PREPRINTS

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Advance Program

8:30-9:15	**Registration**
9:15-9:30	**Welcome and opening remarks**
9:30-11:00	**Session 1 - Keynote Talk 1** *Avionics embedded networks* Christian Fraboul, Lionel Loudet
11:00-11:30	**Coffee Break**
11:30-13:00	**Session 2** *Exploring alternatives to use master/slave full duplex switched Ethernet for avionics embedded applications* Ahlem Mifdaoui, Moris Behnam, Thomas Nolte, Paulo Pedreiras, Luis Almeida, Ricardo Marau *Networked embedded systems for active flow control in aircraft* Eduardo Tovar, Nuno Pereira, Iain Bate, Leandro Indrusiak, Sergio Penna, Jose Negrao, Julio C. Viana, Francois Philipp, Dirk Mayer, Jose Heras, Filipe Pacheco, Joao Loureiro *Worst-case delay analysis for a wireless point-to-point transmission* Katia Jaffres-Runser
13:00-14:30	**Lunch**
14:30-16:00	**Session 3 - Keynote Talk 2** *Satellites embedded networks* Olivier Notebaert
16:00-16:30	**Coffee Break**
16:30-17:30	**Session 4 - Keynote Talk 3** *Performance evaluation of real-time traffic in aggregate-scheduling networks* Giovanni Stea
17:30-18:00	**Panel discussion and closing remarks**

Session 1 - Keynote Talk 1

Avionics embedded networks

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Abstract

The evolution of civilian aircraft avionics systems is mainly due to an increasing complexity which is illustrated by a larger number of integrated functions, a larger volume of exchanged data, and a larger number of connections between functions. Consequently, the growth of the number of multi-point communication links cannot be taken into account by classical avionics mono-emitter data-buses. The solution consists in the utilization of a switched Ethernet technology (named AFDX: Avionics Full Duplex Switched Ethernet), which allows a re-use of development tools as well as of existing communication components while achieving better performance and which has been standardized in ARINC 664. This new communication standard represents a major step in the deployment of modular avionics architectures. The main problem is due to the indeterminism of the switched Ethernet. A network designer must prove that no frame will be lost by the AFDX and must evaluate the end-to-end transfer delay through the network (guaranteed upper bound) according to a given avionics applications traffic.

This talk will explain the main evolutions of avionics systems. It will present the main concepts and mechanisms as well as the methods and tools which are needed mainly for certification purpose. The reasons for the choices will be explained. A feedback will be given as well as some trends for the future.

Session 2

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.

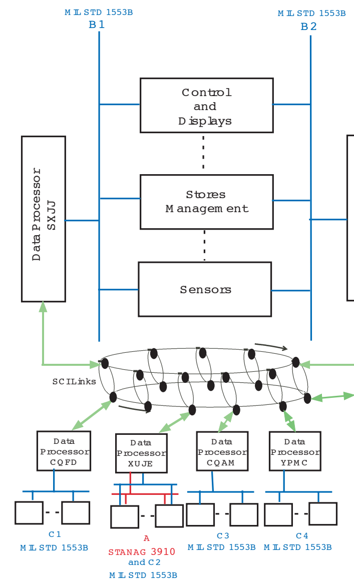

Fig. 1. A representative military aircraft network

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,

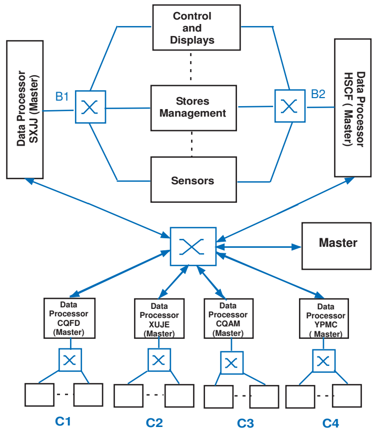

Fig. 2. Proposed communication network using Full Duplex Switched Ethernet

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).

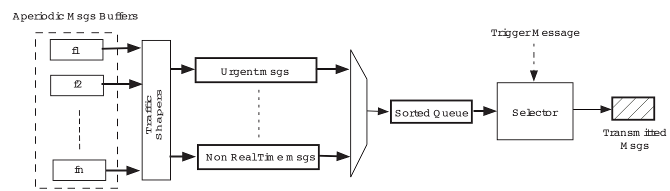

Fig. 3. Arbitration mechanism of aperiodic traffic in the slave

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.

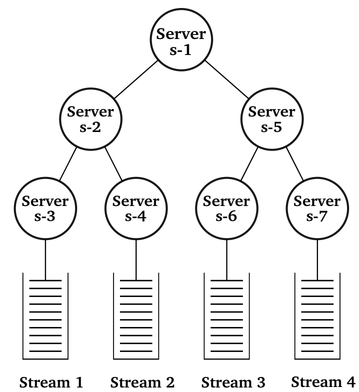

Fig. 4. An example server hierarchy. Bandwidth is allocated to each server. Application messages arrive at the leaf servers.

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.

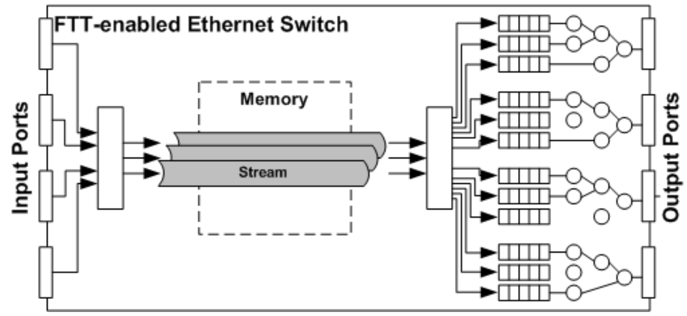

Fig. 5. FTT-enabled Ethernet Switch

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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Networked Embedded Systems for Active Flow Control in Aircraft

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***Abstract*— Aerodynamic drag is known to be one of the factors contributing more to increased aircraft fuel consumption. The primary source of skin friction drag during flight is the boundary layer separation. This is the layer of air moving smoothly in the immediate vicinity of the aircraft. In this paper we discuss a cyber-physical system approach able of performing an efficient suppression of the turbulent flow by using a dense sensing deployment to detect the low pressure region and a similarly dense deployment of actuators to manage the turbulent flow. With this concept, only the actuators in the vicinity of a separation layer are activated, minimizing power consumption and also the induced drag.**

Keywords-sensor/actuator networks; cyber-physical systems; active flow control; avionics

I. INTRODUCTION

Over the 2009-2028 period, world passenger traffic is expected to increase by 4.7% per annum, and the numbers of frequencies offered on passenger routes will more than double (according to the Airbus 2009-2028 Global Market Forecast). Hence, traffic demand will nearly triple, and airlines will more than double their fleets of passenger aircraft (with over 100 seats) from 14,016 at the beginning of 2009 to 28,111 in 2028 [1].

Although a commercial opportunity, the drastic increase of demand on air transportation presents significant challenges in terms of flight capacity, safety, security, and affordability, as well as, time efficiency and environmental effects. Importantly, the environmental impact of the ever increasing number of flights needs to be reduced. This can be achieved through concepts of aircraft morphing and improved aerodynamics.

The reduction of fuel consumption is important for both the environmental effects as well as the cost efficiency. The potential for a 50% reduction in fuel burn in the next 15 years can be attained using a combination of aerodynamic, engine, and structural improvements [3], as expressed by the well-known Breguet range equation:

$$range = \frac{velocity}{fuel\ consumption} \times \left(\frac{lift}{drag}\right) \ln\left(1 + \frac{weight_{fuel}}{weight_{payload} + weight_{empty}}\right) \qquad (1)$$

By inspecting Eq. (1) it becomes obvious that technologies to reduce the aircraft drag and the weight of the empty aircraft are crucial, regardless of selected configuration. Aerodynamic drag is known to be one of the factors contributing more to increased aircraft fuel consumption. In [4], a reported study shows that for a long haul commercial aircraft (325 passengers) a combined reduction of 10% in both skin friction and induced drag (the components that roughly contribute around 80% to the total aerodynamic drag in such type of aircrafts) may lead to a 15% fuel consumption reduction alone.

The drag breakdown of a commercial aircraft shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag for a typical long range aircraft at cruise conditions [4, 5] (see Figure 1).

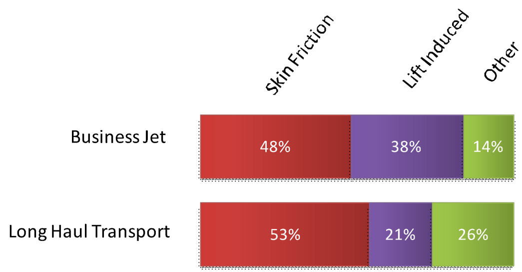

Figure 1. Drag breakdown in commercial aircraft.

Skin friction drag is therefore the main component of the aerodynamic drag. It arises from the friction of air against the skin of the aircraft moving through it. The primary source of skin friction drag during the flight is the boundary layer separation. This is the layer of air moving smoothly in the immediate vicinity of the aircraft (wing, fuselage, tail). The smooth flow (laminar flow) is disturbed by the boundary layer separating from the surface creating a low pressure region and, ultimately, increasing the skin friction drag (turbulent flow). Figure 2 illustrates this.

There are various approaches to reduce the turbulent skin friction, involving different mechanisms, such as: reducing turbulent friction drag through riblets; deformable active skin using smart materials (compliant walls), or by (locally) postponing the boundary layer separation using vortex generators such as dimples or Synthetic Jet Actuators - SJAs. In this latter case, suction from the surface of the wing can be used to remove the low-energy air directly from the boundary layer. Along with this method, additional momentum can be achieved by generating streamwise vortices near the edge of the boundary layer that reenergize the boundary layer flow.

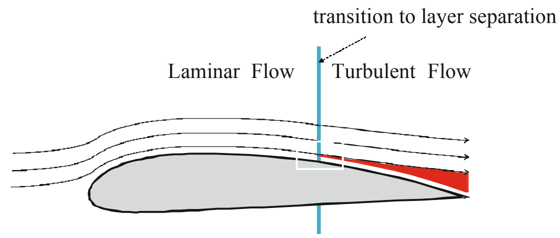

Figure 2. Boundary layer separation exemplified with the wing.

A recent research work [6] uses SJAs running at key positions on the wing to continuously energize the boundary layer and thus delay its separation. However, that approach does not use sensors to detect and trace the separation, and is therefore static and proactive in nature. It results that the efficiency of active flow control (ACF) is compromised and energy resources are wasted when there is no boundary layer separation or when it lies outside the actuators' optimal control field.

We aim a smarter use of the actuators for AFC.

II. A CPS Approach for Active Flow Control

Although the information technology transformation of the 20th century appeared revolutionary, a bigger change is in progress. The term Cyber-Physical Systems (CPS) has come to describe the research and technological efforts that will ultimately allow the interlinking of the real-world physical objects and the cyberspace efficiently [7-8]. The integration of physical processes and computing is not new. Embedded systems have been in place for a long time and these systems often combine physical processes with computing. The revolution is coming from massively deploying networked embedded computing devices allowing instrumenting the physical world with pervasive networks of sensor-rich embedded computation. As Moore's law continues, the cost of a single embedded computer equipped with sensing, processing and communication capabilities drops toward zero. This makes it economically feasible to densely deploy networks with very large quantities of such nodes.

Accordingly, it is possible to take a very large number of sensor readings from the physical world, compute quantities and take decisions out of them. Very dense networks offer a better resolution of the physical world and therefore a better capability of detecting the occurrence of an event; this is of paramount importance for a number of applications where high-spatial sensing (and actuation) resolution is of paramount importance.

Our aimed approach to active flow control is indeed a CPS application where high-spatial resolution sensing and actuation is required, and this opportunity is already being tackled by us [9].

We aim at designing, validating and demonstrating a novel cyber-physical system able of performing an efficient suppression of the turbulent flow by using a dense sensing deployment to detect the low pressure region and a similarly dense deployment of actuators to manage the turbulent flow. With this concept, only the actuators in the vicinity of the separation layer are activated, minimizing power consumption and also the induced drag.

In our approach for turbulence (drag) reduction, we are considering two different types of local actuation (see Figure 3): (i) active vortex generators such as synthetic jet actuators; and (ii) active surface modulation/micro-morphing such as active dimples, active riblets or active fliperons [10]. Concerning the latter, by active it is meant that the local or array geometry is actively changed by a servo-control. These are two different modes of actuation at local level for turbulence management. As far as our knowledge is concerned, none of the technological solutions are commercially (COTS) available yet. In both types of actuation the global concept is the same: a dense network of sensors and actuators will be used to locally modulate the surface and the boundary layer. This dense network aims at maximising sensor observability and improving system controllability.

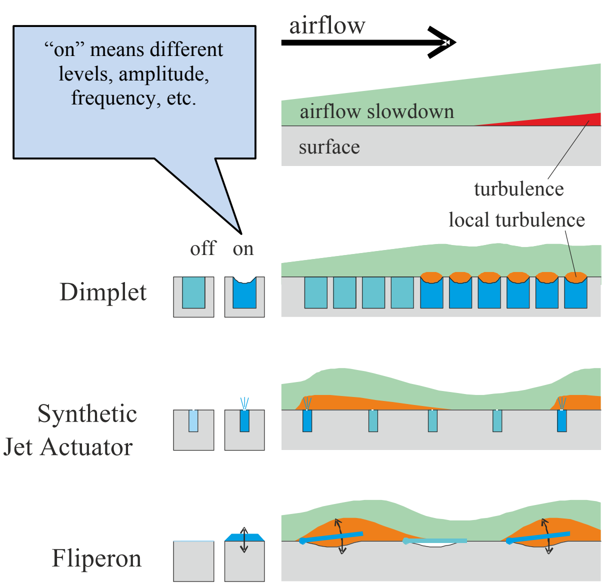

Figure 3. Turbulence management through different local actuation concepts.

The approach we propose for active flow control is challenging however as turbulence management is difficult to achieve. The small length and the time scales that characterize turbulent flows make the design and fabrication of arrays of sensors and actuators very challenging [11]. Active flow control, achieved through local modulation of aircraft skin surfaces, is one such, yet to be seen, technological development with the potential to offer significant reduction of drag and related fuel consumption and emissions.

We want to rectify this.

The challenge is to achieve the desired objective in a dependable manner whilst minimising energy expenditure.

Implementing active flow control through this smart skin approach implies a reliable, highly fault tolerant network of active skin friction reduction components. Importantly, given the characteristics of the physical quantities to be tracked, sensors (e.g., pressure sensors, vibration sensors) might need to be only a few centimetres apart. Therefore, even in the case of a medium-sized passenger aircraft, the sensor / actuator network will be composed of potentially hundreds of sensors, controllers and actuator systems (smart skin patches) (Figure 4) that will be embedded across the aircraft wings and fuselage. Overall, this will be thousands of sensing and actuation devices to perform active flow control.

The concept will be materialized as an active skin system. This active skin system will call for novel solutions in the field of advanced materials for critical applications to drive the effort of integrating the sensors and actuator systems patches with light smart materials technologies (e.g., piezoelectric materials, dielectric elastomers) and integration technologies (e.g., flexible materials, optical fibres, micro-electrical-mechanical-systems). An actual prototype is to be developed.

Such densely instrumented active skin poses a huge challenge in terms of interconnectivity and timely data processing. We plan to develop novel sensor/actuator network paradigms and mechanisms able to deal efficiently with large-scale processing requirements. Scalability will be a concern as well as timeliness. We have already proposed algorithms for obtaining an interpolation of sensor readings from different sensor nodes, and those algorithms present excellent scalability properties for dense instrumented CPS [9, 12]. The active flow control algorithms must operate in a timely fashion to be able to perform efficient flow turbulence cancelling and therefore contribute to a highly efficient fuel consumption reduction.

In our approach, the energy-efficiency of the system is a major concern. Wireless communications [9, 13] are being considered in our concept. In such way we plan to remove the need for complex, heavy (as it is obvious from Eq. (1), cables would increase the aircraft empty weight and therefore would reduce the aircraft range for the same fuel), fixed and replicated wiring looms normally required to implement double or triple redundancy. This is actually in line with the huge eagerness by the industry towards fly-by-wireless [14-16]. However, wireless communication within an aircraft requires advanced security and reliability features. These aspects are being considered in our concept. However, cryptography or error correction schemes have a non-negligible impact on the energy consumption of autonomous sensor nodes deployed within the aircraft. Integrating energy-efficient support through reconfigurable hardware acceleration for these functionalities will be considered to enhance the dependability of the system.

Our recent research [17] has shown that those technologies are achievable for sensor / actuator platforms to be embedded with aircraft structures for even very demanding applications, such as vibration detection and noise cancellation.

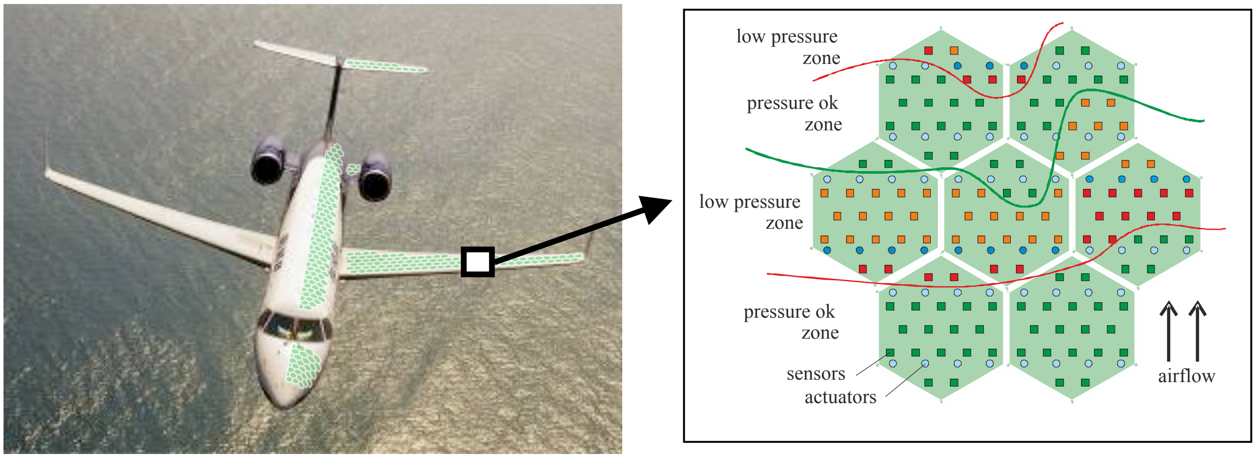

Figure 4. The active skin patch concept.

In this case, an application-specific processor is introduced and fully customized to improve the computational performance of each operation in the digital signal processing algorithms. A similar approach is followed in the project Maintenance on Demand (MoDe) [20] for condition-based maintenance of selected parts of a truck, or in the research project AdRIA (Adaptronics, Research and Innovation) for adaptronic applications [18]. Existing solutions include the utilization of low power reconfigurable computing [21] or specialized streaming processors [18].

Given the high density of sensors and actuators to be deployed for active airflow control, the aggregate power consumption requirements are expected to be relatively significant. This can potentially impact the fuel economy in case some or all of this power is supplied by the aircraft. Therefore, in our concept we plan to explore battery powered solutions and energy harvesting techniques that will exploit structural vibration to generate electrical energy. Some nodes like actuators, which have higher power requirements for actuation, processing, and communication, will possibly operate on the aircraft power supply. Some sensors may also be powered by the aircraft to provide added design redundancy and enhance the overall network reliability. In any case, maximizing the energy efficiency of the active skin is an important design goal. Skills exist as well to explore and propose solutions where sensor nodes can drain power from a layered substrate (such as the Pushpin concept of MIT [19]).

With our approach, the sensing capabilities of the active skin system are also to cover as well Structural Health Management (SHM) functions. Besides pressure sensing capabilities, other sensors may be integrated in the system to convey structural-health information. In that way, real-time information from the aircraft skin (both concerning aerodynamics and structural-health) can be made available to the avionics systems for pre-flight checks and during in-flight operation. This key information can potentially be invaluable for optimising fuel, operational readiness assessment and structural health management planning policies to achieve even other levels of efficiency [22].

We aim at considering dependability as a crosscutting aspect of the system. It is felt this is fundamentally important to the concept and gives it a unique contribution and direction. The reason behind this is not related to the intention of delivering a certified system, but instead it is aimed to direct the other areas of research so that methods and techniques are not developed that are un-certifiable. A particular example is that whilst we could develop a dependable communications infrastructure, however unless we can gather evidence of dependability then it is not useful. This is a particular concern for instance as many communications protocols use highly adaptive features that are normally not allowed by certification standards, e.g. DO178B [23, 24].

III. Related Work and Challenges

A. *Aeronautical applications of WSANs*

Some of the many potential benefits of using Wireless Sensor/Actuator Networks (WSAN) for aircraft systems include weight reduction, ease of maintenance and an increased monitoring capability. Current systems, which are based on wired connections, are complex, difficult to route, heavy and prone to damage and degradation due to wear. The idea of using WSAN in aircrafts so far has been primarily focused on structural and engine health monitoring. For example, Harman [2] summarizes some applicable wireless technologies and [25] describes the architecture of a WSAN for aircraft engine health monitoring, which comprises a number of sensors and a central engine control unit. Interestingly, operational WSAN in spacecraft applications can be found in the International Space Station and NASA's Space Shuttle. WSAN have been successfully deployed to gather data in retrofit applications, which otherwise would have been prohibitively difficult or expensive [26]. In terms of health monitoring for aeronautic applications, special care must be put in the robustness and the security of the data collection process [27].

In the context of aircraft with morphing capabilities, monitoring the shape of morphing structures has been deemed essential for their effective and safe operation [28]. In that work, a novel class of sensors was introduced to address the limitations with previous attempts to monitor the shape and health of morphing structures using fibber optic sensors. It relies on a specially configured distributed network of wires that is embedded in the composite fabric of the monitored structures. The output of the sensor network is wirelessly transmitted to a control processor to compute the linear and angular deflections, the shape, and strain maps over the entire surface of the morphing structure.

B. Communication in large-scale Dense WSANs

In our initiative we are interested in building a distributed sensor/actuator control system, where the sensing and actuating is performed at a very fine granularity in space and time. To achieve this goal, it is necessary to observe that there is a close interaction between the computation (performed by the control algorithms) and the physical quantities (e.g. air pressure, vibration). The control algorithms should perform computations that are based on sensor readings from many sensor nodes, in order to acquire a high-resolution representation of the state of the physical world. To this end, sensor nodes must communicate using a shared broadcast medium (such as a shared bus or a wireless channel), as it would be unfeasible (due to the number of nodes) to deploy dedicated communication channels for each sensor/actuator node. Finally, we would like to be able to acquire this representation with a low (and bounded) delay. This follows from the fact that the control algorithm should do its computations based on a representation of the state of the physical world that is not too old.

Due to the large number of devices, wireless communication bemomes challenging, and obtaining a representation of the physical world with a low (and bounded) delay can be a major obstacle. To overcome this obstacle, it is required to enable energy-efficient in-network processing targeting minimization of wireless communication, thus reducing the probability of network congestion, critical packet losses, transmission delays, as well as improving network lifetime (due to lower energy consumption).

Many research efforts have focussed towards optimizing the process of collecting data from wireless sensor networks. It is possible to find, for example, approaches to minimize the energy consumption in radio-usage [29], or to make use of spatial correlation of sensed data [30] to reduce the number of message exchanges. Efficient data collection can also require in-network aggregation schemes for reducing the number of packets and also the overall latency. Aggregation in wireless sensor networks is a well-researched area with several well-known techniques [31-34].

Collecting data from high-density networks can make use of specific properties of the communication medium to collect aggregates in fast and energy-efficient manner. WiDom [35] is such a medium access protocol that can be employed to efficiently compute aggregates in a timely manner with significantly lesser message exchanges, as shown elsewhere [35, 9]. With that approach, the number of messages exchanged and time to gather an aggregate are not dependent on number of nodes in a given broadcast domain, thus facilitating dense networks without correspondingly high-energy costs.

As mentioned earlier, gathering data from dense networks can also cause latency issues that may not be favourable for real-time control applications. In [36] are outlined various challenges in real-time communication in sensor networks. Quality-of-Service oriented approaches, like [37], provide probabilistic timing and reliability guarantees based on the application requirements. Such provisions are necessary in systems with real-time requirements, and especially in critical systems employed in aeronautical applications. Reducing the radio power can help not only to achieve energy-savings, but can also limit the radio-coverage in dense networks, thereby reducing packet collisions. Low-power radio designs [36, 37] have been proposed that can help on achieving the above goals.

Another approach to reduce the delay induced by wireless communication is the adoption of decentralized computation. The analysis of sensor data within a small cluster of nodes or locally on single nodes with the objective of extracting data features relevant for the application will contribute to the reduction of the communication traffic. However, it must be ensured that the energy and time saved on the communication is not lost with the additional processing. The computation capabilities of the node must be then adapted accordingly, using for example reconfigurable computing [21].

C. Control in Large-Scale WSANs

The design of the control system and actuation are an important aspect that requires skills in control system design, aerodynamics, and system simulation. Consider many sensors and many actuators that are attached to a surface. We desire to control the surface to achieve a certain objective, for example, if the surface is an aircraft wing then we may desire to minimize fuel consumption. The research literature in feedback control systems refers to such a system as a MIMO-system. It is possible to design a single controller for such a system but typically the problem is decomposed into many SISO-controllers, which exchange information. In [38] the authors address the issue of control algorithms in sensor networks, as traditional control theory is not sufficient for modelling distributed sense-actuate systems.

For the control of turbulent waves with dynamic actuators like SJAs, the goal is to excite a counteracting wave that cancels the disturbances travelling along the surface. A possible implementation is based on feed-forward control concepts, which utilize a reference of the disturbance measured with a suitable sensor and generate the control signal from this. By the application of adaptive filters and the use of an error sensor positioned downstream to the actuator for this task, the on-line optimization of the control signal with respect to the current disturbance signals is enabled [39].

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Worst case delay analysis for a wireless point-to-point transmission

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***Abstract*—Wireless technologies are currently being intensively investigated for real-time applications because of their appealing ease of deployment and scalability. Dimensioning a wireless network for safety-critical applications is still an open problem mainly because of the intrinsic non-deterministic nature of the wireless medium. This paper discusses the derivation of a worst case delay (WCD) measure for a point-to-point wireless transmission. A WCD performance measure is central to the performance evaluation of wireless networks subject to hard real-time constraints. To capture the non-deterministic nature of the wireless channel, our measure relies on a probabilistic link model where transmissions are guaranteed using an acknowledgement mechanism. The delay is expressed by the number of emissions necessary for a packet to arrive at its destination. The WCD is expressed as the P_d-percentile of this number of emissions. The proposed WCD metric is computed for an interference-free scenario considering AWGN and Rayleigh fading channels. Interference-limited scenarios are discussed as well to highlight the perspectives of this work.**

***Keywords*-Wireless transmission, unreliable link model, performance evaluation, worst case delay analysis**

I. Introduction

The deployment of wireless technologies for real-time applications is rapidly gaining momentum because of their appealing ease of deployment and scalability. First analysis of legacy wireless protocols [1] (e.g. IEEE802.11, Bluetooth or IEEE802.15.4) in the factory automation context called for the design of novel solutions meeting the needs of real-time systems. New protocols have been specified for industrial process control such as WirelessHART [2] [3] or ISA100.11a [4]. Both solutions provide a pure time division multiple access to its real time users to prevent unbounded channel access delays. Channel hopping techniques with blacklisting is implemented at the physical layer to be more robust to interference. In the context of nuclear plant or warship monitoring, dedicated wireless sensor network protocols such as OCARI and MACARI [5] have been developped.

Temporal behavior of such protocols have to be thoroughly assessed for such critical applications. As such, a comprehensive performance evaluation of transmission delay is needed. Together with controlling the variance of transmission delays, it is of foremost importance to derive a safe bound on the worst case transmission delay. This safe bound can be accounted for to check that transmission delays meet their temporal requirements in the protocol integration process. Worst case delay analysis in wired networks has been performed using two types of derivations: deterministic (network calculus [6], trajectory approach [7]) and probabilistic (stochastic network calculus [8]).

In this paper we propose a probabilistic derivation of the worst case delay (WCD) bound for a point-to-point wireless communication. This choice is clearly motivated by the non-deterministic nature of the wireless channel whose most valid models are stochastic. Thus, our WCD bound relies on a probabilistic link model where transmissions are guaranteed using an acknowledgement mechanism. The overall transmission delay is measured as a function of the number of emissions necessary for a packet to arrive and be decoded at its destination. The WCD delay is defined as the P_d-percentile of the overall transmission delay. As such, there is a probability of $P_{th} = (1 - P_d)/100$ for the delay to be larger than the WCD, providing a confidence level on the calculated WCD bound. The proposed WCD metric is completely derived and calculated for an interference-free scenario considering AWGN and Rayleigh fading channels. Interference-limited scenarios are discussed at the end of the paper to show the perspectives of this work.

This paper is organized as follows. Section II presents our WCD analysis for a point-to-point interference-free transmission. Next, Section III discusses the main issues related to the WCD analysis in interference-limited scenarios. Section IV concludes the paper.

II. Worst case delay for interference-free transmissions

This section details firstly the unreliable wireless link model, then it briefly presents the average transmission delay computation before introducing the derivation of the stochastic WCD bound.

A. Unreliable wireless link model

The unreliable link model captures the wireless link availability between two nodes i and j. It is defined as the *probability* p_ℓ of a successful transmission over the link $\ell = (i, j)$. Characterization of the link probability is

Table I
TRANSMISSION PARAMETERS [12]

Symbol	Description	Value
N_b	Number of bits per packet	2560
R	Transmission bit rate	$1\ Mbps$
N_0	Noise level	$-154dBm/Hz$
f_c	Carrier frequency	$2.4GHz$
G_T	Transmitter antenna gain	1
G_R	Receiver antenna gain	1
α	Path-loss exponent	3
L	Circuitry losses	1

impacted by enhancements and impairments at the physical layer: transmission power, modulation type, channel fading, etc. Such a realistic link model captures the non-deterministic nature of a wireless transmission and has been used in recent performance studies [9] [10] [11] focusing on various metrics such as energy consumption, average delay or reliability. It is derived for the transmission of a packet of N_b bits. Formally,

$$p_\ell(\gamma_\ell) = (1 - BER(\gamma_\ell))^{N_b} \tag{1}$$

where $BER(\gamma_\ell)$ is the bit error rate (BER) corresponding to the signal to noise ratio (SNR) γ_ℓ on link ℓ. Note that consequently $p_\ell(\gamma_\ell) = 1 - PER(\gamma_\ell)$, with $PER(\gamma_\ell)$ the corresponding packet error rate. The BER depends on the transmission chain technology (modulation, coding, etc.) and channel type (AWGN, Rayleigh, Rician). It is defined as the average probability to decode one bit. Thus it is a function of the SNR γ_ℓ experienced by the destination calculated by [12]:

$$\gamma_\ell = \frac{K_1 \cdot P^t \cdot d_\ell^{-\alpha}}{N_0 \cdot B}, \tag{2}$$

with

$$K_1 = \frac{G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2 \cdot L}, \tag{3}$$

where d_ℓ is the transmission distance between nodes i and j, $\alpha \geq 2$ is the path loss exponent, P^t is the transmission power, N_0 the noise power density in mW/Hz, G_T and G_R are the antenna gains for the emitter and receiver respectively, B is the bandwidth of the channel and is set to the emission rate ($B = R$), λ is the wavelength and $L \geq 1$ summarizes losses through the transmitter and receiver circuitry. For a given transmission technology, K_1 is constant and $p_\ell(\gamma_\ell)$ is a function of d_ℓ and P^t: $p_\ell(d_\ell, P^t)$. Values considered herein are listed in Table I.

In the following, a transmission scenario using Binary Phase Shift Keying (BPSK) modulation and coherent detection is assumed. Closed form expressions of $BER(\gamma_\ell)$ for AWGN (Additive White Gaussian Noise) and Rayleigh flat fading channels as follows:

AWGN CHANNEL: Derivation of $BER(\gamma_\ell)$ for BPSK and coherent detection follows the derivation in [13]:

$$BER(\gamma_\ell) = \alpha_m \mathrm{Q}(\sqrt{\beta_m \gamma_\ell}) \tag{4}$$

with the Q function, $\mathrm{Q}(x) = \int_x^\infty \frac{1}{\sqrt{\pi}} e^{-u^2/2} du$ and α_m, β_m the modulation type and order, respectively. For BPSK, $\alpha_m = 1$ and $\beta_m = 2$.

RAYLEIGH FLAT FADING: The general expression for the BER in Rayleigh flat fading channel for $\gamma_\ell \geq 5$ [13] is assumed:

$$BER_f(\gamma_\ell) \approx \frac{\alpha_m}{2\beta_m \gamma_\ell} \tag{5}$$

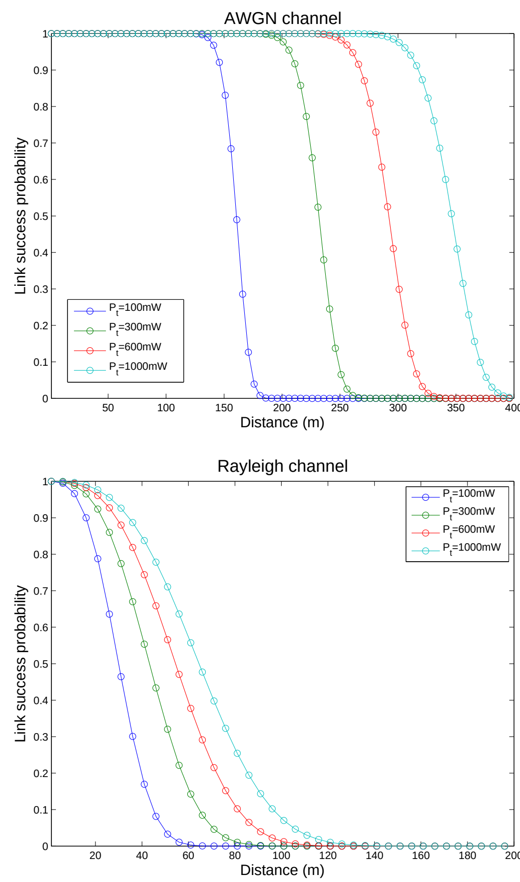

Figure 1. Link probability as a function of distance at different transmission power values, for AWGN and Rayleigh flat fading channels.

Link probability values for both channel types and different values of P^t are represented in Figure 1. The curves can be divided into three parts: reliable transmission, unreliable transmission and impossible transmission. For instance, in an AWGN channel at a transmission power of 100mW, transmission is always successful until about 150 meters. Transmission is impossible beyond 180 meters and in between, the transmission is unreliable. In the Rayleigh flat fading environment, the perfectly reliable transmission is nearly inexistent and most of the links are unreliable links. Rayleigh fading characterizes harsher propagation environments where nodes are usually not in line of sight and transmission is deeply affected by multi-path such as it is the case in heavily built up city centers. There is no main line of sight transmission component. In this case, the envelope of the received SNR is Rayleigh distributed. Other channel models can be considered, depending on the environment the wireless network is deployed in. For instance, Rician fading is appropriate when communication with a direct line of sight is possible in a harsh propagation environment with lots of scatterers.

The probabilistic model contrasts to previous models such as the switched link model where a transmission between nodes i and j is successful if and only if the SNR is above a minimal threshold value. With the switched link model, there are either completely reliable links or no communication is possible. Unreliable links have been leveraged to properly evaluate connectivity [14], derive multi-objective performance trade-offs [10] [11] and design optimal routing and resource allocation strategies [11]. We show in this paper that the unreliable link model is particularly suited to become the building block of a worst case delay analysis of wireless networks.

B. Average delay metric

To combat packet losses on an unreliable radio link, we assume here a general acknowledgement procedure where the complete packet is retransmitted if no acknowledgement is received before T_{NACK} milliseconds have elapsed. A maximum number of retransmissions N_R^{max} can be set. If transmission is successful, the acknowledgement packet is received within T_{ACK} milliseconds. For simplicity, we assume $T_{ACK} = T_{NACK}$ but different, realistic values of both durations can be accounted for if needed.

The delay for a packet to be emitted once by i and acknowledged by j over ℓ, d_1, is the sum of three delay components. The first component is the queuing delay during which a packet waits at i for being transmitted. The focus of this paper is on the delay introduced by the transmission and thus, queuing delay is out of the scope of this analysis. The second component is the transmission delay equal to N_b/R and the third component is T_{ACK}. Propagation delay is neglected because transmission distances in current technologies emitting in the 2.4GHz band are usually short (≤ 100m).

T_{ACK} and N_b/R being constant, d_1 is set to be 1 unit. Due to link unreliability, packets suffer from the delay introduced by their possible retransmissions. As such, we introduce the random variable N_R which represents the number of retransmissions needed before receiving a positive acknowledgement. For a given value of N_R, the complete transmission delay D_ℓ over ℓ is thus given by:

$$D_\ell = (N_R + 1) \cdot d_1 \tag{6}$$

since N_R unsuccessful and one successful transmissions are needed.

From (6), D_ℓ is a random variable giving the time before a positive acknowledgement is received in j. Having d_1 constant, the expectation of random variable D_ℓ is derived from the average number of retransmissions $\overline{N_R}$ [15] using $\overline{D_\ell} = (\overline{N_R} + 1) \cdot d_1$. Assuming a maximum number of retransmissions N_R^{max}, $\overline{N_R}$ follows:

$$\overline{N_R} = \sum_{r=0}^{N_R^{max}} r \cdot P[N_R = r] \tag{7}$$

with $P[N_R = r] = p_\ell \cdot (1 - p_\ell)^r$ the probability for a packet to necessitate r retransmissions. For a perfect transmission, $N_R^{max} = \infty$ and $\overline{N_R} = 1/p_\ell(d_\ell, P^t)$.

C. Worst case delay metric

The distribution of N_R knowing the link probability p_ℓ is given by $P[N_R = x] = p_\ell \cdot (1 - p_\ell)^x$. The distribution of the delay D_ℓ is derived according to (6):

$$P[D_\ell = x] = P[N_R = \frac{x}{d_1} - 1] \tag{8}$$

Definition The *worst case delay* is defined in this paper by the value D_ℓ^w of D_ℓ below which P_d percent of the observations fall, with $P_d = (1 - P_{th}) * 100$. Formally:

$$\max_{D_\ell^w \in D_\ell} D_\ell^w \text{ s.t. } P[D_\ell \geq D_\ell^w] \leq P_{th} \tag{9}$$

The worst case delay D_ℓ^w is the P_d-percentile of the transmission delay D_ℓ on link ℓ. D_ℓ^w is a function of the random variable N_R. It is thus a probabilistic bound that can be exceeded with probability P_{th}. Closed form expression of D_ℓ^w is:

$$D_\ell^w = \left\lceil \frac{d_1 \cdot \ln(P_{th})}{\ln(1 - p_l)} \right\rceil \tag{10}$$

Proof: We have $P[D_\ell \leq D_\ell^w] = p_\ell \cdot \sum_{x=0}^{\frac{D_\ell^w}{d_1}-1} (1 - p_\ell)^x$ from (8). This is a geometric serie of rate $(1 - p_\ell)$ and thus

$$P[D_\ell \leq D_\ell^w] = p_\ell \frac{(1 - p_\ell)^{D_\ell^w/d_1} - 1}{-p_\ell} = 1 - (1 - p_\ell)^{D_\ell^w/d_1}$$

From (9), $1 - (1 - p_\ell)^{D_\ell^w/d_1} \leq 1 - P_{th}$, leading to

$$D_\ell^w \leq \frac{d_1 \cdot \ln(P_{th})}{\ln(1 - p_l)}.$$

Since we are looking for the largest integer value of D_ℓ satisfying (9), we have:

$$D_\ell^w = \left\lceil \frac{d_1 \cdot \ln(P_{th})}{\ln(1 - p_l)} \right\rceil$$

■

Average delay $\overline{D_\ell}$ and worst case bounds D_ℓ^w expressed for different P_{th} values are represented in Figures 2 and 3, for both AWGN and Rayleigh fading channels. Figure 2

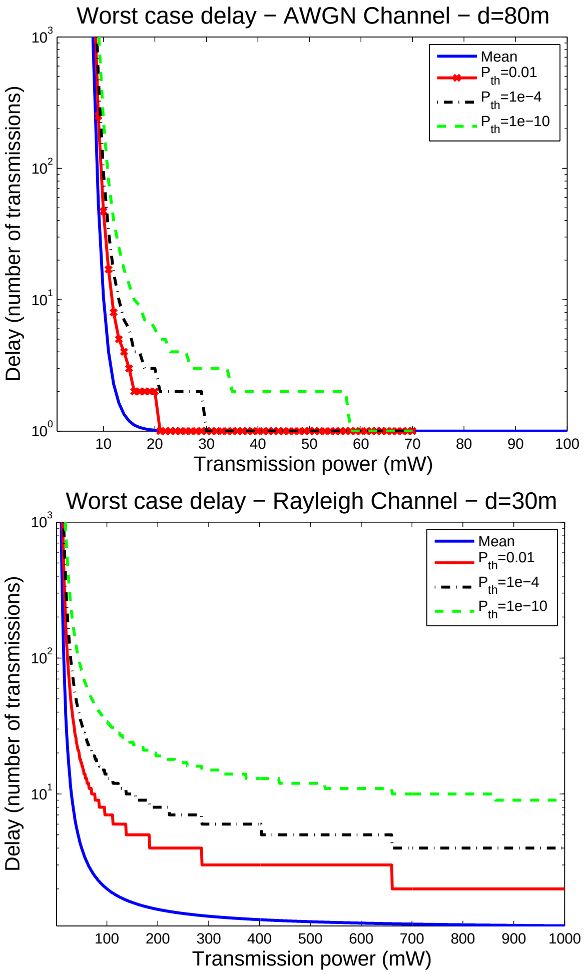

Figure 2. Mean and worst-case delay as a function of the transmission power for different percentile values, for AWGN and Rayleigh flat fading channels.

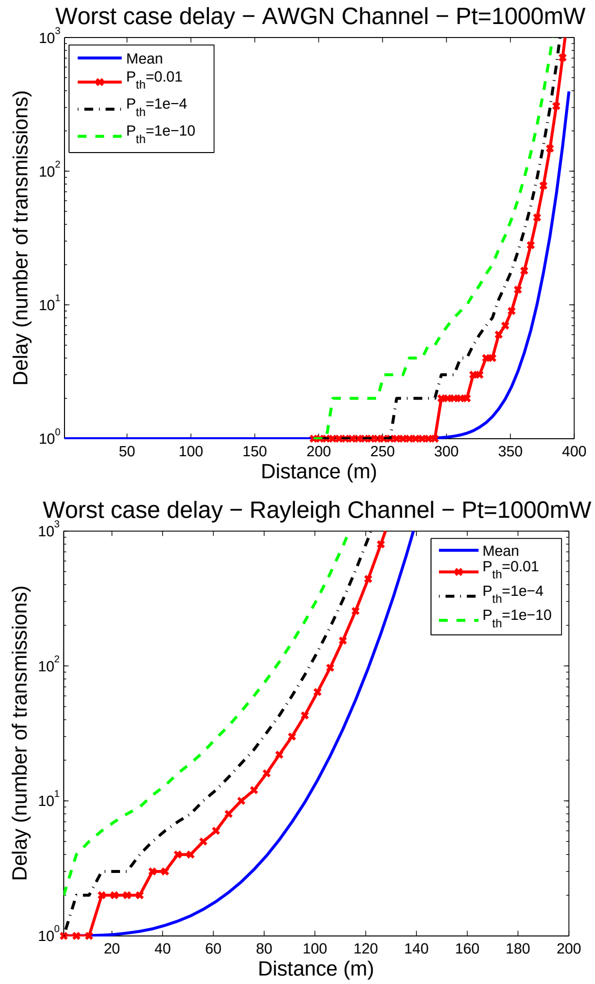

Figure 3. Mean and worst-case delay as a function of the distance for different percentile values, for AWGN and Rayleigh flat fading channels.

focuses on the impact of the transmission power for a fixed inter-node distance while Figure 3 concentrates on the impact of the inter-node distance for a fixed transmission power.

In Figure 2, delay decreases with the increase in power. Indeed, as power is increased for a fixed inter-node distance, the link becomes more and more reliable, reducing the number of retransmissions needed to transmit a packet. For the AWGN channel, no communication is possible for a power below 20 mW: average and WC delay are infinite. Practically, infinite delays are not tolerable in a transmission and a maximum number of retransmissions is introduced N_R^{max} (which is not represented in this figure). WCD bounds are presented for P_{th} values as small as 1.10^{-10}, providing a really tight probabilistic bound on the worst case delay in this context.

Impact of inter-node distance at fixed power is represented in Figure 3. As expected, delay (and thus link reliability) increases with distance. Similar conclusions to Figure 2 can be drawn here: a tight bound is obtained, at the cost of little computation since a closed form expression exists in (10).

III. Accounting for interference in WCD analysis

This section introduces the main issues in accounting for interference created by multiple concurrent transmissions in our WCD analysis. Firstly, we concentrate on the interference-limited unreliable link model. Next, we discuss the main steps and problems to integrate elaborated channel access protocols if interference-free medium access is not achievable.

A. Interference-limited link model

In this section, we still discuss a point-to-point wireless communication on link ℓ between two nodes i and j. We assume here that this communication is interference-limited due to the other active links in the network as represented in

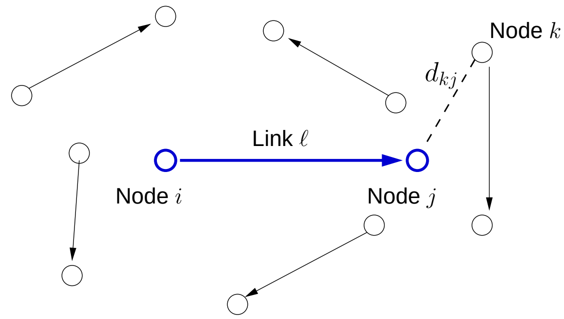

Figure 4. Interference-limited link model.

Figure 4. The complete network is static. More specifically, this scenario illustrates the study case where i is transmitting data to an access point j. Other nodes may interfere this communication because they have ad hoc communications with other nodes and can not detect the ongoing transmission between i and j for some reason (hidden terminal problem for instance).

Interference originates from concurrent transmissions in the wireless channel link ℓ. Medium access control prevents nodes from the same network to interfere with each other. Interference can be completely mitigated using Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA). In this case, each user is assigned its own resource (time slot or frequency) and no other node is allowed to transmit in this resource. Worst case delay analysis resumes in this case to the previously defined point-to-point interference-free model of Section II.

TDMA or FDMA medium access may suffer from both under-utilization of the network bandwidth and additional overhead for resource allocation. This is mostly the case when the network is lightly loaded. In this case, Carrier Sense Medium Access (CSMA) is an alternative that reduces resource allocation overhead and provides a faster access to the wireless channel. The drawback of CSMA is that interference can not be completely mitigated anymore, mostly because of the hidden terminal problem.

As for the interference-free case, the formulas for the BER hold, but this time they depend on the Signal to Noise and Interference ratio γ_ℓ^I (SINR) instead of the SNR γ_ℓ. Interference I_ℓ experienced at receiver j is added to the thermal noise in equation (2) to derive the SINR:

$$\gamma_\ell^D = \frac{K_1 \cdot P_i^t \cdot d_\ell^{-\alpha}}{N_0 \cdot B + I_\ell^D} \tag{11}$$

with I_ℓ^D defined as the sum of the power at j received from all other emitters transmitting at the same time. In this notation, D represents the set of interfering nodes. In this formulation, nodes can use different transmission power values. Thus, P_i^t represents the transmission power a node i is using. Formally, I_ℓ^D is defined as:

$$I_\ell^D = \sum_{k \in D} K_2 \cdot P_k^t \cdot d_{kj}^{-\alpha} \tag{12}$$

where $K_2 = G_T \cdot (\lambda/4\pi)^2$ and d_{kj} the distance between interferer k and destination node j. This computation of interference power captures the geometry of the network. As such, if the location of all nodes in the network is known, I_ℓ^D can be calculated using (12) and its corresponding link probability using (11) and (1). Similarly, if the node distribution follows a given law (e.g. a Poisson point process or a power law distribution for scale-free networks), interference distribution may be derived as well.

B. *Worst case delay metric and medium access control*

The set of interferers D affecting the communication on link ℓ depends on the decisions made by the medium access control (MAC) layer. For ideal TDMA (one user is assigned to one time slot at any time), the set D is empty. For a CSMA-oriented MAC protocol, we are interested in deriving the distribution of the bit error rate values over all possible interfering sets.

A set of interferers D belongs to the power set $\mathcal{P}(N)$ of N, with N the set of all nodes of the network different from i and j. For each set of interferers $D \in \mathcal{P}(N)$, a SINR value can be computed with (11) and its corresponding BER using (4) or (5). The distribution of $BER(\gamma_\ell^D)$ is given by the distribution of the set of interferers: $P[BER(\gamma_\ell^D) = x] = P[D \text{ active}]$, with D the set producing $BER(\gamma_\ell^D)$.

A node is said to be active if it can emit in the same channel than i. The activity of a node is captured by the probability it is emitting on the channel as proposed in [11]. Two types of such *emission probabilities* may be considered:

1. Independent emission probability: It is captured by τ_i, the probability node i is emitting. Using τ_i values, it is shown in [11] that it is possible to derive the probability of any set D of interferers to be active using:

$$P[D \text{ active}] = \prod_{i \in D} \tau_i \cdot \prod_{j \in N \setminus D} (1 - \tau_j)$$

The average link probability is deduced from the distribution of BER values using the law of total probabilities:

$$\bar{p}_\ell = \prod_{D \in \mathcal{P}(N)} p_{\ell,D} \cdot P[D \text{ active}] \tag{13}$$

where $p_{\ell,D} = \left[1 - BER(\gamma_\ell^D)\right]^{N_b}$ is the link probability experienced for the set D of interferers.

2. Conditional emission probability: The independent channel access model is a simplified model where transmission decisions are independent from eachother, which is usually not the case in a MAC protocol. Interaction between nodes could be for instance captured by $\tau_{i/j}$, the probability the channel is occupied by a transmission of node i knowing j is *not* transmitting. This conditional channel probability can be leveraged to derive the probability of a set of interferer K to be active.

Two types of worst case delays can be computed. The first one can be derived from (10) using the average link probability $\bar{p}_\ell$ derived in (13). A safer estimation but more pessimistic probabilistic bound can be computed from the *worst case link probability* which is experienced as the channel between i and j is the *most interfered*. Knowing the BER distribution and similarly to the definition of the worst case delay D_l^w, we can define the worst case link probability.

Definition The *worst case link probability* is defined as the value p_ℓ^w of p_ℓ above which P_d percent of the observations fall, with $P_d = (1 - P_{th}) * 100$. Formally:

$$\min_{p_\ell^w \in p_\ell} p_\ell^w \text{ s.t. } P[p_\ell \leq p_\ell^w] \leq P_{th} \tag{14}$$

The safer delay bound is then computed from (10) using the worst case link probability of (14).

Worst case delay bounds are straightforward to calculate if channel activity of each node is known (i.e. node emission probabilities). Different medium access protocols can be characterized using such node emission probabilities. Future studies will study the impact of these node emission probabilities on the worst case delay, and work on modeling medium access decisions either as independent or conditional emission probabilities, possibly accounting for incoming traffic models, memory size or node distribution.

IV. Conclusion

This paper discusses the derivation of the worst case delay (WCD) bound for a point-to-point wireless communication. This bound is guaranteed not to be exceeded with a probability of $(1 - P_{th})$, with P_{th} arbitrarily small. The proposed WCD metric is computed for an interference-free scenario considering AWGN and Rayleigh fading channels. Interference-limited scenarios are discussed as well to highlight the perspectives of this work. The next step is to fully characterize the WCD for the interference-limited case and concentrate on mapping MAC protocol decisions to emission probabilities. Therefore, protocol performance evaluation models derived from the one proposed by Bianchi in [16] for IEEE802.11 DCF can be leveraged.

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Session 3 - Keynote Talk 2

Satellite embedded networks

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Abstract

There are many types of spacecraft such as satellites for science, observation or telecommunications in near Earth orbit, inter-planetary probes, launchers, in-orbit infrastructures and their service vehicles or rovers for planetary surface exploration. These vehicles require on board data management systems including on-board communications between computers, memories, sensors and actuators. The data handling architecture of typical spacecraft systems will be presented showing different needs and solutions for onboard communications networks such as: large on-board sensing networks for low speed, low frequency communication between one or several computing units and many small sensors; Highly reliable command control master-slave communication system between a central control unit, sensors and actuators; High bandwidth data routing and processing systems for payload instruments data.

Within a limited business volume and highly specific environmental constraints, space Agencies and Industry has to focus technology development efforts on a limited set of standard solutions selected for their ability to cover generic needs, and to develop adaptations to the space environment specific constraints. For instance, the Mil-Std-1553 and the Can bus are widely used for spacecraft real-time command and control. The SpaceWire standard (ECSS-E-50-12C) will be presented in more details. This standard was adapted from the IEEE 1355 to provide high bandwidth data communications between on-board payload instruments and mass memories. A network layer was also developed including the definition of routing devices thus enabling high performance and reliable onboard data networks for future space missions. Communication protocols are also developed to ensure better communication determinism and interoperability between devices. SpaceWire is now used worldwide for many science missions. Current development efforts now focus on the Gigabit range of performance (SpaceFiber) and on innovative on-board data management toward on-board modular avionics allowing significant competiveness improvements just like recently performed in the aeronautical domain with the development of the Integrated Modular Avionics (IMA) and the Avionics Full DupleX switched ethernet (AFDX).

Session 4 - Keynote Talk 3

Performance evaluation of real-time traffic in aggregate-scheduling networks

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Abstract

The "holy grail" of the future Internet is to support the provisioning of reliable real-time services on a wide scale. In order to achieve this goal, per-aggregate resource management is nowadays regarded as a mandatory choice (see, e.g., the DiffServ and MPLS architectures). Real-time services, however, require firm QoS guarantees, such as a bound on the end-to-end delay experienced by the packets of single flows. The latter are very difficult to derive in networks employing per-aggregate resource management. Network Calculus, a powerful framework for worst-case analysis, can be used to address this issue. This talk will introduce basic Network Calculus principles, and then focus on how to exploit the latter to compute reliable bounds in FIFO feed-forward networks.