Gateway Optimization for an Heterogeneous avionics network AFDX-CAN

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***Abstract*—The gateway impact on the end to end system performances is a major challenge in the design process of heterogeneous embedded systems. In this paper, this problem is tackled for a specific avionics network AFDX with CAN to identify the main interconnection issues. The results herein show the possible enhancements of the system performances thanks to an optimized gateway based on a frames pooling strategy, compared to a basic gateway.**

***Keywords*-heterogeneous embedded networks; CAN; AFDX; gateway; performance analysis; optimization**

I. Context and Related works

During the last few decades, many specific data buses have been successfully implemented in various critical embedded applications like CAN [1] for automotive and ARINC 429 [2] for civil avionics. However, with the increasing complexity of interconnected subsystems and the expansion of exchanged data quantity, these data buses may be no longer effective in meeting the emerging requirements of the new embedded applications in terms of bandwidth and latency.

In order to handle this problem, the current solution consists in increasing the number of used data buses and integrating dedicated data buses with higher rates like FlexRay [3] for automotive and AFDX [2] for civil avionics. Using these different data buses makes global interconnection system heterogeneous and requires special gateways to handle the problem of existent dissimilarities between the subnetworks. This clearly leads to increasing communication latencies and making real-time constraints guarantees difficult to prove.

Hence, the gateways characteristics analysis and their impact on the end-to-end performances become one of the major challenges in the design process of multi-cluster embedded systems. Various approaches are recently offered to handle the problem of design space exploration and optimization of heterogeneous embedded networks. Nevertheless, these proposed approaches have often ignored the gateways impacts on the systems performances. In this specific topic, the approach of Pop et al. [4] focuses on the optimization of multi-cluster embedded systems interconnected via gateways to find a system configuration satisfying the different temporal constraints. The gateway was considered as a simple frames converter and the issue of optimizing this interconnection function was not tackled. Another paper [5] deals with the same problem in the specific case of Ethernet and CAN interconnection by predicting average flows latencies using simulation.

The aim of this paper is first to identify the main challenges concerning the interconnection function in heterogeneous embedded systems and its impacts on the end to end system performances, through a representative avionics case study which consists in interconnecting an AFDX network with CAN buses. Then, in order to enhance the bandwidth utilization and delivered Quality of Service on the AFDX network, we proceed to the interconnection function optimization to determine an accurate frames pooling strategy that fulfills the system requirements.

In the next section, the avionics case study is described and the main interconnection function issues are detailed. Then, in section 3, the definition of a basic gateway and the end-to-end performance analysis are presented. The obtained results through the case study lead to some identified limitation of this proposal towards the bandwidth utilization on the AFDX and to overcome this problem a gateway optimization process is proposed in section 4.

II. Avionics case study: AFDX-CAN

A. Description

Our case study is a representative avionics network as shown in figure 1 which consists of an AFDX network, considered as a central network where avionics calculators and end-systems exchange their data, and two CAN buses where the first one is used to collect the sensors data needed for avionics calculators functioning while the second one is used to transmit generated calculators command data to the actuators, via a specific interconnection function equipment.

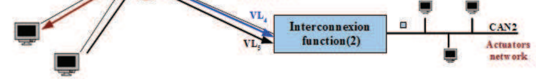

Figure 1. *Interconnection of CAN buses to an AFDX backbone network*

This case study is a representative heterogeneous avionics embedded network where:

- the AFDX network is based on Full Duplex Switched Ethernet protocol at 100Mbps, successfully integrated into new generation civil aircraft like the Airbus A380. Thanks to the virtual link (VL) concept [2] which gives a way to reserve a guaranteed bandwidth to each traffic flow and policing mechanisms added in switches, this technology succeeds to support the important amount of exchanged data.
- The CAN is a 1Mbps data bus that operates following an event triggered paradigm where messages are transmitted using the priority based mechanism and the collisions are resolved thanks to the bit arbitration method [1].

The works presented in this paper are mainly focused on the interconnection function to guarantee communications between the CAN sensors network and the AFDX and exclude the communication between the AFDX and the CAN actuators network for visibility reasons. The considered messages are described in table II-A. There are transmitted from 25 sensors on CAN to the interconnection equipment, to be then transmitted to the AFDX.

Messages	Number	Length(bytes)	Period(ms)
m_1	3	8	2
m_2	2	8	4
m_3	16	2	10
m_4	4	2	10

Table I
SENSORS TRAFFIC DESCRIPTION

B. Interconnection Function issues

As it can be noticed, the main heterogeneity parameters for this case study concern the communication paradigms and the protocols characteristics like frame format and transmission capacity. Clearly, these dissimilarities lead to an increasing interconnection function complexity to handle the different heterogeneity aspects. The main arising issues to define the interconnection equipment are three fold.

- *End to end communication semantics*: the key idea here is to keep the communication transparency between an AFDX calculator and a CAN sensor to avoid the alteration of existent hardware in these equipments. Hence, for an AFDX calculator the source of the transmitted Virtual Link is the interconnection equipment, while for a CAN sensor the transmitted data is consumed by the interconnection equipment. Consequently, the conversion of CAN frames on AFDX frames is exclusively performed in the interconnection equipment which guarantees the required communication transparency and spares the end to end communication semantics definition between AFDX and CAN nodes.
- *Addressing problem*: the main issue here is to handle the dissimilarities between the CAN and AFDX communication models, where the former is based on a producer/consumer model while the latter on a client/server one. Hence, the interconnection equipment has to map the CAN messages identifiers to Virtual Link source addresses. A static mapping is considered in our case where for each CAN identifier there is an associated Virtual Link on the AFDX.
- *End to end temporal performances*: For avionics embedded applications, it is essential that the communication network fulfills certification requirements, e.g. predictable behavior under hard real time constraints and temporal deadlines guarantees. The use of an interconnection equipment may increase the communication latencies and makes the real time constraints difficult to verify. In order to deal with the worst case performance analysis of such network, schedulability analysis are used based on the Network Calculus formalism [6] and scheduling theory. The analysis will be detailed in the next section.

III. Performances analysis with (1:1) Gateway

A. (1:1) Gateway Definition

Giving the identified issues in section II-B, an interconnection function on the application level seems the most suitable solution to handle the end to end communication semantics problem. Hence, we define the interconnection equipment as a gateway which is described in figure 2 and it proceeds as follows: first, each received CAN frame on the CAN interface is decapsulated to extract the payload; then, thanks to the static mapping table, the associated Virtual Link is identified and the obtained AFDX frame is sent through the AFDX interface. This gateway is called (1:1) Gateway where one CAN frame is converted to one AFDX frame.

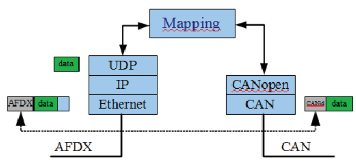

Figure 2. *A (1:1) Gateway functioning*

B. End-to-end delay Definition

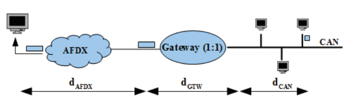

Figure 3. *End to end delay definition*

In order to investigate the end to end temporal performances, the main metric that has been chosen is the worst case end to end delay that will be compared to the temporal deadline of each message. The end to end delay of a given message sent from a CAN sensor to and AFDX calculator via the gateway can be defined as shown in figure 3 as follows:

$$d_{eed} = d_{AFDX} + d_{GTW} + d_{CAN} \quad (1)$$

where,

- d_{AFDX} is the maximal delay bound for a given AFDX message crossing the AFDX network, which was modeled and calculated using the Network Calculus formalism in [7];
- d_{GTW} is the duration a frame might be delayed in the gateway and is equal to the payload extraction and mapping latency, which can be modeled as a maximal constant delay ϵ;
- d_{CAN} is the maximal delay bound for a given CAN message to be received by the gateway, which corresponds to the message maximal response time using the scheduling theory and a non preemptive Rate Monotonic-based model.

C. Results and identified limitations

The end to end delay bounds are calculated for the case study described in section II-A. The obtained worst case delays for each message type are described in table III-C. First, the AFDX delays are extracted from [7] results using the Network Calculus formalism. Then, the CAN delays are calculated using the scheduling theory tool Cheddar [8]. The technological latency in the gateway is assumed constant where $\epsilon = 50\mu$s. Clearly, one can see that all end-to-end delay bounds are smaller than respective deadlines (periods) which means that all the temporal constraints are respected.

Messages	$d^i_{AFDX}(ms)$	$d^i_{CAN}(ms)$	$d^i_{eed}(ms)$	$Period(ms)$
m_1	1	0.44	1.49	2
m_2	2	0.62	2.67	4
m_3	4	1.81	5.86	10
m_4	5	1.95	7	10

Table II
MAXIMAL END TO END DELAY BOUNDS

In order to evaluate the impact of this basic (1:1) gateway where for each CAN frame we associate a Virtual Link on the AFDX, the virtual link numbers for each message type and the associated burst and rate for the aggregate traffic are described in table III-C. As one can notice, this gateway strategy implies an important number of VLs on the AFDX with an important burst quantity and required bandwidth guarantees. This is essentially due to the introduced overhead to send small data (less than 8 bytes) within an AFDX frame (64 bytes at least). This fact can increase dramatically the AFDX delays which depend linearly on the burst quantity, especially if there are many sensor CAN buses interconnected to the AFDX via similar gateways. Clearly, an optimization of the Gateway functioning is needed to handle this problem. Our key idea is to find an optimal strategy of pooling many CAN frames inside the gateway to send their data within the same AFDX frame to reduce the burst quantity transmitted from the gateway to the AFDX. This gateway is called (N:1) Gateway and is detailed in the next section.

Messages	VLs number	burst (bytes)	rate (Mbps)
m_1	3	192	$0,768$
m_2	2	128	$0,256$
m_3	16	1024	$0,829$
m_4	4	256	$0,205$

Table III
INDUCED VLS CHARACTERISTICS

IV. OPTIMIZATION PROCESS: (N:1) GATEWAY

A. (N:1) Gateway Definition

The optimized gateway internal architecture is shown in figure 4 and it proceeds as follows: the static mapping is no longer based on associating one Virtual Link for each CAN frame but it is optimized to associate one Virtual Link to a group of CAN frames. The mapping is encoded thanks to the introduced "Multiple" layer that defines the offset of each CAN payload inside the AFDX frame.

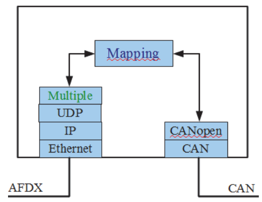

Figure 4. *A (N:1) Gateway functioning*

The pooling strategy inside the gateway is illustrated within the figure 5. An introduced timer Δ allows the accumulation of many CAN frames at the gateway CAN interface. Then, when the timer expires, the accumulated data will be sent in the same AFDX frame. Hence, the gateway pooling strategy depends on the parameter Δ and the calculus of its optimal value is detailed in the next section.

B. Optimization Process

The gateway pooling strategy is modeled as a maximal waiting delay Δ at the input gateway CAN interface in addition to the existing delays explained in section III-B. The key idea here is to calculate the optimal Δ which

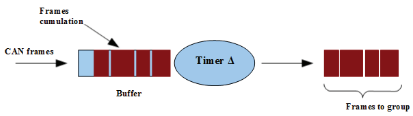

Figure 5. *The Gateway Pooling strategy*

enhances the AFDX bandwidth utilization induced by the sensors and satisfies the temporal and memory system constraints. The optimization problem can be analytically described as follow:

$$Maximize(\Delta)$$

Subject to:

- temporal constraints

$$\forall i, \quad d^i_{CAN} + \Delta + \epsilon + d^i_{AFDX} \leq deadline_i \qquad (2)$$

- gateway memory constraint

$$C_{CAN} * \Delta \leq W \qquad (3)$$

Where W is the memory size in the gateway and C_{CAN} is the transmission capacity on the CAN bus. Combining 2 and 3, we obtain a maximal bound for Δ:

$$\Delta \leq min_i(\frac{W}{C_{CAN}}, T_i - (d^i_{CAN} + \epsilon + d^i_{AFDX})) \qquad (4)$$

C. Results and interpretations

First, we proceed by the calculus of Δ for the considered case study using (4) and the obtained results are described in table IV-C. We assume that $W = 1500$ bytes and $\epsilon = 50\mu$s. Hence, the maximal admissible bound for the researched parameter is the minimal obtained value $\Delta_{opt} = 0.51ms$.

Messages	$Period(ms)$	$d^i_{AFDX}(ms)$	$d^i_{CAN}(ms)$	$\Delta(ms)$
m_1	2	1	0.44	0.51
m_2	4	2	0.62	1.33
m_3	10	4	1.81	4.14
m_4	10	5	1.95	3

Table IV
POOLING STRATEGY PARAMETER CALCULUS

Then, we analyze the impact of the gateway pooling strategy on the number of induced Virtual Links and the transmitted burst quantity on the AFDX in this case. The pooling strategy effect is shown in the diagram (figure 6) which is obtained with the scheduling theory tool Cheddar. For visibility reasons, we present only the first period duration and we consider the aggregate traffic for each message type. However, to perform the pooling strategy analysis, we consider the individual messages. As you can see, we tried to calculate the CAN frames number that could be accumulated during Δ and the obtained pooled frames are shown in the last line of the diagram. The idea is to send these obtained frames within the same Virtual Link on the AFDX. The obtained burst and rate in this case are described in table IV-C. The comparison of the two gateway strategies shows a noticed amelioration of the induced burst quantity and the required rate on the AFDX with the optimized gateway strategy (N:1).

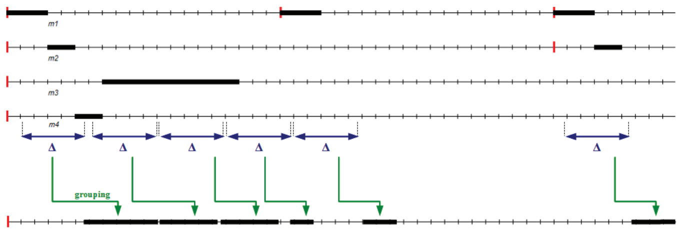

Figure 6. *An example of the gateway pooling strategy*

Strategy	VL(s)	burst(bytes)	rate (Mbps)
$(1:1)$	25	1600	$2,068$
$(N:1)$	1	215	0.86

Table V
THE TWO GATEWAY STRATEGIES COMPARISON

V. CONCLUSION

The optimization of the interconnection function and its impacts on the end to end performances for a particular avionics network: AFDX-CAN are analyzed in this paper. The obtained results are encouraging and we are currently working on the generalization of the gateway pooling strategy to other case studies.

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