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Design and Analysis of UWB-based Network for Reliable and Timely Communications in Safety-Critical Avionics

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Abstract—Cable-less avionics implementation will clearly improve the efficiency of aircraft while reducing weight and maintenance costs. Therefore, with the technological progress of wireless technologies, an alternative avionic communication architecture based on Ultra WideBand (UWB) technology is proposed to fulfill these new needs. To adapt this wireless technology to safety-critical avionics, first, the tuning process of the MAC layer and the integration of accurate reliability mechanisms to achieve timely and reliable communications are presented. Then, an efficient timing and reliability analysis of such a communication network based on Network Calculus is detailed. This analysis integrates the impact of non-preemptive message transmission, various service policies in end-systems, e.g., First In First Out (FIFO) and Fixed Priority (FP), and transmission errors. Third, this general analysis is illustrated in the case of a realistic avionic application to replace the AFDX backup network with our proposed UWB-based network to support timely and reliable communications.

I. INTRODUCTION

The complexity of avionic communication architecture is increasing inherently due to the growing number of interconnected subsystems and the expansion of exchanged data quantity. Although the current architecture in modern aircraft fulfills the main avionic requirements, it leads at the same time to inherent weight and integration costs due to the significant quantity of wires and connectors. For instance, the new generation aircraft A380 contains 500 km of cables, one of the main reasons for production delays and cost overruns estimated at \$2 billion [12]. In addition to the cost issue, avionic interconnects are still subject to structural failure and fire hazard which decrease reliability and ramify maintenance efforts.

To cope with these issues, cable-less avionics implementation will clearly improve the efficiency and reliability of aircraft, while reducing integration, fuel consumption and maintenance costs. Therefore, with the technological progress of wireless technologies, an alternative avionic communication architecture based on wireless connectivity is proposed in this paper to fulfill these new needs. Indeed, wireless technology becomes a most cost effective solution thanks to its ubiquity, simplicity and maturity. Furthermore, using wireless technologies in the specific area of avionics brings significant advantages such as quick installation and maintenance, reduced weight and suitable communication patterns for avionics, e.g., multicast. However, to guarantee hard real-time requirements

of avionics, many interesting challenges remain to be handled due to wireless communication non deterministic behavior and its sensitivity to interference and jamming.

In [9], as a first step the authors identified the main challenges when using wireless technologies in avionics. Then, an assessment of Commercial Off The Shelf (COTS) wireless technologies versus avionic requirements was conducted and Ultra WideBand [4] was selected as the most accurate one for critical avionic applications because of its high data rate, contention-free access protocol and high security mechanisms.

In this paper, the design of an alternative avionic network based on Ultra WideBand [4] technology is proposed with Time Division Multiple Access (TDMA) as the arbitration protocol to guarantee timely communications and diversity mechanisms, e.g. time and frequency, to guarantee reliability requirements. Then, the relevant aspects of such a proposal and analytical evaluation of offered guarantees in terms of predictability and reliability in the case of a realistic avionic application are investigated, with reference to analytical approaches such as Network Calculus [17]. Many challenges arise from conducting such an analysis. First, safety-critical avionics are based on non-preemptive communication where a message transmission cannot straddle two slots, and consequently if the remaining time during a slot is insufficient for a complete transmission, then the message has to wait for the next slot. Second, the avionic end-systems implement service policies, such as First In First Out (FIFO) and Fixed Priority (FP) policies. The impact of such policies on delays needs to be integrated. Third, transmission errors and reliability mechanisms may increase communication latencies, and have to be taken into account during analyses.

Hence, our main contributions in this paper are threefold. First, to adapt Ultra WideBand technology to avionics context and fulfill the needed requirements, the tuning process of the MAC layer and the choice of adequate reliability mechanisms to achieve timely and reliable communications are presented. Then, an efficient timing and reliability analysis of such a communication network based on Network Calculus is detailed. This analysis integrates the impact of non-preemptive communication, various service policies in end-systems and transmission errors. Third, this general analysis is illustrated in the case of a realistic avionic application which consists in replacing the AFDX [8] backup network with our proposed UWB-based network to reduce cables while guaranteeing

timely and reliable communications.

In the next section, we review the most relevant approaches to provide timely and reliable communication over wireless technologies and relate them to our work. Afterwards, the design and analysis of our proposal is tackled as follows. First, the avionic network background and the adaptation of UWB technology to avionics context are detailed in Sections 3 and 4. Then, timing analysis in an error-free environment and its extension to error-prone environment are conducted in Sections 5 and 6. Finally, the practical feasibility of our proposal is illustrated within a realistic avionic application.

II. RELATED WORK

Wireless technology has been recently implemented for many real-time applications such as wireless industrial networks [24], wireless sensor networks [21] and biomedical applications [15]. In the specific area of aerospace, the idea of using wireless technologies has been introduced in 1995 in [26] and more recently elaborated with the creation of the *Fly-By-Wireless* workshop [10] in 2007. This workshop brings together leaders from industry such as Airbus and NASA to discuss recent advances in wireless communications for aerospace applications. Recent solutions based on wireless technologies were proposed for avionics to enhance non-critical functions, e.g., In-Flight Entertainment Network (IFE) [2], in-cabin communication [18] and aircraft health monitoring [25].

Unlike existing approaches in this area, this paper focuses on safety-critical functionality where a wireless network based on UWB technology, with TDMA arbitration protocol and diversity mechanisms [19], is proposed as an alternative backup network for the AFDX backbone network in new generation aircraft. The timing analysis of such a network is then conducted based on Network Calculus [17] in an error-free environment and then extended to an error-prone environment. The offered guarantees in terms of predictability and reliability are evaluated in the case of a realistic avionic application.

Network Calculus [17] has been used in many real-time application fields, e.g., wireless sensor networks [14] [16] and aerospace networks [20] [11]. In the area of timing analysis for TDMA-based networks, some interesting works based on Network Calculus have been proposed [23] [14] [16] [7]. These approaches were applied in error-free environments and ignored or relaxed non-preemptive message transmission. Hence, these approaches are not directly applicable in our case since they can result in optimistic end-to-end delay bounds. We propose extended Network Calculus models to integrate the impact of non-preemption and transmission errors. The efficiency of our proposed models is highlighted through a realistic avionic application.

III. BACKGROUND

As shown in Figure 1, the current avionic network consists of a redundant backbone network AFDX [8] to interconnect the avionic end-systems and some specific end-systems have dedicated sensors/actuators network based on CAN [13] or ARINC429 buses [5]. Furthermore, to increase the reliability level, a backup network based on Switched Ethernet guarantees

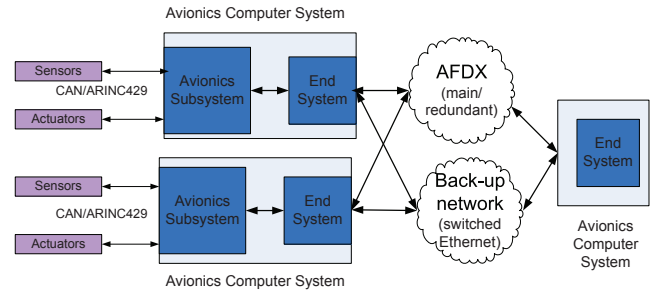


Figure 1: Current Avionic Network

a continuous service in case of failure on the redundant AFDX backbone. This redundant communication architecture leads to a significant quantity of wires and connectors.

To integrate an alternative backup network based on wireless technology that reduces cables in an aircraft, one needs to consider the specifics of AFDX networks to offer at least the same performance to avionic applications.

The AFDX [8] network is based on the Full Duplex Switched Ethernet protocol at 100 Mbps, successfully integrated in the A380 and A350. This technology supports the important amount of exchanged data due to policing mechanisms added in switches and the Virtual Link (VL) concept. This latter provides a way to reserve a guaranteed bandwidth to each traffic flow. The VL represents a multicast communication which originates at a single end-system, and delivers packets to a fixed set of end-systems. Each VL is characterized by: (i) BAG (Bandwidth Allocation Gap), ranging in powers of 2 from 2 to 128 milliseconds, which represents the minimal inter-arrival time between two consecutive frames; (ii) MFS (Maximal Frame Size), ranging from 64 to 1518 bytes, which represents the size of the largest frame that can be sent during each BAG.

Moreover, these main requirements have to be considered:

- **Predictability:** avionic network must behave in a predictable manner where the timeliness of data has to be guaranteed for determinism concerns. Therefore, information transmission latencies have to be bounded and respect the deadline constraints;
- **Reliability:** in terms of fault tolerance, avionics network has a high criticality level and necessary fault detection and recovery mechanisms have to be implemented to satisfy this condition;
- **Electromagnetic Compatibility:** the avionic network has to cope with a harsh physical environment with important vibration, temperature variation and humidity. In addition, it must operate normally in the presence of intense radio frequency noise, and should not cause interference to other aircraft systems.

IV. UWB-BASED NETWORK DESIGN FOR SAFETY-CRITICAL AVIONICS

In [9], UWB [4] was selected as the most suitable COTS technology in avionics context. In this section, the specifications of a wireless backup network are presented. Then,

the UWB characteristics and its identified limitations versus avionics requirements are detailed. Afterwards, the tuning process of the MAC layer to guarantee timely communications and the choice of adequate reliability mechanisms are defined.

A. Specifications of a wireless backup network

To replace the current backup network with an alternative wireless network, the requirements described in Section III have to be guaranteed. Hence, the main identified characteristics of physical and MAC layers for the alternative wireless backup network are described in table I.

Table I: Physical and MAC layers Characteristics

| | | |
|-----------|--|---|
| PHY Layer | Per link data rate Range (meters) Topology Com. pattern | $\geq 100\text{Mbps}$ 4 – 6meters Fully-connected Multicast |
| MAC Layer | Mechanism Delay Reliability Energy | Contention-free access End-to-end delays guarantee End-to-end reliability guarantee No specific limitations on power consumption |

B. HR-UWB Characteristics and Limitations

High Rate Ultra WideBand (HR-UWB) technology [4] operates at the large frequency band from 3.1 GHz to 10.6 GHz divided into 14 non-overlapping 528 MHz-Bands. HR-UWB can support data rate of 110, 200 and 480Mbps in a range of 10, 6 and 2m, respectively. Hence, for a short range between 4 and 6 meters, it offers a data rate of 200 Mbps which satisfies the required physical layer characteristics for the backup network.

HR-UWB supports the fully-connected topology and two MAC protocols: Prioritized Contention Access (PCA) and Distributed Reservation Protocol (DRP). The former is a contention-based protocol with prioritized Quality of Service (QoS), whereas the latter is similar to TDMA-based protocol to guarantee a contention-free access. However, DRP is different from classic TDMA protocol because of beaconing mechanisms to guarantee synchronization between nodes. The superframe has a fixed length (about 65ms), and includes a fixed number of slots each with fixed duration. To handle synchronization, 32 slots are used for the beacon period. Hence, HR-UWB supports the required topology, communication pattern and contention-free access protocol for the backup network. However, the superframe format has to be adapted to avionics context to guarantee shorter deadlines (about 2 ms).

In terms of reliability, HR-UWB supports FEC convolutional codes with different coding rates at the physical layer, and retransmission mechanisms with Immediate Acknowledgment (Imm-ACK) and Block Acknowledgment (B-ACK) at the MAC layer. In [1], a summary of measurement results about UWB fading channel characterization and modeling was presented. It shows that UWB technology offers the advantage of low fade margins. In addition, a UWB channel is frequency-selective and the temporal correlation coefficient is very low. Hence, using diversity mechanisms such as time and frequency will decrease the Packet Error Rate (PER) and consequently increase the communication reliability level.

C. Tuning MAC protocol for Predictability Requirement

To guarantee predictable behavior under hard real time constraints, the supported DRP protocol is more adequate to an avionics context. However, the classic superframe format may imply a long synchronization phase and long transmissions delays which are unsuitable for avionic applications with short deadlines ranging from 2 to 128 ms. Hence, the slots allocation and the TDMA cycle duration must be carefully configured, since it must efficiently handle different types of traffic and guarantee different temporal constraints.

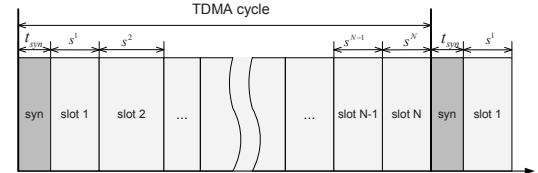


Figure 2: Modified UWB Superframe

The modified superframe, as shown in Figure 2, is constructed based on the following assumptions: (i) since all generated messages are known a priori, the slots allocation mechanism is configured off-line and will be followed in a static manner by all end-systems during the network deployment; (ii) during each superframe, the allocated time slot for each end-system is fixed and has a defined duration that depends on its generated traffic. Hence, the time slots are not equally allocated to the different end-systems, and the number of slots during a superframe depends on the number of end-systems; (iii) the classic beaconing mechanism to guarantee synchronization is disabled and replaced with an optimized version of the IEEE1588 protocol for broadcast communications and peer to peer topology, called IEEE 1588-PBS (Pairwise Broadcast Synchronization) [3]. The main objective of this protocol is reducing the synchronization phase overhead and minimizing the energy consumption, while still achieving a precision of 200 nanoseconds.

IEEE 1588-PBS is based on one time master to perform the synchronization mechanism; and one active slave to receive the synchronization message and send the request to the master. Other nodes are passive. They listen to the exchanged data between master and active slave to estimate the current time. IEEE 1588-PBS mechanism offers a high availability level since if the active node fails, then one of the passive nodes can be elected to perform synchronization.

D. Integrated Reliability Mechanisms

To integrate the multicast communication pattern required by avionic applications, the classic reliability mechanisms based on retransmissions and acknowledgement are disabled. Hence, the required reliability level is guaranteed due to time and frequency diversity mechanisms which are more adequate for avionics context because of good properties of UWB technology and mainly low fade margins.

The disabling of the acknowledgment mechanism allows the activation of the burst mode where the frame structure shown in Figure 3 implies less overhead with shorter preamble and minimum inter-frame space (MIFS), compared to the normal mode.

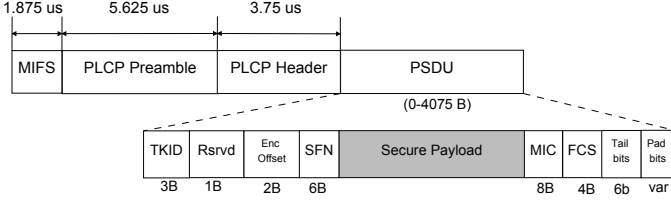


Figure 3: UWB Frame Structure

Furthermore, in order to avoid interference and jamming risks, adequate electromagnetic shielding solutions have to be implemented. The geographical concentration of end-systems in a short range of 6 meters facilitates the isolation of the backup network by using various methods described in [22], e.g., painting and lightweight anechoic chamber.

Due to these different reliability mechanisms, bursty packet errors are avoided and the Packet Error Rate can be decreased to achieve the required Packet Error Rate level.

V. TIMING ANALYSIS FOR ERROR-FREE ENVIRONMENT

To conduct timing analysis of the proposed UWB-based network described in Section IV, initially we ignore transmission errors and reliability mechanisms to focus on the impact of non-preemptive message transmission and implemented service policies in end-systems, e.g. FIFO and FP. First, we present the Network Calculus concepts [17] and the considered schedulability test to conduct timing analysis of such a network. Then, we detail the models of traffic, end-systems and TDMA arbitration protocol to compute end-to-end delay bounds. Finally, we give some numerical results.

A. Network Calculus Concepts

The worst-case performance analysis of our proposed network in this paper is based on *Network Calculus* theory [17], adapted to controlled traffic sources, and providing maximal bounds on delays and backlogs.

Delay bounds depend on the traffic arrival described by the so called *arrival curve* α , and on the availability of the traversed node described by the so called minimum *simple or strict service curve* β . The definitions of these considered curves are explained as following.

Definition 1: (Arrival Curve) a function α is an arrival curve for a data flow with an input cumulative function R , such that $R(t)$ is the number of bits received until time t , iff:

$$\forall t, s \geq 0, s \leq t, R(t) - R(s) \leq \alpha(t - s)$$

Definition 2: (Simple service curve) The function β is the minimum simple service curve for a data flow with an input cumulative function R and output cumulative function R^* iff:

$$R^* \geq R \otimes \beta$$

where $(f \otimes g)(t) = \inf_{0 \leq s \leq t} \{f(t - s) + g(s)\}$

Definition 3: (Strict service curve) The function β is the minimum *strict* service curve for a data flow with an input

cumulative function R and output cumulative function R^* , if for any backlogged period $]s, t]^1$, $R^*(t) - R^*(s) \geq \beta(t - s)$.

The delay bound D is the maximum horizontal distance between α and β called $h(\alpha, \beta)$; whereas the backlog bound B is the maximum vertical distance called $v(\alpha, \beta)$. Finally, in order to compute delay bounds of individual traffic flows, we need the residual service curve according to the following theorem.

Theorem 1: (Residual service curve - Blind Multiplex) [6] let f_1 and f_2 be two flows crossing a server that offers a *strict* service curve β such that f_1 is α_1 -constrained, then the residual service curve offered to f_2 is:

$$\beta_2 = (\beta - \alpha_1)_\uparrow$$

where $f_\uparrow(t) = \max\{0, \sup_{0 \leq s \leq t} f(s)\}$

B. Sufficient Schedulability Test

Using Network Calculus, an upper bound on end-to-end delay of each transmitted message m , D_m^{eed} , is computed and then compared to its respective temporal deadline, DI_m . Hence, 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 as follows:

$$\forall m \in \text{messages},$$

$$D_m^{eed} \leq DI_m \implies \text{The messages set is schedulable}$$

The end-to-end delay of each transmitted message m consists mainly of three parts:

- the arbitration delay that corresponds to the maximum waiting time since the arrival instant of the message until it starts being transmitted on the network medium. This delay is due to interferences caused by other messages from the same end-system, and the waiting time due to TDMA arbitration protocol;
- the transmission time that corresponds to the communication time of the message on the medium; it depends on the message size and the medium transmission capacity;
- the propagation delay needed to propagate the signal from the source to its final destinations. In our case, this delay is considered insignificant since the network is fully-connected, e.g., one-hop communication, and distance between end-systems is short (about 6 meters).

To compute upper bounds on end-to-end delays of transmitted messages using Network Calculus, we need to model each message flow to compute its maximum arrival curve, and the behavior of end-systems and the TDMA arbitration protocol to compute the minimum service curve. Then, the maximum horizontal distance between these two curves corresponds to an upper bound on end-to-end delay of the associated message flow. These models are detailed in the next sections.

¹ $]s, t]$ is called backlogged period if $R(\tau) - R^*(\tau) > 0, \forall \tau \in]s, t]$

C. Traffic Model

The proposed UWB-based network, as an alternative backup network for the AFDX backbone network, has to integrate the specifics of AFDX network and consequently Virtual Links. As described in Section III, Virtual Links are characterized by minimal inter-arrival time (BAG), maximal frame size (MFS), a source and a set of destinations.

Hence, each data generated by an avionic application is encapsulated in an UWB frame, shown in Figure 3, and contains the source and destination addresses. Afterwards, we define the characteristics of each periodic (or sporadic) message flow i as (T_i, D_i, L_i, e_i) for period (and minimum inter-arrival time for sporadic flow), deadline (equal to T_i unless otherwise explicitly specified), frame size integrating the UWB frame structure overhead and delivery time (i.e., $e_i = L_i/B$ where B is the medium transmission capacity), respectively.

The arrival curve of message flow i , based on a packetized model is as follows.

$$\alpha_i(t) = L_i \lceil \frac{t}{T_i} \rceil \quad (1)$$

D. End-systems and TDMA protocol Models

Avionic end-systems transmit their generated message flows according to a TDMA arbitration protocol using two possible service policies, i.e., FIFO or FP. The end-systems follow a static TDMA schedule to transmit their message flows. A TDMA schedule is defined as a sequence of time slots repeated each cycle with a fixed duration, called c . During each cycle, end-system k can only transmit during its predetermined time interval, called TDMA time slot s^k . In an avionics context, the time slots associated to end-systems have not necessarily equal durations and the message transmission is non-preemptive. Consequently, if the remaining time during a slot is insufficient for a complete message transmission, then the message has to wait for the next slot. Hence, the cycle duration is as follows:

$$c = \sum_{k=1}^M s^k + t_{sync} \quad (2)$$

where M is the number of end-systems and t_{sync} the duration of the synchronization phase described in Section IV-C.

The classic timing analysis of TDMA arbitration protocol is based on the following key idea: a computing unit with a time slot s may not have access to the shared network during at maximum $c - s$. After this maximum duration, the computing unit has exclusive access to the medium during its time slot s to transmit with the medium transmission capacity, B .

Hence, the classic service curve when FIFO policy is implemented in the computing unit has the following analytical expression:

$$\beta_{c,s}(t) = B \max(\lfloor \frac{t}{c} \rfloor s, t - \lceil \frac{t}{c} \rceil (c - s)), \forall t \geq 0 \quad (3)$$

When considering a FP policy, each message flow will be transmitted before all lower priority flows and after all higher priority flows. Consider N message flows f_1, \dots, f_N where f_i has higher priority than f_j if $i < j$. The residual service curve

offered to message flow f_i using Theorem 1 has the following analytical expression:

$$\beta_i(t) = (\beta_{c,s}(t) - \sum_{1 \leq j \leq i-1} \alpha_j(t))_{\uparrow} \quad (4)$$

These models are extended in next sections to integrate the impact of non-preemptive message transmission with FIFO and FP policies.

1) *FIFO Policy*: The maximum waiting time to access to the medium and the lower bound of offered TDMA time slot have to be adjusted in case of non-preemptive message transmission, and then used to extend the service curve guarantee.

Consider an end-system with a TDMA time slot s during each TDMA cycle c . This end-system generates N messages flows with associated maximum and minimum delivery times e_{max} and e_{min} , respectively. Based on the worst-case scenario illustrated in Figure 4, the corresponding parameters are as following.

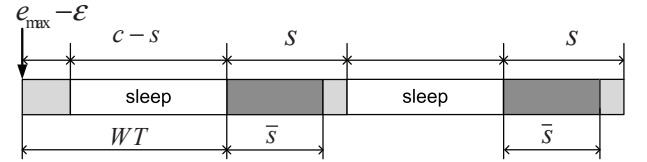


Figure 4: Worst case scenario with FIFO policy

- The *maximum waiting time* WT occurs when the first message of a backlogged period has a maximum delivery time e_{max} and arrives just at the instant when the remaining time during the current slot is slightly less than the required delivery time, i.e., $e_{max} - \epsilon$ ($0 < \epsilon \ll 1$). In this case, the message has to be delayed until the next slot and the *maximum waiting time* is then $WT = e_{max} + c - s$ instead of $c - s$ in classic model.
- The *lower bound of offered TDMA time slot* \bar{s} depends on message flows characteristics. If the generated messages are homogeneous, i.e., all the messages have the same delivery time e , then the end-system can send at maximum $\lfloor \frac{s}{e} \rfloor$ messages during its respective time slot s . Else, the idle time is always less than e_{max} and the *lower bound of offered TDMA time slot* is always greater than e_{min} . Hence, \bar{s} is as follows:

$$\bar{s} = \begin{cases} \lfloor \frac{s}{e} \rfloor e & \text{if } e_{max} = e_{min} = e \\ \max\{s - e_{max}, e_{min}\} & \text{Otherwise} \end{cases} \quad (5)$$

The *maximum waiting time* WT may occur only at the beginning of the backlogged period. Then, during the next cycles the node may wait at most $c - \bar{s}$ to access to the network and transmit messages. Hence, the strict service curve guaranteed in this case is $\beta_{c,\bar{s}}(t - (WT - (c - \bar{s})))$ which represents the curve shifted to the right with the positive duration $WT - (c - \bar{s})$ of $\beta_{c,\bar{s}}(t)$ defined in Eq. 3 and extended in our model with $\beta_{c,\bar{s}}(t) = 0, \forall t < 0$.

This is explicitly defined in the following theorem. The corresponding proof is not detailed because of page limitation.

Theorem 2: Consider an end-system having a lower bound of offered time slot \bar{s} , generating N message flows and implementing a FIFO policy, the offered strict service curve when considering non-preemptive message transmission is:

$$\beta_{c,\bar{s}}(t - WT + (c - \bar{s})), \forall t \geq 0$$

where

$$WT = e_{\max} + c - s$$

and

$$\bar{s} = \begin{cases} \lfloor \frac{s}{e} \rfloor e & \text{if } e_{\max} = e_{\min} = e \\ \max\{s - e_{\max}, e_{\min}\} & \text{Otherwise} \end{cases}$$

This extended service curve is illustrated in Figure 5. As we can notice, extended service is lower than classic service, described in Eq. 3 which leads to greater delay bounds, mainly due to the non-preemptive message transmission.

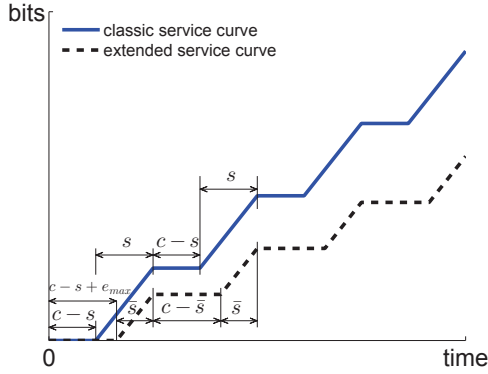


Figure 5: Classic vs extended service curves with FIFO policy

2) *FP Policy:* As for the FIFO policy case, the *maximum waiting time* to access to the medium and the *lower bound of offered TDMA time slot* for transmission have to be adjusted in case of non-preemptive message transmission. First, we compute the offered service curve for the aggregate message flow $f_{\leq i}$ including message flows f_1, \dots, f_i with priorities higher or equal to i . Then, we deduce the individual service curve for each message flow f_i applying Theorem 1. Based on the worst-case scenario illustrated in Figure 6, the corresponding parameters are as follows:

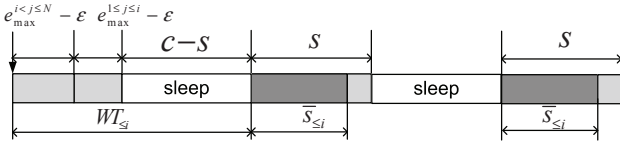


Figure 6: Worst case scenario with FP policy

- The *maximum waiting time* $WT_{\leq i}$ occurs when the first message of the aggregate message flow $f_{\leq i}$ arriving at the beginning of a backlogged period and having a maximum delivery time $e_{\max}^{1 \leq j \leq i}$ is blocked during the transmission time of a message with lower priority and maximum delivery time. This blocking time corresponds to $e_{\max}^{i < j \leq N} - \epsilon$ ($0 < \epsilon \ll 1$). Furthermore, after that blocking time, the remaining time during

the current slot is slightly less than the required delivery time of the considered message and is equal to $e_{\max}^{1 \leq j \leq i} - \epsilon$ ($0 < \epsilon \ll 1$). In this case, this message has to wait until the next slot to be transmitted. The *maximum waiting time* is then bounded by $e_{\max}^{i < j \leq N} + e_{\max}^{1 \leq j \leq i} + c - s$. However, if TDMA time slot s is smaller than $e_{\max}^{i < j \leq N} + e_{\max}^{1 \leq j \leq i}$, then the *maximum waiting time* is reduced to one cycle c . Hence, for aggregate flow $f_{\leq i}$, the *maximum waiting time* is as follows:

$$WT_{\leq i} = \min(e_{\max}^{i < j \leq N} + e_{\max}^{1 \leq j \leq i} + c - s, c) \quad (6)$$

- The *lower bound of offered TDMA time slot* associated to aggregate message flow $f_{\leq i}$, called $\bar{s}_{\leq i}$, can be deduced from Eq. 5 by considering only aggregate flow $f_{\leq i}$ instead of all the generated flows. Hence, $\bar{s}_{\leq i}$ associated to aggregate flow $f_{\leq i}$ is as follows:

$$\bar{s}_{\leq i} = \begin{cases} \lfloor \frac{s}{e} \rfloor e & \text{if } e_{\max}^{1 \leq j \leq i} = e_{\min}^{1 \leq j \leq i} = e \\ \max(e_{\min}^{1 \leq j \leq i}, s - e_{\max}^{1 \leq j \leq i}) & \text{Otherwise} \end{cases} \quad (7)$$

The extended service curve with FP policy is defined in the following theorem and the mathematical proof is not detailed because of page limitation.

Theorem 3: Consider aggregate message flow $f_{\leq i}$ having a lower bound of offered TDMA time slot $\bar{s}_{\leq i}$, transmitted by an end-system implementing FP policy, the strict service curve guaranteed to $f_{\leq i}$ when considering non-preemption feature is:

$$\beta_{c,\bar{s}_{\leq i}}(t - WT_{\leq i} + (c - \bar{s}_{\leq i})), \forall t \geq 0 \quad (8)$$

where

$$WT_{\leq i} = \min(e_{\max}^{i < j \leq N} + e_{\max}^{1 \leq j \leq i} + c - s, c),$$

and

$$\bar{s}_{\leq i} = \begin{cases} \lfloor \frac{s}{e} \rfloor e & \text{if } e_{\max}^{1 \leq j \leq i} = e_{\min}^{1 \leq j \leq i} = e \\ \max(e_{\min}^{1 \leq j \leq i}, s - e_{\max}^{1 \leq j \leq i}) & \text{Otherwise} \end{cases}$$

Hence, using Theorems 1 and 3, the residual service curve offered to message flow f_i is as follows:

$$\bar{\beta}_i(t) = (\beta_{c,\bar{s}_{\leq i}}(t - WT_{\leq i} + (c - \bar{s}_{\leq i})) - \sum_{j=1}^{i-1} \alpha_j(t))_{\uparrow} \quad (9)$$

This extended service curve is illustrated in Figure 7. Extended service is lower than the classic service which leads to greater delay bounds due to the non-preemptive message transmission.

E. Upper Bounds on End-to-End Delays

Upper bounds on end-to-end delays can easily be computed as the maximum horizontal distance between the maximum arrival curve of the traffic, described in Section V-C, and the minimum service curves guaranteed by each end-system when implementing FIFO or FP policies, described in Section V-D.

Consider an end-system generating N message flows and each message flow f_i characterized with the maximum arrival

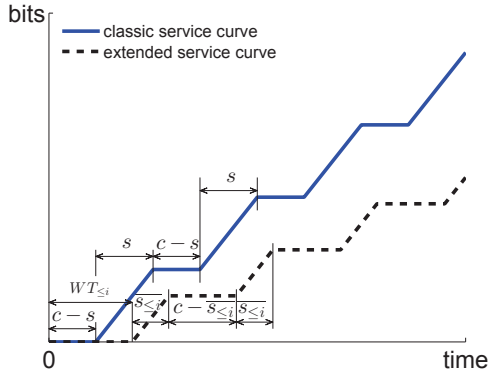


Figure 7: Classic vs extended service curves with FP policy

curve $\alpha_i(t)$, the upper bound end-to-end delay D_i^{eed} associated to flow f_i depends on the implemented service policy in the end-system:

- with FIFO policy, D_i^{eed} is the upper bound on end-to-end delay guaranteed to the aggregate message flow generated by the same end-system when considering the minimum service curve $\beta(t)$. Hence,

$$\forall i D_i^{eed} = h(\alpha, \bar{\beta}) \text{ where } \alpha(t) = \sum_{i=1}^N \alpha_i(t) \quad (10)$$

- with FP policy, D_i^{eed} is the maximum horizontal distance between the maximum arrival curve $\alpha_i(t)$ and the guaranteed residual service curve $\bar{\beta}_i$ defined in Eq. 9. Hence,

$$\forall i D_i^{eed} = h(\alpha_i, \bar{\beta}_i) \quad (11)$$

F. Numerical Results

We consider an example of a wireless UWB network with transmission capacity $B = 200\text{Mbps}$ and 10 end-systems with a TDMA cycle duration of 1 ms. Each end-system has an allocated TDMA time slot duration of 100 μs and generates message flows of type f_1 and f_2 , described in Table II. The end-to-end delay bounds are calculated when considering FIFO and FP policies in end-systems, and varying the network utilization of the network by increasing the number of generated messages flows in each end-system. In this traffic configuration, f_1 and f_2 belong to traffic classes TC_1 and TC_2 , respectively, where TC_1 and TC_2 represent the high and low traffic priorities with FP policy, respectively.

Table II: Message flows characteristics

| | T(μs) | Dl(μs) | e(μs) |
|-------|--------------------|---------------------|--------------------|
| f_1 | 8000 | 8000 | 40 |
| f_2 | 16000 | 16000 | 30 |

As illustrated in Figure 8, the end-to end delay bounds increase when the network utilization increases. With FIFO and FP policies, the traffic configuration becomes unschedulable when the network utilization is greater than 0.33 and 0.497, respectively. Hence, we have better traffic schedulability under FP policy than FIFO. Furthermore, the maximum network utilization is limited due to the non-preemptive message

transmission. Indeed, according to Eq. 5, the lower bound of offered TDMA time slot is equal to 60 μs which means that the maximum network utilization could not be greater than $60/100 = 0.6$.

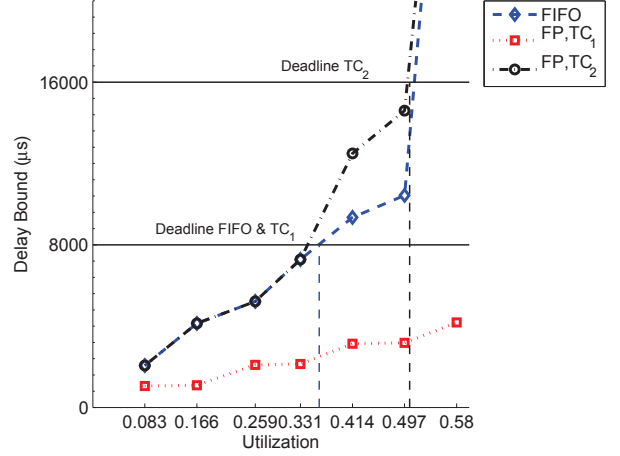


Figure 8: Delay vs Network Utilization with FIFO and FP policies

VI. TIMING ANALYSIS FOR ERROR-PRONE ENVIRONMENT

In this section, we first extend the timing analysis detailed in Section V to integrate the impact of transmission errors and reliability mechanisms described in Section IV-D. Then, we show some analytical results.

A. Reliability Mechanisms Modeling

As described in Section IV-D, to guarantee the required level of Packet Error Rate of avionic applications, PER_L , we consider time and frequency diversity mechanisms to enhance the offered Packet Error Rate of UWB technology, PER_{UWB} . To conduct timing analysis of such a network, we need to integrate the impact of reliability mechanisms which certainly will increase the offered reliability level but at the same time increase the end-to end delay bounds.

We consider η_f the number of frequency channels due to frequency diversity mechanism, and η_t the number of packet transmissions on each frequency channel due to a time diversity mechanism. Consequently, if the two diversity mechanisms are combined, then each message is transmitted $\eta_f \times \eta_t$ times. Hence, the offered Packet Error Rate of such a network is equal to $PER_{UWB}^{\eta_f \times \eta_t}$ and the avionic reliability requirement is guaranteed if the following condition is verified:

$$PER_{UWB}^{\eta_f \times \eta_t} \leq PER_L \quad (12)$$

Hence, at least one of the following conditions has to be verified:

- the minimum number of packet transmissions η_t is at least equal to $\lceil \log_{PER_{UWB}}(PER_L) \rceil$. This minimum is obtained when only time diversity mechanism is used;

- the minimum number of frequency channels η_f is at least equal to $\lceil \log_{PER_{UWB}}(PER_L) \rceil$ when only frequency diversity mechanism is used;
- the minimum number of packet transmissions $\eta_f * \eta_t$ is at least equal to $\lceil \log_{PER_{UWB}}(PER_L) \rceil$ when both time and frequency diversity mechanisms are used.

Increasing the number of transmissions of the same message leads to increasing the quantity of traffic generated by each end-system and consequently the associated maximum arrival curve. The decorrelated η_f frequency channels can be modeled as η_f redundant wireless links, and on each considered wireless link there are η_t copies of the same generated message by any end-system. Hence, the upper bounds on end-to-end delays computed in Eqs. 10 and 11 are updated as following.

- with FIFO policy,

$$\forall i D_i^{eed} = h(\eta_t * \alpha, \bar{\beta}) \text{ where } \alpha(t) = \sum_{i=1}^N \alpha_i(t) \quad (13)$$

- with FP policy,

$$\forall i D_i^{eed} = h(\eta_t * \alpha_i, \bar{\beta}_i) \quad (14)$$

B. Numerical Results

We consider the same example in Section V-F where the PER_L is equal to 10^{-10} , the PER_{UWB} is varying in $[10^{-5}, 1]$, the number of frequency channels $\eta_f \in \{1, 2, 3, 4\}$ and the network utilization is equal to 0.083.

First, the number of packet transmissions η_t is calculated when varying the number of frequency channels η_f and the PER_{UWB} , and the obtained results are illustrated in Figure 9. As expected, for a given PER_{UWB} , η_t decreases when η_f increases. Furthermore, when η_f increases, the tolerated PER_{UWB} which respects the traffic schedulability increases. However, for high value of PER_{UWB} , η_t goes to infinite.

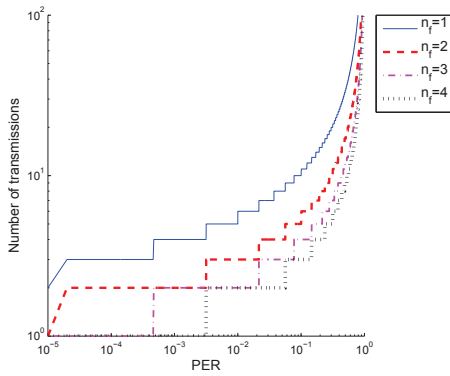


Figure 9: Number of transmissions vs PER and frequency number

Then, the end-to-end delay bounds are calculated with FIFO and FP policies when varying the number of frequency channels η_f and the PER_{UWB} . The obtained results are illustrated in Figures 10, 11 and 12, respectively. With FIFO and FP policies, for a given PER_{UWB} , end-to-end delay bounds decrease when η_f increases. Furthermore, the tolerated PER_{UWB}

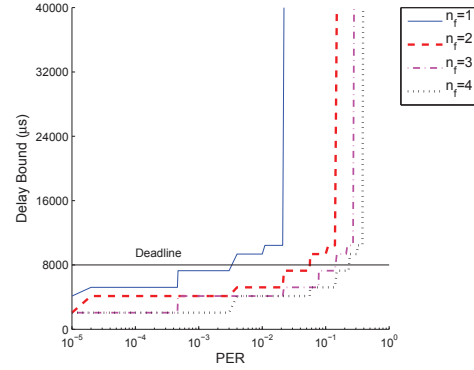


Figure 10: End-to-end delay bounds under FIFO policy

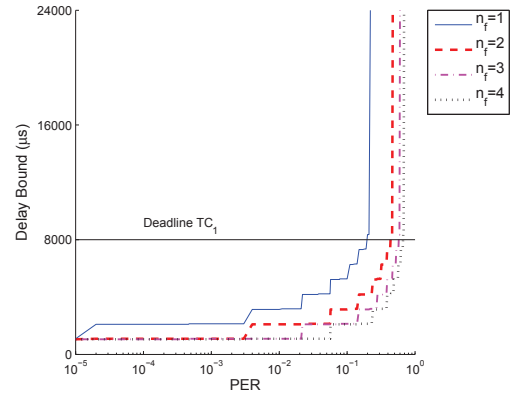


Figure 11: End-to-end delay bounds of high priority traffic under FP policy

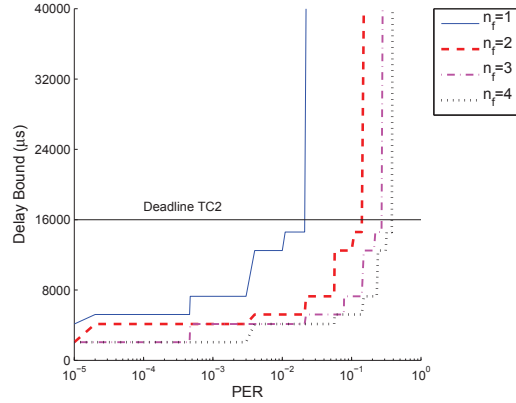


Figure 12: End-to-end delay bounds of low priority traffic under FP policy

value which respects the traffic schedulability increases when η_f increases. For instance, with FIFO policy, with one frequency channel, the tolerated PER_{UWB} is in $[10^{-3}, 10^{-2}]$ interval, while with FP policy is in $[10^{-2}, 10^{-1}]$ interval when considering the schedulability of the lowest priority traffic. Hence, it is better to use FP policy than FIFO policy to enhance the system's predictability and reliability when using the same

number of frequencies.

Afterwards, the end-to-end delay bounds are calculated when considering FIFO and FP policies in end-systems, fixing the $PER_{UWB} = 10^{-3}$ and varying the number of frequency channels and network utilization of the network. The results are illustrated in Figures 13 and 14, respectively. With FIFO and FP policies, increasing the number of frequency channels enhances the maximum network utilization which respects the traffic schedulability. Moreover, when $\eta_f = 4$, we have $\eta_f = 1$ and consequently similar performance to the error-free environment case shown in Figure 8. Hence, in addition to enhancing system's predictability and reliability, FP policy extends system's scalability compared to FIFO policy.

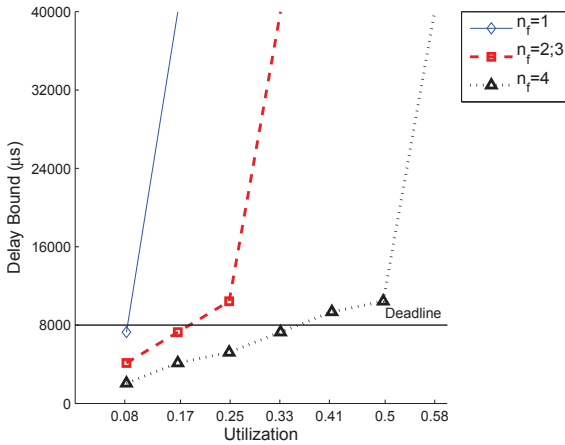


Figure 13: Delay bounds vs Network utilization and number of frequencies with FIFO

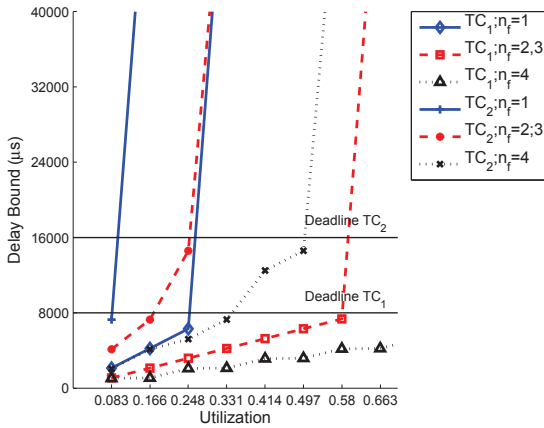


Figure 14: Delays bounds vs Network utilization and number of frequencies with FP

VII. AVIONIC CASE STUDY

We now present a representative avionic case study replacing an AFDX backup network with our proposal. Results are obtained considering predictability and reliability requirements.

A. Description

The considered network consists of $N = 52$ end-systems and there are three traffic classes generated in end-systems as described in Table III. The offered Packet Error Rate by UWB technology is fixed, $PER_{UWB} = 10^{-3}$, and the Packet Error Rate level is equal to $PER_L = 10^{-10}$. The main objective here is to determine the minimum TDMA cycle duration and the minimum number of frequency channels required to guarantee the schedulability condition of the generated traffic and the reliability level when using FIFO or FP policies in end-systems. Hence, we consider TDMA cycle duration varying as follows: $c \in \{2.5, 3, 3.5, 4\}$ ms to respect the shortest deadline (4 ms); and number of frequency channels as follows $\eta_f \in \{1, 2, 3, 4\}$. The end-to-end delay bounds of traffic classes are computed for the different system configurations to find the best configuration that guarantees the required timely and reliable communications. Obtained results are illustrated in next section.

Table III: Parameters of Traffic Classes

| | T (μ s) | DI (μ s) | Payload (B) | Transmission time (μ s) |
|--------|--------------|---------------|-------------|------------------------------|
| TC_1 | 4000 | 4000 | 482 | 33 |
| TC_2 | 16000 | 16000 | 288 | 25 |
| TC_3 | 32000 | 32000 | 16 | 14 |

B. Performance Analysis

The obtained delay bounds with frequency channel number $\eta_f \leq 3$ are infinite because the traffic rate at the input of the network increases due to time diversity and becomes higher than the offered service rate. Hence, only delay bounds obtained for network configurations based on frequency channel number $\eta_f = 4$ are presented herein. Figures 15 and 16 illustrate the end-to-end delay bounds obtained with FIFO and FP policies respectively when varying the TDMA cycle duration. As we can notice, with FIFO policy, the only network configuration that respects predictability and reliability requirements corresponds to a cycle duration equal to 4ms. However, with FP policy, all the network configurations obtained when varying the TDMA cycle durations respect predictability and reliability requirements.

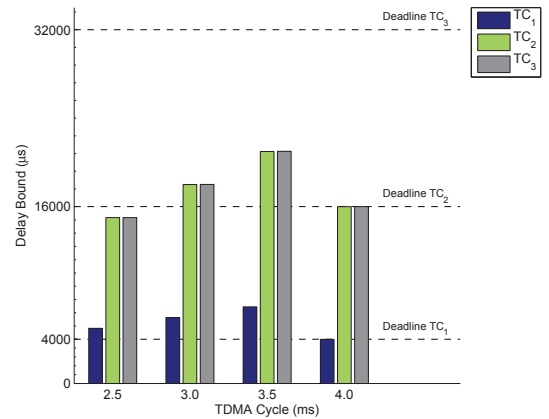


Figure 15: Delay bounds of traffic classes with FIFO policy

Hence, these results confirm our first conclusions in the previous section where FP policy is considered as a better

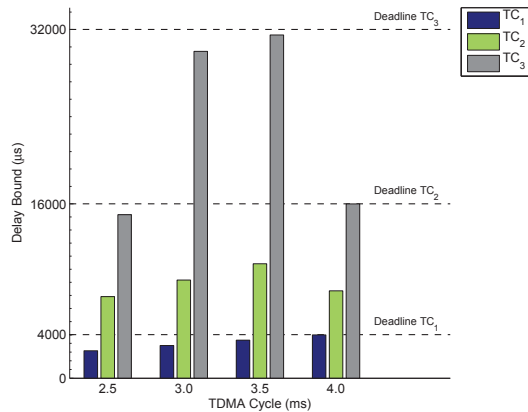


Figure 16: Delay bounds of traffic classes with FP policy

choice than FIFO policy to enhance system's predictability and reliability. Moreover, each system parameter, i.e. cycle duration, number of frequency channels, service policy, should be integrated during the system design to have the best configuration that fulfills the system requirements.

VIII. CONCLUSION AND FUTURE WORK

An UWB-based network has been designed as an alternative backup network for avionic applications to reduce weight and consequently decrease costs and maintenance for new generation aircraft. Communication predictability is enhanced due to a TDMA arbitration protocol, while the reliability requirement is guaranteed using time and frequency diversity mechanisms. A timing analysis, based on Network Calculus, was conducted in an error-free environment and then extended to an error-prone one. Results for a representative avionic case study show the efficiency of our proposal to provide reliable and timely communications that fulfill avionic requirements.

The optimization of such a network in terms of analytical modeling, time slots allocations and reliability mechanisms overhead is an on-going work.

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