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Performance analysis of a Master/ Slave Switched Ethernet for Military Embedded Applications

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***Abstract*—Current military communication network is a generation old and is no longer effective in meeting the emerging requirements imposed by the next generation military embedded applications. A new communication network based upon Full Duplex Switched Ethernet is proposed in this paper to overcome these limitations. To allow existing military subsystems to be easily supported by a Switched Ethernet network, our proposal consists in keeping their current centralized communication scheme by using an optimized master/slave transmission control on Switched Ethernet thanks to the Flexible Time Triggered (FTT) paradigm. Our main objective is to assess the performance of such a proposal and estimate the quality of service we can expect in terms of latency. Using the Network Calculus formalism, schedulability analysis are determined. These analysis are illustrated in the case of a realistic military embedded application extracted from a real military aircraft network, to highlight the proposal's ability to support the required time constrained communications.**

***Index Terms*—Switched Ethernet, Master/ Slave protocol, Performance Evaluation, Schedulability Analysis, Embedded Applications, Network Calculus**

I. Introduction

During the last few decades, many specific data buses have been successfully used in various military embedded applications, like MIL STD 1553B [1], STANAG 3910 [2] and SCI links [3]. However, with the increasing complexity of interconnected subsystems and the expansion of exchanged data quantity, these data buses are a generation old and may be no longer effective in meeting the emerging requirements of the next generation military embedded applications in terms of bandwidth and latency. In addition, using these data buses makes the global communication network heterogeneous and real time guarantees difficult to prove. Clearly, a new homogeneous communication network is needed to fulfill these requirements.

Currently, there is a new trend to use Commercial Off The Shelf (COTS) technologies instead of dedicated solutions in many applications domains to reduce the development costs and facilitate the maintenance process. However, the problem with COTS is reconciling the different requirements of commercial and critical applications. For military embedded applications, it is essential that the communication network fulfills a set of requirements, e.g. predictable behavior under hard real time constraints, temporal deadlines guarantee and the use of several classes of traffic (periodic and aperiodic) with guaranteed quality of service.

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Among several high speed COTS networks, Switched Ethernet is incontestably the most cost effective solution thanks to its ubiquity, simplicity and maturity and it became the communication network in many application domains e.g. an ARINC 664-compliant Avionics Full Duplex Switched Ethernet (AFDX) [4] network has been integrated recently into new generation civil aircrafts like the A380, to replace the ARINC 429 data buses [5]. Thanks to control mechanisms added in switches, this technology succeeds to support the important amount of exchanged data ([6], [7], [8], [9]). It is worth to note that this technology is initially designed to support civil requirements where only periodic traffic is considered, whereas for military requirements several classes of traffic (periodic and aperiodic) are needed in severe military environments.

Therefore, a new communication network based upon Full Duplex Switched Ethernet is proposed in this paper to fulfill the requirements of the next generation military embedded applications. However, the key argument against using Switched Ethernet in this context lies in its non deterministic behavior that makes it inadequate to deliver hard real time communications due to the possible congestions in switches. Hence, achieving a real time behavior with low latency over Switched Ethernet still needs the use of specific real time mechanisms. Various real time communication solutions are recently offered for Switched Ethernet. These approaches range from enhancing the switch behavior like Ethereal [10] and using specific scheduling algorithms [11], to implementing techniques to control and prevent switches overloads like Traffic Shaping [12], TDMA (Time Triggered Ethernet (TTE) [13]) and master/slave mechanism (Ethernet PowerLink (EPL) [14], EtherCAT [15], Flexible Time Triggered Switched Ethernet (FTT-SE) [16]). An overview of these solutions can be found in [17] and [18].

In ([19], [20]), as a first step the authors propose a network with a distributed communication scheme based upon Full Duplex Switched Ethernet for military applications. The obtained results for a realistic military application show the ability of this proposal to improve global throughput and system's flexibility and to satisfy the real time constraints. However, the existing subsystems typically use a centralized communication scheme, influenced by the widely used command/response data bus MIL STD 1553B [1]. Therefore, migrating all existing applications into a distributed communication scheme compliant form could be a complicated and expensive step. To avoid this process, our proposal in this paper consists in keeping the current military centralized communication scheme upon Switched Ethernet by using a master/ slave protocol within the adaptation of FTT-SE to military context. FTT-SE presents significant interests thanks to its optimized master/ slave transmission control and its flexibility. This paper focuses on the relevant aspects of such proposal and the offered real time guarantees in the case of a realistic military application, with reference to Switched Ethernet temporal analysis and use of theoretical tools like Network Calculus [21]. **Unlike existing approaches in this area like [12], [22] and [23] developped for industrial applications, this paper focuses on a specific solution based on Master/ Slave mechanism to fulfill the military applications requirements and deals with the schedulability analysis of such proposal. It is worth to note that compared to common industrial applications, one of the main constraints for military applications is keeping the existing applications whereas the bandwidth utilization is not necessarely the primary design concern.**

Hence, our main contributions in this paper are three fold. **First**, to adapt FTT-SE to the context of the referred applications, new mechanisms are introduced to handle periodic and aperiodic traffic based on a bandwidth reservation method to guarantee predictable transmissions and the stability of the system temporal behavior. **Second**, in order to deal with the worst case performance prediction of such proposal, schedulability analysis are used based on the Network Calculus formalism [21]. To our best knowledge, this kind of analytic study has not been addressed yet for a master/ slave Switched Ethernet protocol. **Third**, these general analysis are illustrated in the case of a realistic military aircraft network, considered as a representative military embedded application, to highlight the proposal's ability to support the required time constrained communication.

In the next section, we review the most relevant master/slave approaches to provide real time communication over Switched Ethernet and relate them to our work. Afterward, the performance analysis of such proposal is tackled as follows. First, the adaptation of FTT-SE to the military context is explained in section 3. Then, Schedulability analysis and an optimization process of system resources are detailed in section 4. Finally, its practical feasibility within a realistic application is illustrated in section 5. Section 6 concludes the paper.

II. MASTER-SLAVE ETHERNET PROTOCOLS

Various real time communication solutions were offered for Switched Ethernet. However, since the idea in this work consists in keeping the centralized communication scheme used in current military embedded applications, we review in this section only the most relevant solutions using the master/ slave approach.

Ethernet Powerlink (EPL) is supported by the Ethernet Powerlink Standardization Group [14]. A key concept in this protocol is the EPL cycle which is a fixed time slot used to transfer traffic on the bus. The following time periods exist within one cycle: (1) Start period where the master sends a special frame to slaves to signal the beginning of the cycle; (2) Isochronous period to send and receive isochronous traffic; (3) Asynchronous period to transfer only one asynchronous message; (4) idle period used to assure the temporal isolation between isochronous and asynchronous data. *"This protocol offers hard guarantees for the preplanned traffic and soft guarantees for the on demand traffic"* [18]. However, EPL is a bandwidth inefficient protocol given its pure master/slave control, which is not able to exploit the parallel forwarding paths in the switch. It typically uses special repeater hubs but regular switches can be used only if the application is jitter-tolerant.

EtherCAT is supported by the EtherCAT Technology Group [15]. The basic concept of this protocol lies in the EtherCAT segment device which receives and sends standard Ethernet frames from and to the master. This specific device may consist of a large number of EtherCAT slaves arranged in an open ring. These slaves can process the incoming frames "on the fly" to extract (or insert) data from (into). Each slave in the EtherCAT segment transfers the frame to the next slave and the last slave will send the frame back to the master. Such devices are realized with specific ASICs and special interfaces to guarantee the frame transfers between slaves. This protocol offers good performance with very short cycle times (30μs) [17]. However, it is based on non standard hardware which conflicts with the main interests of using Ethernet e.g costs, availability and compatibility. Moreover, it also presents some limitations in terms of scalability.

FTT-SE [16] uses an optimized master/ slave mechanism compared to standard master/ slave protocol where the master addresses periodically several slaves with a single Trigger Message (TM) instead of using one control message for each slave. This fact allows an efficient bandwidth utilization and saves overheads compared to standard master/ slave protocol. A key concept in this protocol is the Elementary Cycle which is a fixed time slot used to schedule traffic in the bus; and within each Elementary Cycle two windows are considered synchronous and asynchronous, dedicated to periodic traffic transmission and aperiodic traffic transmission, respectively. The temporal isolation between the two windows has to be guaranteed to provide the temporal system's stability. FTT-SE presents several advantages that are relevant to our application scope. For example, it makes an efficient use of the aggregated bandwidth using its optimized master/ slave transmission control; it has a good flexibility in terms of configuration and operation mainly concerning the combination of periodic and aperiodic traffic; and finally it is fully compatible with COTS components. Hence, this protocol is selected and adapted to the military context to guarantee the main requirements of determinism and predictability. These adaptations are detailed in the next section.

III. THE ADAPTATION OF FTT SWITCHED ETHERNET TO THE MILITARY CONTEXT

Our proposal is based on the Flexible Time Triggered (FTT) paradigm. In this section, the basic concepts of the current version of FTT Switched Ethernet (FTT-SE) proposed by Almeida and Marau [16] are presented. Then, the identified limitations of this protocol to be used in a military context are described. Finally, the proposed adaptation mechanisms to overcome these identified limitations are detailed.

A. Basic Concepts

FTT paradigm was initiated by Almeida, within its implementation on CAN (FTT CAN [24]). Then, this paradigm was extended to Ethernet by Pedreiras (FTT Ethernet [25]) and recently to Switched Ethernet by Marau (FTT-SE [16]). The main concepts of the latter used in this paper are presented herein.

The Elementary Cycle starts with the Trigger Message transmission to synchronize the network (figure 1).

For periodic traffic, the messages that must be transmitted within the respective Synchronous Window are identified within the Trigger Message. Upon TM reception, nodes decode the TM and transmit immediately the periodic messages triggered by the master during the synchronous window. The periodic traffic scheduling is done centrally in the master which facilitates the scheduling policy choice and the communication requirements update.

For aperiodic traffic, FTT-SE uses a signaling mechanism explained in ([26]) that exploits the full duplex features of Switched Ethernet. The idea consists in encoding in one message the characteristics of the generated aperiodic messages during one Elementary Cycle, namely length and destination, and sending this encoded message to the master during the TM reception and decoding (called guarding and turn around windows). When receiving the aperiodic requests, the master will schedule such traffic and trigger its transmission using the TM, such as for the periodic traffic [27].

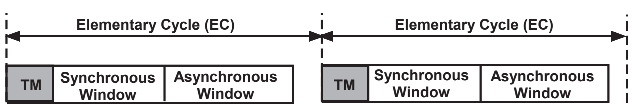

Fig. 1. Elementary Cycle structure

B. Identified Limitations

1) Handling Periodic Transmissions: The master builds each Elementary Cycle schedule so that the periodic communication activity is limited to the maximum duration of the synchronous window LSW. This means that each selected periodic message has to be transmitted and received within the synchronous window of that Elementary Cycle. Hence, the communication activity time of periodic traffic depends mainly on the communication medium load and particularly crossed switches.

In [16], stop conditions are defined in the master to build the Elementary Cycle schedule. These conditions are based on checking the load of uplinks and the finishing transmission instant for downlinks, against the end of the synchronous window. However, these conditions only guarantee that the traffic scheduled for one Elementary Cycle can effectively be transmitted in that Elementary Cycle. The traffic schedulability is not verified by these conditions and further conditions and analysis are needed to reach this aim.

2) Handling Aperiodic Transmissions: In the current version of FTT-SE protocol [26], aperiodic requests are handled by the master thanks to a signaling mechanism explained in section III-A. This signaling mechanism admits the transmission of one signaling message with minimum size (64 bytes) per node in each Elementary Cycle, during the TM reception and decoding by nodes. However, this option limits the number of nodes in the system. For example, with a Fast Ethernet network (100Mbps) a standard hardware configuration for slaves (decoding time about 200μs) and TM size about 300 bytes, the maximum number of messages is 33. Admitting one such message per node and per cycle, only 33 nodes can be served with aperiodic communication. In this case, the use of a standard switch with 32 ports can limit the signaling latency to two Elementary Cycles in the worst case and the polling latency to one elementary Cycle.

As one can notice, this approach depends mainly on the **decoding time** and a **specific hardware implementation** can inherently reduce the **nodes number** and consequently increase the worst case response time of messages. For example, with a decoding time about 50μs, the maximum number is reduced to 11 nodes. In the case of using the 32 ports switch to serve 32 nodes, the signaling messages can be multiplexed leading to a signaling latency of four Elementary Cycles in the worst case; and given this important signaling latency the polling latency can inherently increase depending on the **ready messages** in the master and **the scheduling policy**. The benefits of this approach are interesting for messages with long inter-transmission times compared to the Elementary Cycle duration. However, if it is not the case, the response times could be unacceptable. **In addition, there is an important number of parameters as explained before like the decoding time, the hardware, the number of nodes and the scheduling policy that have to be taken into account, which can increase the unreliability of the response time upper bounds.**

3) Schedulability Analysis: **The mechanisms used in the current version of FTT-SE [16] to handle periodic and aperiodic transmissions make the traffic schedulability verification not possible. However, these analysis are essential to prove the predictability and the determinism of the system required by military applications.**

C. Proposed Adaptation Mechanisms

1) Handling periodic transmissions:

a) Periodic Requirements Table: The communication system management is carried out in the master using a data structure, called System Requirements Database (SRDB). This structure contains information concerning periodic traffic, aperiodic traffic and system configuration. The description of periodic traffic is given in the Periodic Requirements Table (PRT).

PRT $= \{PM_i(L_i, D_i, T_i, Sd_i, Rc_i), i = 1..N_p\}$
where

- i: message identifier and there is N_p periodic messages stored in the PRT structure;

- L_i: maximum message length in bytes;
- D_i: message deadline;
- T_i: message period;
- Sd_i: identifies the sender node;
- Rc_i: identifies destination address. It could be the address of one node or a group of nodes.

The periodic traffic set is scheduled by the master according to a static priorities scheduling policy which is commonly used in military applications to guarantee the system predictability and to reduce its complexity. Particularly, we will focus on Rate Monotonic (RM) and Deadline Monotonic (DM) scheduling. The transmission of messages is non preemptive but long messages are automatically fragmented and scheduled sequentially by the master on a per-packet basis. In this case, preemption is allowed at the message level, between packets.

b) Periodic Messages Scheduling: In order to guarantee the traffic schedulability, a different approach than in [16] is considered which consists in constraining the traffic in the source nodes so that the traffic limitation per Elementary Cycle and its schedulability are both guaranteed together. For this purpose, a bandwidth reservation mechanism is integrated in the master where an upper bound to the transmitted periodic traffic during an Elementary Cycle is guaranteed to each node, called $\sigma^{p,j}$ for node j. Then, the master schedules the messages according to RM or DM scheduling and builds an Elementary Cycle schedule with the ready messages to be transmitted. This schedule is encoded in the Trigger Message (TM) broadcast to the nodes. The concerned senders during that Elementary Cycle transmit the messages identified in the TM. Figure 2 illustrates this scheduling mechanism inside the master.

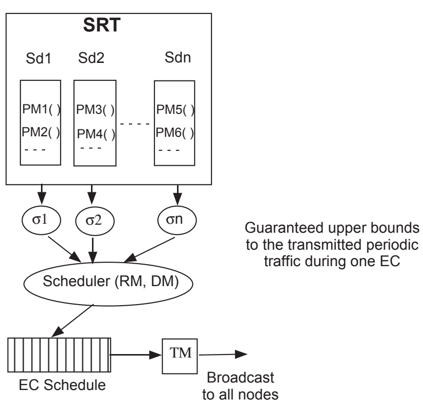

Fig. 2. Scheduling model of periodic traffic in the master

This mechanism leads to a pessimistic bandwidth utilization due to using upper bounds to the communication requirements. For example, the obtained network utilization of the considered case study with 1Gbps as a transmission capacity (see section V) is about 34%. Unlike industrial applications, this over design of resources would be well accepted in the military context because of scalability requirements. Hence, this approach guarantees the main military requirements of predictability to periodic messages, while the bandwidth utilization may not be the primary design concern.

2) Handling Aperiodic transmissions:

a) Aperiodic Requirements Table: The description of aperiodic traffic is given in the Aperiodic Requirements Table (ART).

ART $= \{AM_i(L_i, D_i, mit_i, Sd_i, Rc_i), i = 1..N_a\}$

Each aperiodic message i has a minimum inter-arrival time mit_i that must elapse between two consecutive messages. Aperiodic messages are then modeled as sporadic messages to assess the worst-case performances. The four other parameters are the same as in PRT table.

b) Aperiodic Messages Scheduling: Unlike the periodic traffic, the aperiodic traffic handling is not resolved by the master due to its lack of information concerning the exact aperiodic messages to transmit during each Elementary Cycle. **However, to guarantee that aperiodic messages transmission fits within the asynchronous window, a bandwidth reservation mechanism is used inside the master, the same as for periodic traffic, to impose an upper bound to the transmitted aperiodic traffic for each node during an Elementary Cycle. Then, each node transmits in an autonomous way only the aperiodic traffic that respects this guaranteed upper bound imposed by the master every asynchronous window**.

For this aim, the solution consists in constraining the amount of generated messages in each slave by using traffic shapers to respect the minimal inter-arrival times defined in the master ART table, and assuring a good isolation level for urgent messages with hard deadline constraints by using a fixed priorities multiplexer implementing Deadline Monotonic policy (the urgent aperiodic message with the smallest deadline will be tagged with the highest priority and the non real time messages without a finite deadline with the lowest priority). The obtained sorted queue at the multiplexer output is submitted to a selector which guarantees that only the messages that respect the guaranteed upper bound of aperiodic traffic imposed by the master are transmitted. Figure 3 illustrates this arbitration mechanism of aperiodic traffic used inside each slave.

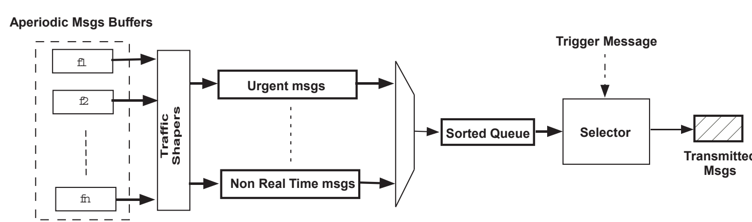

Fig. 3. Arbitration mechanism of aperiodic traffic in the slave

3) Schedulability Analysis: The schedulability of our proposal are determined using response time based schedulability test and Network Calculus formalism.

Response-time based schedulability tests are usually used for non preemptive fixed priorities scheduling e.g RM and DM, in distributed systems where the critical resource is not the computational power but the transmission medium bandwidth utilization. In Switched Ethernet networks, this latter depends mainly on switches output ports load which makes the exact Worst Case Response Time (WCRT) calculus very complex due to the huge possibilities of messages arrivals in switches. In order to handle this problem, an upper bound to the WCRT is considered herein and compared to the respective deadline. However, this schedulability test results in a sufficient but not necessary condition due to the pessimism introduced by the upper bounds. Nevertheless, we can still infer the traffic schedulability by comparing the computed WCRTs with the respective deadlines, i.e.,

$\forall i \in messages$, WCRT$_i \leq Deadline_i \Longrightarrow$ The messages set $messages$ is schedulable

The Worst Case Response Time (WCRT) consists of three parts as shown in figures 4 and 5 for periodic and aperiodic traffic, respectively:

- the parameter $WT1$ that corresponds to the waiting time between the arrival instant of the message and the instant the message effectively enters arbitration;
- **the parameter $WT2$ that corresponds to the waiting time between the instant the message effectively enters arbitration until the message is completely transmitted on the network medium, due to the interference caused by other priorities messages from the same source node**;
- the parameter $WT3$ that corresponds to the communication time of the message between the instant the message is completely transmitted on the network medium until its arrival to its destination, due to the transmission medium utilization.

Hence, the upper bound of the WCRT of a given message in this case corresponds to its maximal end to end delay bound from its source node to its destination node. However, the maximal end to end delay communication bound of a given message i sent by a source node j and crossing a set of network components defined by $path_i$, is as follows:

$$D_{eed}^{i,j} = D_{SRC}^{i,j} + \sum_{k \in path_i} (D_{SW}^{i,k} + D_{PROP}) \tag{1}$$

Where:

- $D_{SRC}^{i,j}$ is the maximal processing delay bound for transmission at the source node and it corresponds to the waiting time in the source node until the message is completely transmitted on the network medium. Then,

$$WT1^{i,j} + WT2^{i,j} \leq D_{SRC}^{i,j} \tag{2}$$

- D_{PROP} is the propagation delay needed to propagate the electrical signal from the source node to the switch and then from one switch to another until the destination, which is proportional to the length of used cables. In our model, this delay is considered as insignificant.
- $D_{SW}^{i,k}$ is the maximal duration a frame might be delayed in the switch and is equal to the technological switch relaying latency (ϵ) plus the queuing delay (t_q). The latter bound represents the time a queued frame stays in the queue of the switch output port, including the time needed to be emitted on the output cable. Therefore, the sum of switches delay bounds corresponds to the communication time of the message between the instant the message is completely transmitted on the network medium until its arrival to its destination.

$$WT3^{i,j} \leq \sum_{k \in path_i} D_{SW}^{i,k} \tag{3}$$

Hence, the schedulability test becomes as follows:
$\forall i \in messages$ and $\forall j \in sources$, $D_{eed}^{i,j} \leq Deadline_i \Longrightarrow$ The messages set $messages$ is schedulable

These upper bounds to end to end delays are determined analytically using the Network Calculus [21] theory because it is well adapted to controlled traffic sources and provides easily maximal end to end delay bounds. The analytic details are given in section IV.

4) Optimization of system resources: As discussed bellow, the bandwidth reservation mechanism used inside the master to impose an upper bound of transmitted periodic or aperiodic traffic during an Elementary Cycle allows predictable transmissions and system stability, in particular the temporal isolation between the synchronous and asynchronous windows. However, this method can lead to a pessimistic bandwidth utilization when the upper bounds on transmitted traffic by each node are excessively large. In fact, the system's performance depends mainly in this case on the bandwidth reservation mechanism parameters.

In order to increase the efficiency of bandwidth utilization and delivered Quality of Service, a system resources optimizer is integrated in the master's structure to interact with the system requirements database and determine the accurate system parameters e.g. Elementary cycle duration, synchronous or asynchronous window duration, the upper bounds to transmitted periodic and aperiodic traffic that minimize wasted bandwidth. The scheduling process in the master is modeled as an optimization problem with a set of constraints, a set of variables and an objective function. The profiled Switched Ethernet admits different temporal and system constraints:

- stability constraint that consists in enforcing both periodic and aperiodic messages to be confined within their respective windows;
- system integrity constraint which illustrates the fact that synchronous and asynchronous windows durations have to be less than the Elementary Cycle duration;
- deadline constraints where the end to end communication delays of periodic and aperiodic traffic have to respect their respective deadlines.

The improvement of the bandwidth utilization in the system will be directly reflected on the end to end communication delays. Hence, the considered objective function of this optimization problem is the minimization of the sum of end to end delay bounds over all flows on the network. The variables set of this problem consists of Elementary Cycle duration and synchronous window duration. The originality of this introduced process consists in using the Network Calculus formalism and defining a worst case dimensioning method of the network. First, all the identified constraints and the

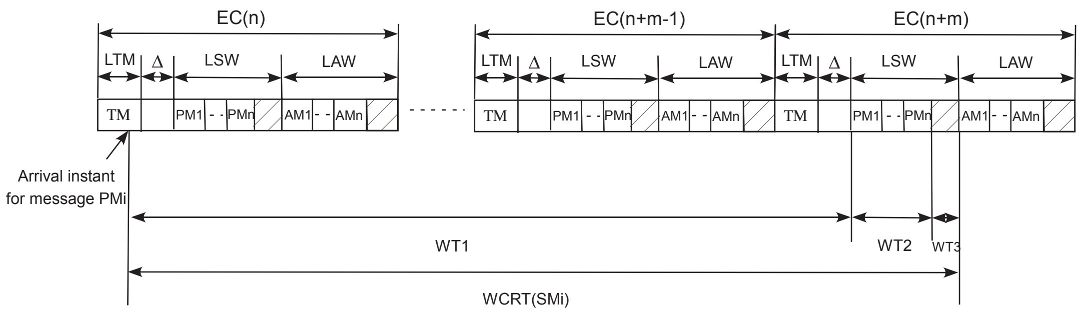

Fig. 4. WCRT for a periodic message

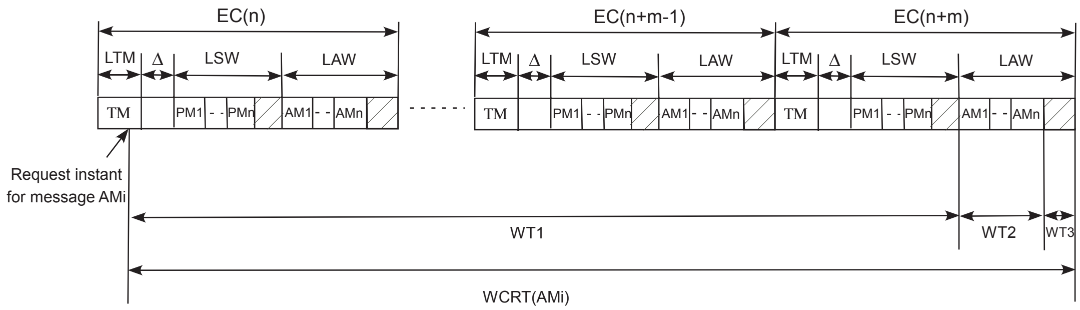

Fig. 5. WCRT for an aperiodic message

objective function are defined using the Network Calculus theory. Then, the main idea of the worst case dimensioning method is:

if the optimization problem associated to this scheduling problem admits a solution, then the schedule is feasible. If there is no admissible solution for the associated optimization problem, the network capacity is increased until finding an admissible solution.

This method guarantees the use of the accurate network capacity and avoids the over-dimensioning of the network caused by arbitrary capacity choice. The analytic details of this optimization process are given in section IV-E.

IV. Schedulability Analysis and Optimization Process

In this part, we explain the calculation of the maximal processing delay bound for source node j, $D^{i,j}_{SRC}$, and the maximal switch processing delay bound $D^{i,k}_{SW}$ for each switch $k \in path_i$, using the Network Calculus formalism [21]. Notations described in **table I** are used in this section.

A. Network Calculus Fundamentals

Network Calculus formalism [21] is based on *min-plus* algebra for designing and analyzing deterministic queuing systems where the compliance to some *regularity constraints* is enough to model the traffic. These constraints limit traffic burstiness in the network and are described by the so called *arrival curve* $\alpha(t)$, while the availability of the crossed node is described by a *service curve* $\beta(t)$. The knowledge of the arrival and service curves enables the computation of the delay bound that represents the worst case response time of a message, and

TABLE I
Notations

EC	Elementary Cycle duration
LSW	Synchronous Window Length
LAW	Asynchronous Window length
LTM	End to end transmission time for the Trigger Message (TM)
Δ	Maximum decoding time of the TM by a node
ϵ	Technological switch relaying latency
C	Links capacity
$B^{p,j}$	The sum of maximal lengths of periodic messages generated by node j
$\rho^{p,j}$	The sum of maximal rates of periodic messages generated by node j
$B^{p,j}_i$	The sum of maximal lengths of periodic messages with a priority i (where priority 0 is the highest priority) generated by node j
$\rho^{p,j}_i$	The sum of maximal rates of periodic messages with a priority i (where priority 0 is the highest priority) generated by node j
$B^{a,j}$	The sum of maximal lengths of aperiodic messages generated by node j
$\rho^{a,j}$	The sum of maximal rates of aperiodic messages generated by node j
$B^{a,j}_i$	The sum of maximal lengths of aperiodic messages with a priority i (where priority 0 is the highest priority) generated by node j
$\rho^{a,j}_i$	The sum of maximal rates of aperiodic messages with a priority i (where priority 0 is the highest priority) generated by node j
$\sigma^{p,j}$	The maximal transmitted quantity of periodic traffic guaranteed to node j during an Elementary Cycle
$\sigma^{a,j}$	The maximal transmitted quantity of aperiodic traffic guaranteed to node j during an Elementary Cycle
L^p_{max}	The maximum message length belonging to periodic traffic
L^a_{max}	The maximum message length belonging to aperiodic traffic
$L^{p,i}_{max}$	The maximum message length belonging to periodic traffic with priority i (where priority 0 is the highest priority)
$L^{a,i}_{max}$	The maximum message length belonging to aperiodic traffic with priority i (where priority 0 is the highest priority)

the backlog bound that is the maximum queue length of the flow.

The delay bound D is the maximal horizontal distance between $\alpha(t)$ and $\beta(t)$ whereas the backlog bound B is the maximal vertical distance between them. The calculation of these bounds is greatly simplified in the case of a linear arrival curve $\alpha(t) = b + rt$ with b the maximal burst and r the rate (we say that the flow is (b, r)-constrained); and a rate latency service curve $\beta(t) = \max(0, R(t - T))$ with latency T and rate R. Bounds in this case are simply $\frac{b}{R} + T$ for the delay and $b + rT$ for the backlog. In our analysis, we will use the previous linear arrival curve and rate-latency service curve since they are well adapted to our system.

This formalism gives an upper bound for the output flow $\alpha^*(t)$, initially constrained by $\alpha(t)$ and crossing a system with a service curve $\beta(t)$,**using min plus deconvolution** $\oslash$ where:

$$\alpha^*(t) = sup_{s \geq 0}(\alpha(t + s) - \beta(s)) = (\alpha \oslash \beta)(t)$$

The output arrival curve of the flow $\alpha(t)$ in the case of a linear input arrival curve $\alpha(t)$ and a rate-latency service curve $\beta(t)$ is simply $\alpha^*(t) = b + r(t + T)$.

Another important result given in the Network Calculus formalism concerning the relationship between a bit by bit system offering a service curve $\beta(t)$ and its packetized version offering a service curve $\beta^*(t)$ is as follow, where L_{max} is the maximum message length of the input flow:

$$\beta^*(t) = \max(0, \beta(t) - L_{max})$$

B. Source Processing Delay

***Theorem** 1: (Upper Delay Bound in a source node)* the maximum delay experienced by a periodic (resp. aperiodic) traffic priority i **(where priority 0 is the highest priority)** in a node j, $D^{i,j}_{SRC}$ is upper bounded like in 4 (resp. 5)

$$\begin{aligned} D^{i,j}_{SRC} &\leq (\left\lceil \frac{\sum_{l \leq i} B^{p,j}_l}{\sigma^{p,j}} \right\rceil - 1)EC \\ &+ LTM + \Delta + LAW + \frac{\sigma^{p,j}}{C} \end{aligned} \tag{4}$$

$$\begin{aligned} D^{i,j}_{SRC} &\leq (\left\lceil \frac{\sum_{l \leq i} B^{a,j}_l}{\sigma^{a,j}} \right\rceil - 1)EC \\ &+ LTM + \Delta + LSW + \frac{\sigma^{a,j}}{C} \end{aligned} \tag{5}$$

Proof: let $A^j = \{A^j_0, A^j_1, A^j_2\}$ be the aperiodic flows set sent by node j, with A^j_i the aperiodic flows subset having the priority i. Each flow $k \in A^j_i$ is $(L_k, \frac{L_k}{T_k})$-constrained. Hence, each aperiodic traffic priority i sent by node j has an arrival curve:

$$\alpha^j_i(t) = \sum_{k \in A^j_i} (L_k + \frac{L_k}{T_k} t) = B^{a,j}_i + \rho^{a,j}_i t \tag{6}$$

Aperiodic traffic is sent according to non preemptive fixed priorities scheduling that guarantees to a given priority level to be selected before the lower priorities and after the higher priorities. However, since the transmission of a message on the network cannot be preempted, in the worst case, one message of maximal length with lower priority is served before. Moreover, the aperiodic traffic transmission begins after a constant delay equal to the TM reception and decoding and the synchronous window duration. Therefore, the service curve offered to the aperiodic traffic priority i is given by the rate latency curve (7).

$$\beta^j_{bb,i}(t) = \max(0, Rate^j.(t - (LTM + \Delta + LSW + Time^j_i))) \tag{7}$$

Where $Rate^j = \frac{\sigma^{a,j}}{EC}$ and $Time^j_i = \frac{\max_{k>i} L^{a,k}_{max}}{C} + \frac{\sum_{k<i} B^{a,j}_k}{Rate^j}$.

Given Le Boudec's results concerning the relationship between offered service curves of a bit by bit system and its packetized version (see section IV-A), the service curve offered by the node j to an aperiodic traffic priority i with variable length messages is given by the rate latency curve (8), obtained from (7).

$$\begin{aligned} \beta^j_i(t) &= \max(0, Rate^j.(t - (LTM + \Delta + LSW + Time^j_i)) \\ &- L^{a,i}_{max}) \end{aligned} \tag{8}$$

Hence, the maximal source processing delay for aperiodic traffic priority i is at most like in (9), which is the maximal horizontal distance between α^j_i and β^j_i.

$$\begin{aligned} D^{i,j}_{SRC} &\leq \frac{B^{a,j}_i}{Rate^j} + LTM + \Delta + LSW \\ &+ Time^j_i + \frac{L^{a,i}_{max}}{Rate^j} \end{aligned} \tag{9}$$

Given explicit $Rate^j$ and $Time^j_i$ expressions, we have

$$\begin{aligned} D^{i,j}_{SRC} &\leq \frac{\sum_{l \leq i} B^{a,j}_l}{\sigma^{a,j}} EC + LTM + \Delta + LSW \\ &+ L^{a,i}_{max} \frac{EC}{\sigma^{a,j}} + \frac{\max_{k>i} L^{a,k}_{max}}{C} \end{aligned} \tag{10}$$

For node j, the Elementary Cycle number required to transmit all its aperiodic traffic with priority equal or higher to i is $\left\lceil \frac{\sum_{l \leq i} B^{a,j}_l}{\sigma^{a,j}} \right\rceil - 1$, then

$$WT1^{i,j} \leq (\left\lceil \frac{\sum_{l \leq i} B^{a,j}_l}{\sigma^{a,j}} \right\rceil - 1)EC + LTM + \Delta + LSW \tag{11}$$

An upper bound to $WT2^{i,j}$ is obtained when the last message in the aperiodic traffic priority i queue effectively enters arbitration and it consists of: (i) the interference caused by the higher and same priority messages in the arbitration process, let's name the correspondent messages set SA^j_i; (ii) the transmission time of the longest message with lower priority; (iii) the packetizer influence compared to a bit by bit system. However, the maximal transmitted quantity of aperiodic traffic guaranteed to node j during an Elementary Cycle is $\sigma^{a,j}$, therefore

$$WT2^{i,j} \leq \frac{\sum_{k \in SA^j_i} L_k}{C} + \frac{\max_{k>i} L^{a,k}_{max}}{C} + L^{a,i}_{max} \frac{EC}{\sigma^{a,j}} \leq \frac{\sigma^{a,j}}{C} \tag{12}$$

The source processing delay bound for aperiodic priority i in node j is as (13):

$$\begin{aligned} WT1^{i,j} + WT2^{i,j} &\leq D^{i,j}_{SRC} \\ &\leq (\left\lceil \frac{\sum_{l\leq i} B^{a,j}_l}{\sigma^{a,j}} \right\rceil - 1)EC + LTM \\ &+ \Delta + LSW + \frac{\sigma^{a,j}}{C} \end{aligned} \tag{13}$$

The theorem is proved for aperiodic traffic with priority i. The proof for periodic traffic with priority i could be done similarly by considering $B^{p,j}_l$, $\sigma^{p,j}$ and $L^{p,i}_{max}$ instead of $B^{a,j}_l$, $\sigma^{a,j}$ and $L^{a,i}_{max}$, respectively. Moreover, the periodic traffic transmission begins after a constant delay equal to the TM reception and decoding and asynchronous window duration. ■

C. Switch processing delay

This delay depends on the scheduling policy used in the switch and in our case, we consider the simple policy FCFS. First, we determine the service curve offered to each flow by the part of the switch that represents the final stage of the forwarding mechanism: the queuing and the multiplexing. Then, given the service curve and the input traffic arrival curve, maximal queuing delay bounds are calculated using the *Network Calculus* [21].

- **One switch Case**: Consider that the periodic (resp. aperiodic) flows set received by the switch output port k is S^p_k (resp. S^a_k) and TS^p_k (resp. TS^a_k) the nodes set transmitting S^p_k (resp. S^a_k). The associated arrival curve to periodic traffic transmitted by each node $j \in TS^p_k$ is then $\alpha^p_j(t) = \sigma^{p,j} + \rho^{p,j}.t$ and the input arrival curve of the global periodic traffic is $\alpha^p_{TS^p_k}(t) = \sum_{j\in TS^p_k} \sigma^{p,j} + \sum_{j\in TS^p_k} \rho^{p,j}.t$. The service curve offered to this traffic is simply $\beta(t) = C.t$. Hence, the maximal switch processing delay bound for each periodic flow i or a periodic traffic priority i **(where priority 0 is the highest priority)** received by the switch port k, obtained by the maximal deviation between $\alpha^p_{TS_k}$ and β is

$$D^{i,k}_{SW} = \frac{\sum_{j\in TS^p_k} \sigma^{p,j}}{C} + \epsilon \tag{14}$$

Similarly, the maximal switch processing delay bound for each aperiodic flow or traffic priority i received by the switch output port k, is:

$$D^{i,k}_{SW} = \frac{\sum_{l\in TS^a_k} \sigma^{a,l}}{C} + \epsilon \tag{15}$$

- **Cascaded Switches Case**: In order to calculate the analytical maximal delay bounds in cascaded switches, we proceed with an iterative calculus that requires the execution of the simple following algorithm 1. This algorithm initially identifies the associated path of each flow in the flows set S (lines 1-4). Then, it determines the received flows set for each crossed switch along that path (line 6). Afterward, the arrival burst is determined for each flow in the identified set by resolving the burstiness constraint evolution of each flow e.g. knowing the arrival curve and service curve, the output arrival curve is calculated. This step concerns individual and aggregate flows sent by other switches or nodes (line 7). The submitted delay bound in the considered switch is given as in (14) for periodic flows and (15) for aperiodic flows thanks to the function *Delay-calculus*. Finally, the delay bound calculus for each flow is propagated from one crossed switch to another to obtain the global delay along its path (line 8).

Algorithme 1 Cascaded switches delay bounds calculus

1: $S \leftarrow \{s_1, s_2 ... s_{n_{flows}}\}$
2: $D - SW \leftarrow$ NULL-VECTOR(S.length)
3: **for** $i = 1$ to n_{flows} **do**
4: Path $\leftarrow$ Vector-crossed-switches($S(i)$)
5: **for** $k = 1$ to Path.length **do**
6: $R \leftarrow$ Vector-rcv-flows($Path(k), S$)
7: $sigma \leftarrow$ Vector-arrival-burst(R)
8: $D - SW(i) \leftarrow D - SW(i)$ + Delay-calculus($sigma$)
9: **end for**
10: **end for**

D. Maximal End to End delay Bound

Since submitted delay bounds are known for each message and in each point of the network, a maximal end-to-end delay bound can be determined for each message along its path. However, the network properties are used here to simplify this calculus. In fact, the temporal isolation between the synchronous and asynchronous windows implies that each traffic category transmission fits within the respective window. Hence, the time spent between the transmission beginning of a given traffic category and its reception end by the destination node is bounded by the respective window duration (see figure 6). Maximal end to end delay bounds are as follow.

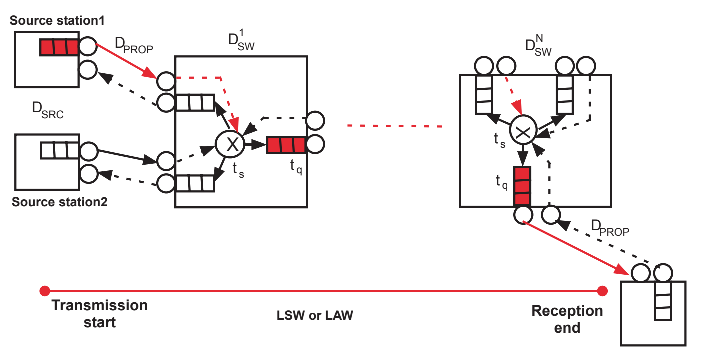

Fig. 6. Schematic diagram of communication delay between the beginning of transmission and the end of reception

***Theorem** 2: (Upper End to End Delay Bound in the profiled Switched Ethernet network)* the maximum end to end delay experienced by any periodic (resp. aperiodic) traffic priority i **(where priority 0 is the highest priority)** transmitted by a node j is upper bounded by 16 (resp. 17), where

$$D^{i,j}_{eed} \leq \left\lceil \frac{\sum_{l\leq i} B^{p,j}_l}{\sigma^{p,j}} \right\rceil EC \tag{16}$$

$$D^{i,j}_{eed} \leq \left\lceil \frac{\sum_{l\leq i} B^{a,j}_l}{\sigma^{a,j}} \right\rceil EC \qquad (17)$$

Proof: Using theorem 1, the maximum end to end delay experienced by any periodic (resp. aperiodic) traffic priority i transmitted by a node j is upper bounded by (18) (resp. (19)).

$$\begin{aligned} D^{i,j}_{eed} \;&\leq\; (\left\lceil \frac{\sum_{k\leq i} B^{p,j}_k}{\sigma^{p,j}} \right\rceil - 1)EC + LTM + \Delta + LAW \\ &+\; \frac{\sigma^{p,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \end{aligned} \qquad (18)$$

$$\begin{aligned} D^{i,j}_{eed} \;&\leq\; (\left\lceil \frac{\sum_{k\leq i} B^{a,j}_k}{\sigma^{a,j}} \right\rceil - 1)EC + LTM + \Delta + LSW \\ &+\; \frac{\sigma^{a,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \end{aligned} \qquad (19)$$

Then, the temporal isolation property implies that LAW and LSW are bounded by (20) and (21), respectively. Using (3) and (12):

$$\begin{aligned} WT2^{i,j} + WT3^{i,j} \;&\leq\; LAW \\ \frac{\sigma^{a,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \;&\leq\; LAW \end{aligned} \qquad (20)$$

$$\begin{aligned} WT2^{i,j} + WT3^{i,j} \;&\leq\; LSW \\ \frac{\sigma^{p,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \;&\leq\; LSW \end{aligned} \qquad (21)$$

In addition, the Elementary Cycle duration (EC) is as follows:

$$EC = LTM + \Delta + LSW + LAW \qquad (22)$$

Hence, given (18), (21) (resp. (19), (20)) and (22), the theorem is proved for periodic (resp. aperiodic) traffic. ■

E. Optimization Process of System Resources

The optimization problem defined in section III-C4 associated to the scheduling process in the master is as follows: Minimize

$$\sum_{i\in flows, j\in nodes} D^{i,j}_{eed}$$

Subject to:

- Deadline constraints: $\forall j \in nodes$ and $\forall i \in flows$
$$D^{i,j}_{eed} \leq D_i$$
- Stability constraint (synchronous window): $\forall j \in nodes$ and $\forall i \in flows$
$$\frac{\sigma^{p,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \leq LSW$$
- Stability constraint (asynchronous window): $\forall j \in nodes$ and $\forall i \in flows$
$$\frac{\sigma^{a,j}}{C} + \sum_{k\in path_i} D^{i,k}_{SW} \leq LAW$$
- System integrity constraint
$$EC = LTM + \Delta + LSW + LAW$$

V. Application Example: Military Avionics Network

A. Case study

Our case study is a representative avionics network in a modern French military aircraft, considered as a representative military embedded application. First, an overview of the current avionics architecture is presented. Then, the proposed network and the replacement method are described.

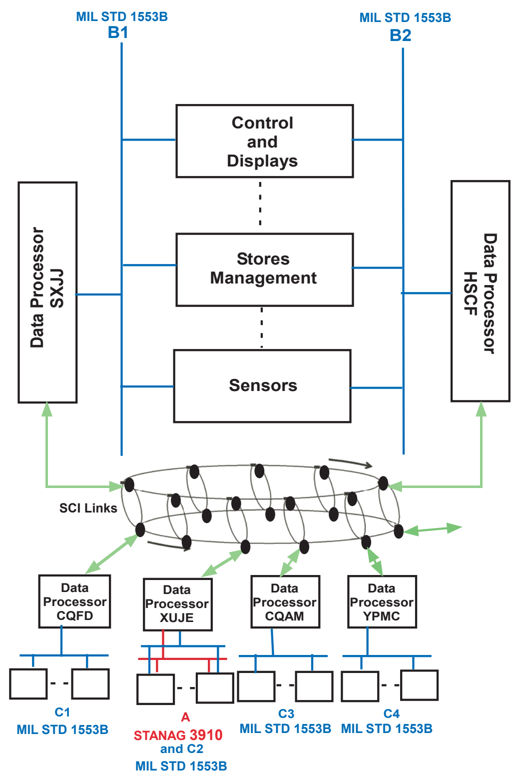

Fig. 7. A representative military aircraft network

1) Current military avionics: The Network consists of six MIL STD 1553B buses, where the busiest one is integrated to a STANAG 3910 bus, and SCI links to assure the communication between the different 1553B Bus Controllers (figure 7). The traffic is circulating between about twenty subsystems on each used MIL STD 1553B. **The different catgories of the Real-time traffic are described in tables II and III. So, one can see that for periodic messages, the largest period is about 160 ms and the most common value is 20 ms; and for aperiodic messages, there are different response time bounds and the most urgent one is about 3 ms.** The transaction table of the MIL-STD 1553B bus is statically defined in such a way that time constraints are enforced and nodes are polled in a determined sequence. As a result, the major table's cycle has a duration of 160 ms and minor table's cycles 20 ms, in order to meet the requirements of the higher update rate messages.

TABLE II
PERIODIC TRAFFIC DESCRIPTION

Period (ms)	**Number of flows**	Data payload (bytes)
20	698	92
40	60	92
80	56	92
160	630	1492

TABLE III
APERIODIC TRAFFIC DESCRIPTION

Response time (ms)	Number of flows	Data payload (bytes)
3	106	14
20	420	92
160	215	92
infinity	360	1492

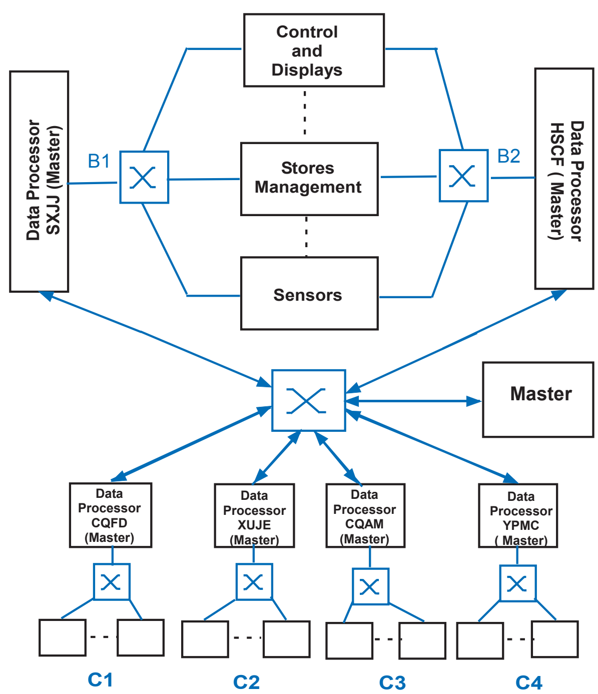

Fig. 8. Proposed communication network using Full Duplex Switched Ethernet

2) Proposed architecture: In order to replace the current data buses with the proposed Full Duplex Switched Ethernet using a centralized communication scheme, a MAC address is attributed to each subsystem and the different subsystems currently connected to a MIL STD 1553B will be connected to one switch. The current Bus Controller on MIL STD 1553B is considered as the FTT master. **Then, communications between the different subnetworks are assured thanks to a central switch with full duplex links which replaces the current SCI links. Each FTT master has two Ethernet interfaces: the first one is used to communicate with its slaves, and the second one is used to communicate with the central FTT master. Since the inter subnetworks communications exclusively take place between master stations, this implementation guarantees a good isolation between subnetworks and the stability of the system temporal behavior**. Figure 8 depicts our general model.

In order to guarantee fault tolerance, the global master and switches are redundant to tolerate faults and such redundancy can be handled with common passive or active replication techniques. This issue was considered complementary to the traffic schedule design and was left out of this paper.

Every 1553B message generated by a 1553B node is encapsulated in an Ethernet frame that respects the minimal frame size (72 bytes) and contains the source and destination addresses. Afterward, we define the characteristics of each periodic (resp. aperiodic) message as described in the Periodic Requirements Table (resp. Aperiodic Requirements Table) given section III. Hence,

- the maximal message length for a message i is $L_i = \max(72, 26 + DPL)$ where DPL is the data payload given in tables II and III;
- the deadline is the period for periodic messages and the maximal response time for aperiodic messages;
- the periods of periodic messages are kept as in table II; and the minimal inter-arrival time for aperiodic messages is 20ms because we suppose that a subsystem can generate at most one aperiodic message of each type once every minor frame (20 ms);
- one can notice that there are only four priorities for periodic traffic (the highest priority 0 for messages with period 20ms and the lowest priority 3 for messages with period 160ms); and there are also four priorities for aperiodic traffic where urgent messages with response time 3ms are tagged with the highest priority 0 and the non real time message without a finite deadline the lowest priority 3.

B. Schedulability Analysis and Optimization process results

1) Impact of System Parameters on End to End Delays: For readability reasons, given the important number of messages it is more convenient to give maximal end to end delay bounds of each periodic and aperiodic traffic priority in a global manner. Hence, for each periodic (resp. aperiodic) traffic priority, the end to end delay bound is calculated as the maximum of end to end delay bounds obtained for received periodic (resp. aperiodic) messages having the same priority.

First, with 100Mbps as a transmission capacity, the maximal end to end delay bounds are computed for different EC and LSW values and obtained results for periodic messages with period 20ms and aperiodic messages with deadlines 3ms and 20ms, are respectively presented in figure 9. Clearly, one can see that for periodic traffic the deadline of 20 ms is not respected for all the considered system configurations. In a global manner, for periodic messages, the delay bounds decrease when the relative synchronous window duration increases. In fact, the best results are obtained when LSW

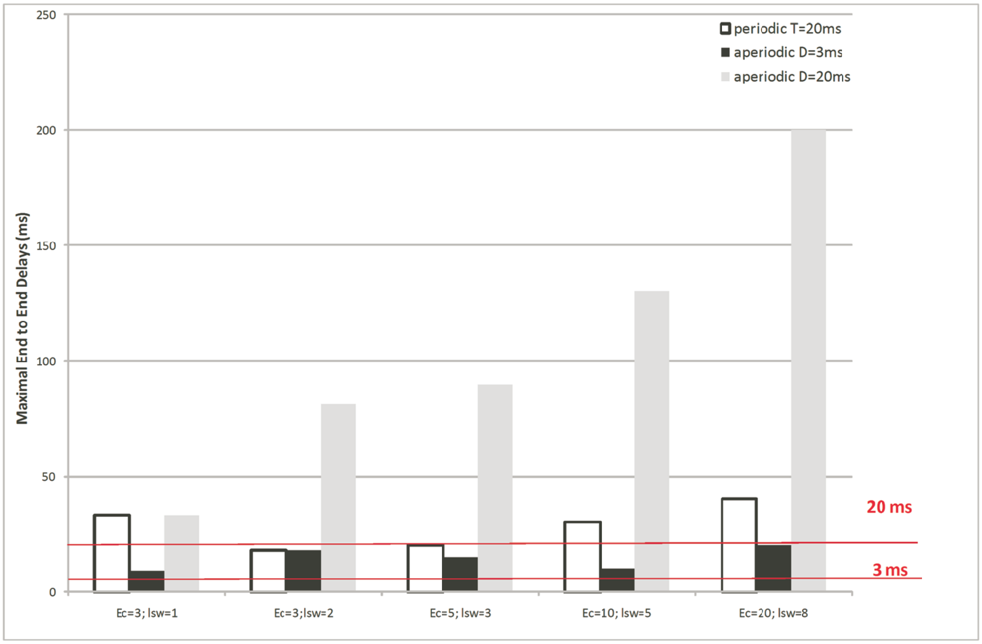

Fig. 9. Maximal Delay bounds with C=100Mbps

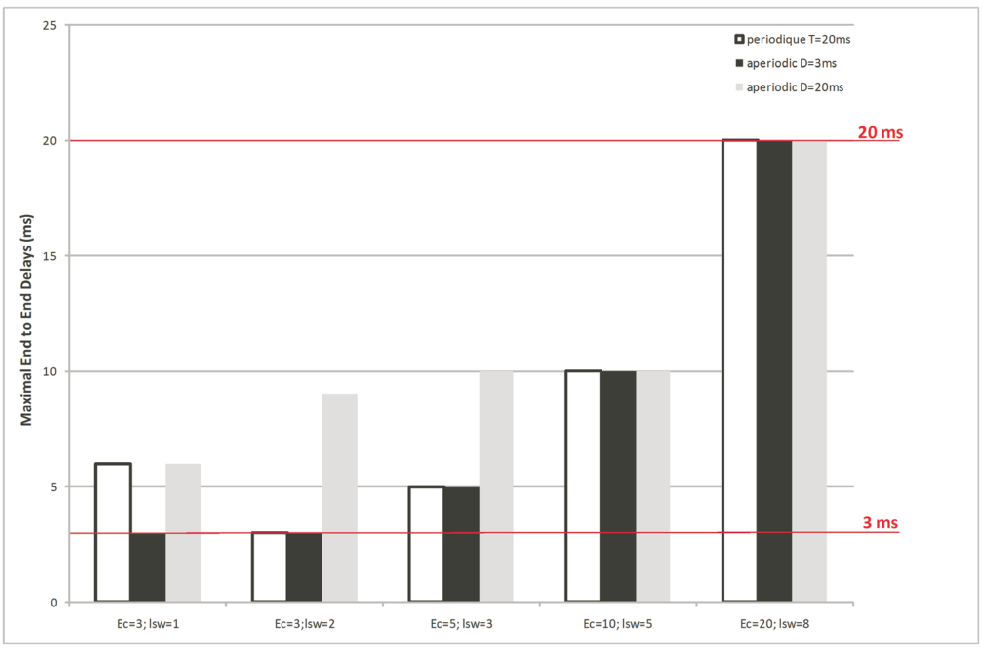

Fig. 10. Maximal Delay bounds with C=1Gbps

represents 66% of EC ($LSW = 2$ms and $EC = 3$ms). For urgent aperiodic messages, the end to end delay bounds with the different system configurations are larger than 3 ms. **So, the deadline constraints associated to this aperiodic traffic priority are not respected. Hence, the obtained results with this transmission capacity are not acceptable and this is essentially due to the capacity limitation.**

Then, the transmission capacity is increased to 1Gbps and the obtained end to end delays for the periodic messages with period 20ms and aperiodic messages with deadlines 3ms and 20ms, are presented in figure 10. These bounds respect the deadline constraints of the considered periodic and aperiodic traffic for the different system configurations; and in a global manner the best results are obtained with the configuration where $EC = 3$ms and $LSW = 1$ms. **It is worth to note that when the Elementary Cycle duration increases, the end to end delay bounds converge to the Elementary Cycle duration. In fact, the reserved bandwidth associated to each traffic category for each node increases with the Elementary cycle duration; and from a given elementary cycle duration each node becomes able to send all its periodic or aperiodic traffic within one cycle.**

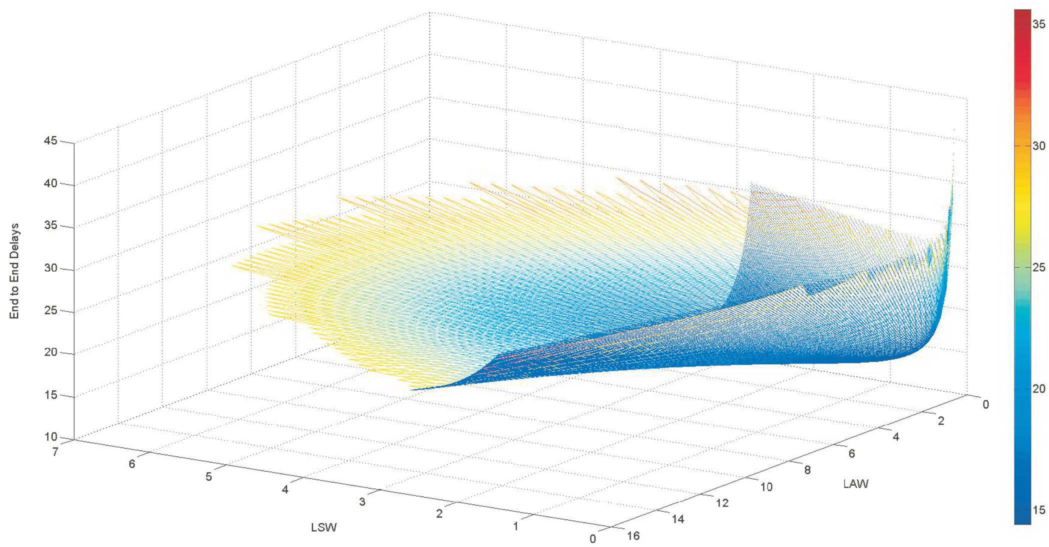

Fig. 11. Admissible Solutions with C=1Gbps

2) Optimization Process Results: The resolution details of the optimization problem associated to the scheduling process in the master could be found in the annex. First, with 100Mbps as a transmission capacity, there is no admissible solution that respects all the system and temporal constraints. Hence, as explained in section III-C4 and according to the defined worst case dimensioning method, the communication capacity is increased to 1Gbps. In this case, the scheduling is feasible and the admissible solution space is presented in figure 11. The optimal solution which minimizes the sum of the end to end delays is obtained for $EC = 2.65$ms and $LSW = 1.25$ms. **The sum of end to end delays in this case is about 13.25ms and the obtained delays for the periodic messages with period 20ms and aperiodic messages with deadlines 3ms and 20ms are 5.3ms, 2.65ms and 5.3ms, respectively**. These analytical results are coherent with the obtained previous results. However, the difference between the obtained optimal solutions ($EC = 3$ms and $LSW = 1$ms in the previous section) is due to the defined objective function which takes into account the sum of end to end delays and not the delay of each traffic priority and also to the relaxation of constraints used to simplify the resolution of the optimization problem.

VI. Conclusion

A Master/ Slave Switched Ethernet is presented here as an attractive candidate to be the new communication network for military embedded applications. This proposal is based on the adaptation of the Flexible Time Triggered Switched Ethernet (FTT-SE) to military context to guarantee predictable behavior. This adaptation consists mainly in defining new arbitration mechanisms to handle periodic and aperiodic traffic and proving schedulability analysis thanks to the Network Calculus formalism. Obtained results in the case of a realistic application show the efficiency of this proposed Switched Ethernet to provide deterministic transmission with respected deadline constraints, as required by military embedded applications.

Hence, our proposal fulfills military requirements since it allows: (1) the use of a COTS technology like Switched Ethernet which reduces development costs; (2) an easy migration of the current military subsystems to a compliant form by keeping the current centralized communication scheme which reduces development time; (3) deterministic and predictable information transmissions that respect the real time constraints; (4) the use of several traffic classes with guaranteed quality of service.

Acknowledgment

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Annex

A. Assumptions

- In our case study, the traffic transfers are only from slaves to the master which makes the switch output port connected to the master the busiest one.
- All the slaves in the set $slaves$ have the same guaranteed transmitted quantity of periodic traffic during an Elementary Cycle. Hence, $\forall j \in slaves$, we have $\sigma^{p,j} = \sigma^p$.
- All the slaves in the set $slaves$ have the same guaranteed transmitted quantity of aperiodic traffic during an Elementary Cycle. Hence, $\forall j \in slaves$, we have $\sigma^{a,j} = \sigma^a$.
- In our case study, each traffic flow crosses only one switch since each master has two Ethernet interfaces to guarantee the isolation between the different subnetworks. Hence, $\forall i \in flows$, $\sum_{k \in path_i} D^{i,k}_{SW} = D^i_{SW}$.

B. Initial Optimization Problem

Minimize $\sum_{i \in flows, j \in slaves} D_{eed}^{i,j}$
Subject to:

- Deadline constraints (periodic traffic): $\forall j \in slaves$ and each periodic traffic priority i

$$(\left\lceil \frac{\sum_{l \leq i} B_l^{p,j}}{\sigma^p} \right\rceil) EC \leq D_{eed}^{i,j}$$

- Deadline constraints (aperiodic traffic): $\forall j \in slaves$ and each aperiodic traffic piority i

$$(\left\lceil \frac{\sum_{l \leq i} B_l^{a,j}}{\sigma^a} \right\rceil) EC \leq D_{eed}^{i,j}$$

- Stability constraint (synchronous window)

$$\frac{\sigma^p}{C} + \epsilon + \frac{\sum_{j \in slaves} \sigma^p}{C} \leq LSW$$

- Stability constraint (asynchronous window)

$$\frac{\sigma^a}{C} + \epsilon + \frac{\sum_{j \in slaves} \sigma^a}{C} \leq LAW$$

- System integrity constraint

$$EC = LTM + \Delta + LSW + LAW$$

C. Constraints Relaxation

The minimization of all the end to end delays is considered as a multi-objective optimization problem. In order to simplify this problem, we make a choice between the different end to end delays to minimize: the end to end delays of the periodic traffic with priority 0 (deadline 20ms and the set is $periodicP0$) and aperiodic traffic with priorities 0 (deadline 3ms and the set is $aperiodicP0$) and 1 (deadline 20ms and the set is $aperiodicP1$). Moreover, To reduce the variables number, we transform $\{\forall i \in flows, \forall j \in slaves\}$ to $\max_{i \in flows, j \in slaves}$. In fact, if the maximum end to end delay, among the respective flows end to end delays, respects the deadline constraint, it will be the case for all the other end to end delays. Hence, the obtained objective function is as follows:

Minimize
$(\max_{i \in periodicP0, j \in slaves} D_{eed}^{i,j} + \max_{i \in aperiodicP0, j \in slaves} D_{eed}^{i,j} + \max_{i \in aperiodicP1, j \in slaves} D_{eed}^{i,j})$

Subject to:

- Deadline constraints: to reduce the variables number, we consider the maximal end to end delay bound for all periodic (resp. aperiodic) traffic with priority 0 (resp. with priorities 0 and 1) and $\forall j \in slaves$ and to relax the constraint we suppress the ceiling of the number. The respective relaxed constraints are as follows:

$$\frac{\max_{j \in slaves} B_0^{p,j}}{\sigma^p} EC \leq 20ms$$

$$\frac{\max_{j \in slaves} B_0^{a,j}}{\sigma^a} EC \leq 3ms$$

$$\frac{\max_{j \in slaves} (B_0^{a,j} + B_1^{a,j})}{\sigma^a} EC \leq 20ms$$

- Stability constraint (synchronous window)

$$0 \leq \frac{(N_{slaves} + 1)\sigma^p}{C} \leq LSW - \epsilon$$

- Stability constraint (asynchronous window)

$$0 \leq \frac{(N_{slaves} + 1)\sigma^a}{C} \leq LAW - \epsilon$$

- System integrity constraint

$$EC = LTM + \Delta + LSW + LAW$$

D. Constraints Propagation

Giving the expressions of σ^p, σ^a and EC, we can express the obtained constraints in function of two parameters LSW and LAW.

- Deadline constraint (aperiodic traffic with priority 0)

  $(\max_{j \in slaves} B_0^{a,j} - \frac{3*10^{-3}C}{N_{slaves}+1}) LAW + (\max_{j \in slaves} B_0^{a,j}) LSW + \max_{j \in slaves} B_0^{a,j} (LTM + \Delta) + \frac{3*10^{-3}\epsilon C}{N_{slaves}+1} \leq 0$

  Hence, this constraint can be written as

$$A_1 * LSW + B_1 * LAW + C_1 \leq 0$$

- Deadline constraint (aperiodic traffic with priority 1)
  $(\max_{j \in slaves} (B_0^{a,j} + B_1^{a,j}) - \frac{20*10^{-3}C}{N_{slaves}+1}) LAW + \max_{j \in slaves} (B_0^{a,j} + B_1^{a,j}) LSW + \max_{j \in slaves} (B_0^{a,j} + B_1^{a,j})(LTM + \Delta) + \frac{20*10^{-3}\epsilon C}{N_{slaves}+1} \leq 0$

  Hence, this constraint can be written as

$$A_2 * LSW + B_2 * LAW + C_2 \leq 0$$

- Deadline constraint (periodic traffic with priority 0)

  $(\max_{j \in slaves} B_0^{p,j} - \frac{20*10^{-3}C}{N_{slaves}+1}) LSW + (\max_{j \in slaves} B_0^{p,j}) LAW + \max_{j \in slaves} B_0^{p,j} (LTM + \Delta) + \frac{20*10^{-3}\epsilon C}{N_{slaves}+1} \leq 0$

  Hence, this constraint can be written as

$$A_3 * LSW + B_3 * LAW + C_3 \leq 0$$

This optimization problem with linear constraints is resolved thanks to Matlab toolboxes and obtained results are given in figure 11.

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