Exploring Alternatives to use Master/Slave Full Duplex Switched Ethernet for Avionics Embedded Applications

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Abstract— **The complexity of distributed real-time systems, including military embedded applications, is increasing due to an increasing number of nodes, their functionality and higher amounts of exchanged data. This higher complexity imposes major development challenges when nonfunctional properties must be enforced. On the other hand, the current military communication networks are a generation old and are no longer effective in facing such increasingly complex requirements.**

A new communication network, based on Full Duplex Switched Ethernet and Master/slave approach, has been proposed previously. However, this initial approach is not efficient in terms of network bandwidth utilization. In this paper we propose two new alternative approaches that can use the network bandwidth more efficiently. In addition we provide a preliminary qualitative assessment of the three approaches concerning different factors such as performance, scalability, complexity and flexibility.

I. Introduction

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

Currently, there is a new trend to use Commercial Off The Shelf (COTS) technologies instead of dedicated solutions in many application domains to reduce development costs and facilitate maintenance. Among several high speed COTS networks, Switched Ethernet is incontestably the most cost effective solution thanks to its ubiquity, simplicity, maturity and relative low cost, which made it the dominating communication technology in many application domains. For example, the 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 to switches, this technology succeeds in exchanging large amounts of data in time ([6]). It is worth to note that this technology was initially designed to support civil requirements, where only periodic traffic is considered, whereas military environments require periodic and aperiodic traffic, both with strict temporal constraints.

As a first step, the authors proposed in [7] 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 while satisfying 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. Therefore, migrating all existing applications into a compliant distributed communication scheme could be a complicated and expensive step. To avoid this process, the proposal in [8] consists in keeping the current military centralized communication scheme upon Switched Ethernet by using a master/ slave protocol.

Among the most relevant solutions using the Master/ Slave approach upon Switched Ethernet ([9], [10]), FTT-SE [11] presents several advantages that are relevant to our application scope such as its optimized Master/ Slave transmission control and its flexibility. To adapt FTT-SE to the context of the referred applications, new mechanisms were introduced in [8] to handle periodic and aperiodic traffic based on a bandwidth reservation method to guarantee predictable transmissions and the stability of the system temporal behavior. Then, in order to deal with the worst case performance prediction of such proposal, schedulability analysis were used based on the Network Calculus formalism [12]. The obtained results for a realistic military applications showed the proposal's ability to support the required time constrained communication. However, this solution led to a pessimistic bandwidth utilization due to the over-dimensioning of the bandwidth reservation mechanism parameters.

Hence, in order to enhance the bandwidth consumption efficiency when using Master/Slave Switched Ethernet, two proposed alternatives are presented and compared in this paper, in terms of performance, scalability and costs integration, using the proposal in [8] as reference. The first solution is based on a similar hardware architecture but with a more optimized schedulability test and an hierarchical server-based scheduling [13] within the master to handle the periodic and aperiodic traffic, respectively. The second solution is based on a different hardware architecture using specific switches, namely FTT-enabled Ethernet switches [14].

This paper is organized as follows. The FTT-SE basic concepts and our case study are presented in Sections 2 and 3, respectively. Then, Section 4 gives an overview of our previous established results based on the bandwidth reservation approach as a reference for the comparative study. Sections 5 and 6 detail the two new alternatives to optimize the Master/Slave protocol upon Switched Ethernet. Finally, a qualitative assessment of the three solutions is provided in Section 7.

II. Background: FTT-SE Overview

The FTT paradigm has been extended to Switched Ethernet by Marau leading to the FTT-SE protocol [11]. In this protocol, a Master node coordinates the transmissions of other nodes (Slaves) by means of the periodic transmission of a Trigger Message (TM) that contains the schedule for a fixed-duration time slot designated Elementary Cycle (EC). Upon TM reception, nodes decode the TM and transmit immediately the messages triggered by the master. The traffic scheduling is done centrally in the master, which facilitates the scheduling policy choice and the communication requirements update.

When scheduling the traffic for each EC, the master limits the periodic traffic to that that can be transmitted within a so-called Synchronous Window. This window allows controlling the maximum bandwidth that can be used by this kind of traffic. Moreover, the master knows all kind of traffic and particularly message activation instants.

Conversely, the main properties of the aperiodic traffic are also known by the master but their activation instants are outside its sphere of control since the messages are activated by the slaves. A signalling mechanism allows the slaves to inform the master once per EC of all pending aperiodic transmissions in the slaves queues. Once transmission requests are known by the master, the aperiodic traffic is scheduled with any appropriate policy and triggered through the TM, similarly to the periodic one. In this case, the scheduling in the master ensures that the scheduled aperiodic traffic per EC fits within the so-called Asynchronous Window, which provides a guaranteed bandwidth to this kind of traffic.

III. Case study: Military avionics network

Our case study is a representative avionics network in a modern French military aircraft, considered as a representative military avionics embedded application (figure 1). The Network consists of six MIL STD 1553B buses, where the busiest one is integrated to a STANAG 3910 bus, and SCI links [8] to assure the communication between the different 1553B Bus Controllers. The traffic is circulating between about twenty subsystems on each used MIL STD 1553B. The different categories of the Real-time traffic are described in tables I and II. As it can be noticed, the largest period for periodic messages is about 160 ms and the most common value is 20 ms, while for aperiodic messages, there are different response time bounds and the most urgent one is about 3 ms.

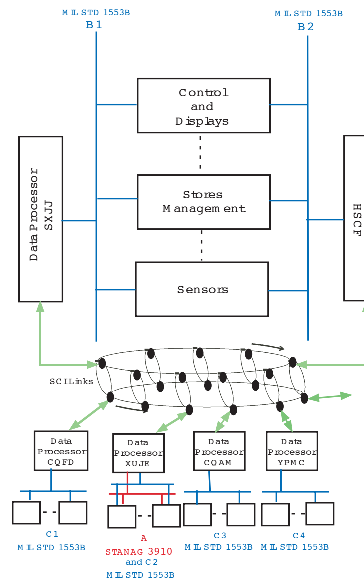

Fig. 1. A representative military aircraft network

TABLE I
Periodic Traffic Description

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

TABLE II
Aperiodic Traffic Description

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

In order to replace the current data buses with the proposed AFDX alternative 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,

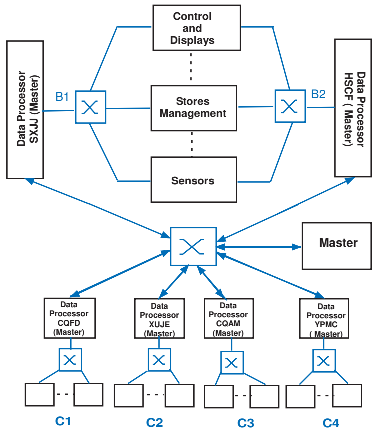

Fig. 2. Proposed communication network using Full Duplex Switched Ethernet

and the second one is used to communicate with the central FTT master. Since the inter-subnetwork communication takes place exclusively via master stations, this implementation guarantees a good isolation between subnetworks and the stability of the system temporal behavior. Figure 2 depicts our considered architecture. In order to guarantee fault tolerance, it is assumed that the global master and switches are redundant to tolerate faults and such redundancy can be handled with common passive or active replication techniques.

IV. FTT-SE WITH BANDWIDTH RESERVATION

In this section, the previous solution, proposed in [8], based on a bandwidth reservation approach is briefly described to be used as a reference solution to conduct the comparative study of the new proposed alternatives in section VII. Then, we provide the obtained results with this approach for our case study as described previously.

A. Handling periodic transmissions

In order to guarantee the traffic schedulability, this approach 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. Then, the master schedules the messages according to the Deadline Monotonic scheduling policy and builds an Elementary Cycle schedule with the ready messages to be transmitted. This schedule is encoded in the TM and broadcast to the nodes. The concerned senders during that Elementary Cycle transmit the messages identified in the TM.

B. Handling aperiodic transmissions

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, and assuring a good isolation level for urgent messages with hard deadline constraints by using a fixed priorities multiplexer implementing Deadline Monotonic policy. 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).

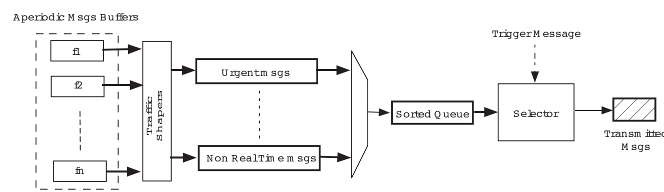

Fig. 3. Arbitration mechanism of aperiodic traffic in the slave

C. Scheduling and Analysis

The schedulability of our proposal is determined using response time-based schedulability test and Network Calculus formalism [12]. The exact Worst Case Response Time (WCRT) calculus could be very complex to analyze due to the huge possibilities of messages arrivals in switches. In order to handle this problem, an upper bound to the WCRT obtained with Network Calculus formalism was considered and compared to the respective deadline. 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, for each message, the computed WCRT with the respective deadline.

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 main idea of this 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 helps to reduce the over-dimensioning of the network caused by arbitrary capacity choice.

D. Obtained results for the case study

First, with 100Mbps as a transmission capacity, there is no admissible solution that respects all the system and temporal constraints. Hence, according to the defined worst case dimensioning method, the communication capacity is increased to 1Gbps and the obtained delays for periodic and aperiodic messages in this case respect the associated deadlines. However, the obtained network utilization per link is about 34% which leads to an over-dimensioning of system's resources. Hence, while this proposed approach guarantees the main military requirements in terms of determinism and predictability, the bandwidth utilization still is not optimized. New alternatives are proposed in this paper to cope with these limitations.

V. FTT-SE WITH RESPONSE TIME ANALYSIS AND HIERARCHICAL SCHEDULING

In this section, we propose the usage of an approach similar to the original FTT-SE protocol to manage the periodic transmission within each master in figure 2, while the aperiodic transmission is scheduled using a hierarchical scheduling algorithm similar to the one presented in [13]. The reason of selecting hierarchical scheduling is that it allows partitioning resources into partitions and assigning them to different components or applications in a composable way, hiding the complexity within each partition behind its respective interface. In addition, it provides means to enforce temporal isolation across partitions during runtime.

A. Handling periodic transmissions

Similarly to the original FTT-SE protocol, during each EC, the master node first schedules the periodic traffic, up to the synchronous window duration, and only then schedules the aperiodic one, using the remaining time in the EC. The fixed priority scheduling is assumed for both types of messages. Afterwards the master node encodes the scheduled messages into the TM and broadcasts it to all slave nodes at the beginning of the next EC.

B. Handling aperiodic transmissions

The aperiodic traffic is triggered by the slave nodes in an event-driven fashion, following the signaling mechanism proposed in the original FTT-SE. Transmission requests are transmitted by slaves to the master at the beginning of each EC. Once all the asynchronous requests arrive at the master, they are scheduled using a hierarchical scheduling algorithm.

The Hierarchical Server-based Scheduling (HSS) framework is formed by a set of servers connected in a hierarchical way in a tree structure. Each server manages a fraction of the network bandwidth that it will provide to its children servers and/or streams, as shown in Figure 4. Each server has an associated scheduler, a set of children servers and/or streams and an interface that specifies its resource requirements. The streams are connected to the leaf servers of the tree and they constitute the actual application load that will consume the network bandwidth. When a server is scheduled, it selects one of its ready children servers. The servers and streams scheduling is carried out by applying an online scheduling algorithm such as Earliest Deadline First (EDF) or Fixed Priority Scheduling (FPS). Then the scheduled child server will also use its own scheduler to select another child server and the same procedure will be repeated down the tree until a leaf server is reached which will finally schedule a message for transmission. The amount of bandwidth given to the scheduled stream is limited by the remaining capacities of all parent servers. If the remaining capacity of a server is exhausted, the server becomes suspended until its capacity is replenished.

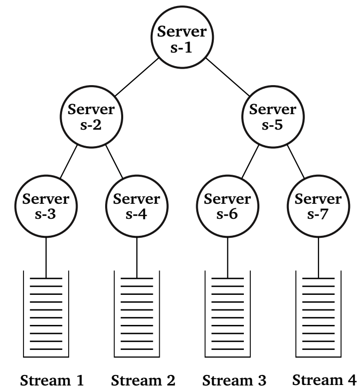

Fig. 4. An example server hierarchy. Bandwidth is allocated to each server. Application messages arrive at the leaf servers.

C. Scheduling and Analysis

The master node maintains a set of hierarchies to schedule all aperiodic messages in which each of the hierarchies serves all messages that are generated from the same source node and will be transmitted to the same destination node. So that during each EC, the master node first schedules the roots of the hierarchies based on the available bandwidth and the scheduled hierarchy will select certain ready messages to be transmitted depending on the capacities of the associated servers and their priorities.

Worst Case Response Time analysis based on scheduling theory for aperiodic messages was presented in [13] and it depends on the capacity of its parent server and the set of messages that share the same parent server (not all messages in the network). The same analysis can also be used for periodic messages by considering the synchronous window as a parent server for the periodic messages.

Hence, compared to the first approach based on bandwidth reservation mechanism, using hierarchical scheduling allows a better bandwidth utilization and more flexibility to manage the aperiodic traffic. In addition, the system resources optimization, presented in the first approach, can be easily extended in this case by integrating the servers (in the HSS framework) parameters as they have a great effect on the system's performance. However, the response time analysis complexity with this alternative increases with the number of messages, which could be a limitation for system's scalability.

VI. Using FTT-enabled Ethernet Switches

In this section, we propose to use a third approach for the network shown in figure 2, in which the COTS switches that were assumed in the first two approaches are replaced by FTT-enabled Ethernet switches [14]. These switches are enhanced with the traffic control capabilities of the FTT paradigm, which basically corresponds to integrating the master functionality with traffic shaping in a custom switch. The former mechanism is applied to the periodic messages, only, while the latter allows handling aperiodic messages transmitted autonomously by the nodes.

A. Handling periodic transmissions

At the beginning of each EC the switch broadcasts the TM to all its slave nodes, i.e., to all its ports, identifying which periodic messages should be transmitted. Fixed priority scheduling algorithm is assumed to schedule the ready periodic messages and the priorities are assigned according to the DM policy.

B. Handling aperiodic transmissions

The aperiodic messages are sent by the respective sources at arbitrary time instants since the switch is able to queue them in dedicated memory pools and transmit them to the respective destinations only during the asynchronous windows so there is no need for an explicit signaling mechanism. Appropriate scheduling mechanisms, e.g. a hierarchical server-based scheduling, may be used to schedule the queued asynchronous messages. The autonomous confinement (shaping) of messages by the FTT-enabled Ethernet Switch is one of the distinctive features of this approach. In particular, it allows connecting legacy nodes without the need for any software or hardware modifications.

Finally, the tight control of the message forwarding combined with the awareness of the message requirements also allows the switch to detect failures in the time domain, such as nodes that transmit asynchronous messages at higher rates than the ones declared or that send synchronous messages not scheduled by the master, preventing their transmission and thus the propagation of the respective timing faults [14].

C. Scheduling and Analysis

The integration of the hierarchical server-based scheduling framework within the FTT-enabled Ethernet switch takes advantage from the hardware/software co-design architecture used in its development. All the low-level server and stream management functions are implemented in hardware (Figure 5), in order to increase the responsiveness of the system compared to the second alternative. Namely the scheduling of the asynchronous messages is performed locally, in each output port, using dedicated hardware resources. It comprises exclusive memory resources, reserved in the central memory, and it can be connected to a configurable number of output ports. Each stream can have a configurable set of associated servers, which is independent from port to port.

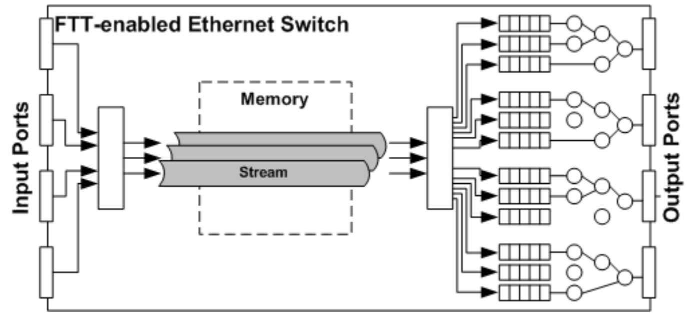

Fig. 5. FTT-enabled Ethernet Switch

In this case, a response-time analysis similar to the one used in the previous approach for the aperiodic messages can be carried out based on each parent server parameters and the messages that share the same parent server in the hierarchy.

VII. Qualitative Assessment

Concerning aperiodic messages, the bandwidth reservation approach, in which a given share of the EC is assigned to each node, might be inefficient, mainly when these messages are seldom transmitted, because it accounts for the worst case traffic load in every EC. Conversely, the second approach uses a signaling mechanism to notify the ready aperiodic messages that adds delay to response times of such messages, despite the potential benefit that can arise from using more efficient scheduling techniques. The third approach combines the best of both, with a relatively low latency in handling requests while supporting a more efficient bandwidth allocation, e.g., allowing to discriminate the most urgent messages.

Schedulability analysis complexity for all the three approaches, considering HSS in the latter two, can be considered low since they are based on resource reservation, thus only messages that share a given resource or set of resources have to be considered in the analysis. This favors scalability.

From the scheduling algorithm point of view, the first approach is simpler since it does not schedule messages but instead transmission slots for nodes, which typically are in a considerably lower number than messages. In this case the slave nodes are responsible to select the local messages to be transmitted based on the bandwidth allocated by the master. For the second approach, the scheduling algorithm in the master node is the most complex since it is responsible for scheduling all ready messages every EC, both periodic and aperiodic. Finally, for the third approach, periodic messages are still scheduled by the master node while the aperiodic messages are scheduled inside the FTT-enabled switch, by dedicated hardware.

Concerning slave complexity, messages are scheduled inside each slave node in the first approach, while for the other two approaches the slaves only need to include a dispatcher, thus having a rather lower complexity.

With respect to scalability, the second approach follows behind the first one since it uses an explicit signaling mechanism for aperiodic messages, which limits the number of slaves

TABLE III
COMPARISON OF THE THREE SOLUTIONS

	Bandwidth Reservation	FTT-SE + HSS	FTT-enabled Ethernet switch
Bandwidth Utilization	low	medium	good
Schedulability complexity	low	low	low
Scalability	high	medium	medium
Masters complexity	low	high	low
Slaves complexity	high	low	low
Certification process	harder	harder	easier
Flexibility	medium	high	low

that can be connected to the switch for a given EC size. This limitation affects mainly systems that need a short EC but it can be circumvented by trading-off with reactivity and multiplexing the signalling messages in every fixed number of cycles. The third approach has lower scalability due to the limited resources (e.g. memory, logical blocks) of any FPGA, thus limiting the total amount of supported servers and streams.

With respect to certification, the first and second approaches require both slave and master nodes to be certified since custom device-drivers must be installed in all nodes to be able to use the FTT-SE protocol (traffic shaping and respecting their scheduling windows). Conversely, the third approach supports *black-box* slaves without need for any modification in their software, thus the certification process is facilitated.

Finally, regarding flexibility, the second approach is more flexible than the other two approaches since changes in the network setting and/or bandwidth should be considered in the master node only, while for the first approach the setting of all slave nodes might need to be changed given the use of distributed traffic shapers. The flexibility of the third approach is limited by hardware programming. In particular, the servers handling policies are fixed or would require a reprogramming of the FPGA. Therefore we consider it the lowest in flexibility. However, when considering a fixed servers policy, it is still a highly flexible approach that also supports the online creation, removal or modification of servers.

The comparison of these three solutions in terms of the different described criteria is summarized in table III. From this analysis, we found that none of the methods supersedes the others in all considered dimensions, with each one having relative advantages and disadvantages.

VIII. CONCLUSION

In this paper we have proposed three different communication methodologies, all based on the Flexible Time-Triggered Switched Ethernet protocol, to support military applications while guaranteeing predictable behavior. The first solution is based on adapting the FTT-SE protocol to reserve bandwidth for each node in the network for every EC. The second solution is based on using the original FTT-SE protocol and a hierarchical scheduling approach to manage the aperiodic traffic. Finally, the third solution is based on an FTT-enabled Ethernet switch, also with hierarchical scheduling to handle the aperiodic traffic. We focused on the qualitative analysis and comparison of such methodologies considering bandwidth utilization efficiency, schedulability, scalability, complexity of system nodes, amenity to certification and flexibility. In future work we will complement this analysis with a quantitative comparison of the three approaches. In addition, we would like to investigate some optimization algorithms to improve certain system parameters such as EC slot time and server capacities according to specific application requirements.

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