Shaping approach used over Switched Ethernet, we are interested in the maximal end to end delay bound in each port of the switch that we compare to the deadline of the urgent messages to be sure that even in the poor case of the arrival messages, we respect the hardest real-time constraint required by the military application.

To calculate the maximum queuing delay in the network switch, we use the network calculus introduced by Cruz [7,8]: the delay bound of a transmit switch port depends on the traffic arriving at that switch port, described by its arrival curve and on the availability of the switch to transmit that data.

In our case, the arrival curve in a switch port depends on the multiplexed arrival curves of the different streams in each terminal. As we have explained when describing the Traffic Shaping approach, thanks to the use of traffic shaper, every stream  $m_{ij}$  has a linear arrival curve  $\alpha_{ij} = b_{ij} + r_{ij} t$ . So, the maximal delay in each switch port is given by the time needed to transmit the bursts of the multiplexed traffic when using a FCFS multiplexer with a capacity  $C$  plus the delay imposed by the electronics of the switch. Thus, the bounded latency in switch port  $i$  is:

$$D_i = \frac{\sum_{j \in S_i} b_{ij}}{C} + \tau \quad [1]$$

### 5.2 Experiments and analysis

In order to have an experimental performance evaluation of the Traffic Shaping approach over Full-Duplex Switched Ethernet, we developed a computing tool based on our model system. Given the traffic characteristics in the input, this software constructs the different arrival curves and calculates

the latency bound in each switch port. The delay bounds for the traffic shaping approach, applied to our real traffic, are demonstrated in figure 2.

We computed latency bounds in the 20 switch ports. Clearly, one can see that in some switch ports, like port 8, the delay bound is high (12 ms) and it is higher than the deadline of the most urgent sporadic messages (3 ms), so, the real-time constraints are violated when using the traffic shaping approach over switched Ethernet. We can conclude that despite the relative speed ratio between Switched Ethernet (10 Mbps) and MIL-STD-1553B (1 Mbps), real-time constraints are not necessarily respected and having a Switched Ethernet with a higher rate is not sufficient to satisfy the real-time constraints required by the military applications.

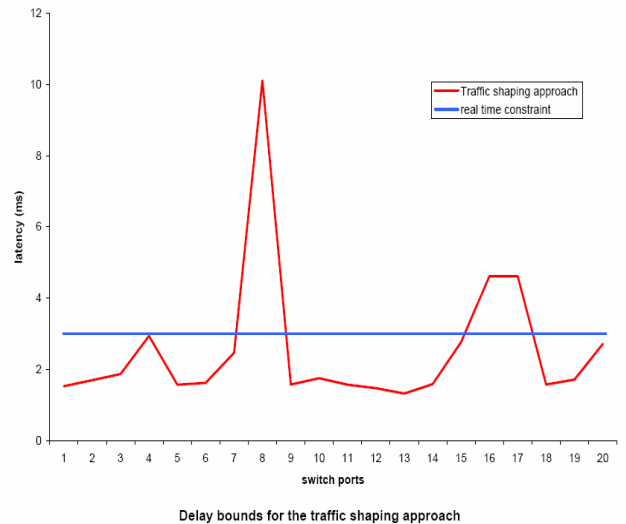


Figure 2: Delay bounds for the traffic shaping approach

In order to meet the delay requirements of the urgent packets, we propose to use a priority handling in addition of the traffic shaping approach. Therefore, we use the priority model of 802.3 (802.1p). This model defines a 3 bits priority field in the extended Ethernet frame. With these 3 bits, eight priority levels can be defined to handle real-time traffic. Current practice of switch manufacturers is to implement at most four queues of different priority per switch port.

In this approach, within a terminal, packets are given different priorities depending on their urgency and their deadline, and a non preemptive fixed priority scheduling is used in switch ports to transmit the

different messages. We consider 4 priority types in each node:

- Priority 0 for the urgent sporadic messages with a requested maximal time of 3 ms
- Priority 1 for the periodic messages
- Priority 2 for the sporadic messages with a requested maximal response time ranging from 20 ms to 160 ms
- Priority 3 for the sporadic messages with a maximal response time bigger than 160 ms.

In this case, we model each terminal by a 4-FCFS multiplexer with four queues, one for each priority. It has been shown in [7,8] that for a regulated arrival pattern set  $S_i$  characterized by  $(b_{ij}, r_{ij})$   $j = 1, \dots, N$  to a 4-FCFS multiplexer with a capacity  $C$ , the maximal latency bound of the priority  $k$ ,  $k = 0, \dots, 3$ , in switch port is is:

$$D_{i,k} = \frac{\sum_{j \in \{r/m_{ir} \in P_l^i, l \leq k\}} b_{ij} + \max_{j \in \{r/m_{ir} \in P_l^i, l > k\}} b_{ij}}{C - \sum_{j \in \{r/m_{ir} \in P_l^i, l < k\}} r_{ij}} + \tau \quad [2]$$

With  $S_i = P_0^i \cup P_1^i \cup P_2^i \cup P_3^i$  and  $P_l^i$  is the set of messages with priority  $l$ .

Intuitively, this means that packets arriving at a given priority are queued on a first-come, first serve basis. When, the link is free, the packet from the queue that has the highest priority among the nonempty queues is selected. If, just after the packet has started to be transmitted, a new packet arrives in a higher priority queue, the newly arrived packet will have to wait until the currently transmitted packet has been completely sent. There is a potential blocking time of the duration of the longest packet because emission may not be preempted.

### 5.3 Final results

In figure 3, we show the computed delay bounds for the traffic shaping approach with the priority handling method. We see that the latency bound for messages with high priority is lower than 3 ms, which represents their maximal response time. So, we respect the deadline constraints for the urgent sporadic messages. Moreover, the latency bound of periodic messages is smaller than the one obtained

without using priorities. These results show that the priority handling method combined with the traffic shaping approach may be a good mean to improve the predictability of the message transfers and to respect the real-time constraints required by the military applications.

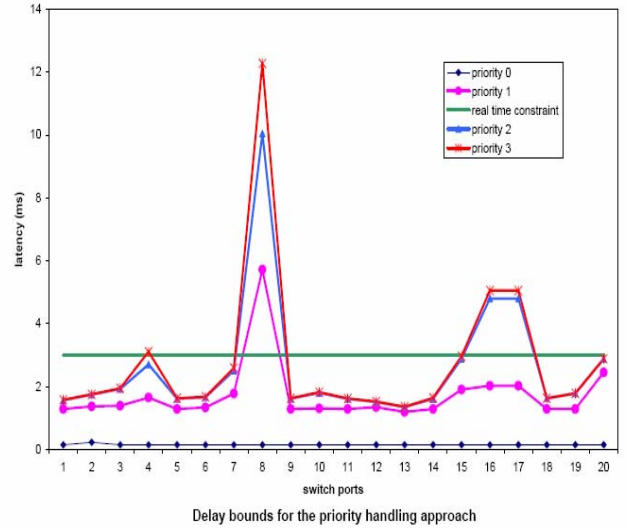


Figure 3: Delay bounds for the traffic shaping approach with the priority handling

## 6. Conclusion

In this paper, we show that Full-Duplex Switched Ethernet could be an attractive candidate to replace the current military data bus, the MIL-STD 1553B, in the future military aircrafts. With an adequate approach to support hard real-time communication, we were able to guarantee a deterministic transmission over Full-Duplex Switched Ethernet operating at 10Mbps.

Among the various real-time transfer solutions, we analyzed the traffic shaping approach with the priority handling. In order to reduce the possible congestions in the switch and to prevent switch queues from overflowing, each station is required to control its traffic to keep the global bus utilization controlled. Specifically, we have installed a traffic shaper per stream to impose a maximal arrival curve that respects the stream characteristics and reduce the possible bursts. Moreover, in each of the terminal equipments, the urgent messages with a small response time are given priority over the other

messages. We have shown in experiments that the traffic shaping approach with priority handling can be used to achieve deterministic frame transmissions with bounded delays that conform to the real-time constraints required by military applications. In the proposed method, there are no modifications of the Ethernet hardware (neither in the switches nor in the Ethernet interface of the terminals), this allows a quick industrial path to the deployment of Ethernet as a real-time embedded network.

Future work will target other QoS guarantees, like jitter which is inherently low on the 1553B applications and we will try to adapt the Token Ring approach to the switched Ethernet, since it seems able to guarantee bandwidth and bounded access time for different stations. Then, we will make a comparative study between the two approaches and give the pros and cons of each one.

## 7. References

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