Real-Time Ethernet Solutions supporting Ring topology from an Avionics Perspective: a Short Survey

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Real-Time Ethernet Solutions supporting Ring topology from an Avionics Perspective: a Short Survey

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Abstract—To cope with the increasing quantity of wires, thus the weight and integration costs in avionics, an implementation of a new avionics communication architecture with less cables will clearly improve the efficiency of aircraft, while reducing the deployment costs. Furthermore, such a communication architecture shall be efficient to meet the design requirements, in terms of predictability and availability, for the least amount of money. Therefore, the AFDX compatibility, a minimized (re)-configuration effort and costs are among the most important issues to guarantee. On the other hand, the recent research effort towards defining new communication solutions, to guarantee a high availability level with limited cabling complexity for real-time applications, has renewed the interest in ring topology. Therefore, the main objective of this paper is benchmarking the most relevant solutions, based on Ethernet technology and supporting ring topology, vs avionics requirements, and we particularly focus on the main Performance Indicators, specified in IEC 61784-2, of each one of them.

Keywords-Avionics, Real-Time Ethernet, Ring topology, QoS, Performance, Availability.

I. INTRODUCTION

The inherent complexity and bandwidth requirement of avionics communication architecture are increasing due to the growing number of interconnected end-systems and the expansion of exchanged data. The Avionics Full Duplex Switched Ethernet (AFDX) [1] has been introduced to provide high speed communication (100Mbps) for new generation aircraft. However, this switched network is deployed in a fully redundant way, which definitely guarantees a high availability level but leads at the same time to significant quantities of wires; thus weight and integration costs. For instance, the A380 contains 500 km of cables [2]. To cope with these emerging issues, an implementation of an avionics communication architecture with less cables will clearly improve the efficiency and reliability of aircraft, while reducing integration, fuel consumption and maintenance costs.

On the other hand, the objective of defining a new communication solution to guarantee high availability level with limited cabling costs and complexity for real-time applications has revealed the interest of the ring topology, which provides an implicit redundant path by introducing only one additional connection between the two end nodes, compared to line or star topologies [3]. Ring-based networks have been recently

used for industrial applications with the implementation of many Real Time Ethernet (RTE) profiles cited in IEC 61784-2 [4], e.g., EtherCAT [5], Profinet-IRT [6] and Ethernet/IP [7], and in other application fields like automotive, e.g. RACE [8], TTE[9] [10], and avionics, e.g., AeroRing [11].

Therefore, the main objective of this paper is benchmarking the most relevant Real-Time Ethernet (RTE) solutions supporting ring topology vs avionics requirements, and we particularly focus on their main Performance Indicators, specified in the document IEC 61784-2 [4], to assess their effectiveness, in terms of predictability and availability as well as scalability and resource efficiency.

The remainder of the paper is organized as follows. In the next section, the current avionics communication architecture and its main requirements are described, then the main benefits and challenges to introduce a ring-based RTE solution in avionics are presented. In Section III, the most relevant RTE solutions supporting a ring topology are described and their pros and cons versus avionics requirements are discussed. Section IV details the performance evaluation of such solutions for a representative avionics network setup.

II. PROBLEM STATEMENT

In this section, we first present the current Avionics Network, based on the AFDX [1], and its main requirements. Then, we describe the main benefits and risks of using RTE solutions supporting a ring topology in avionics context.

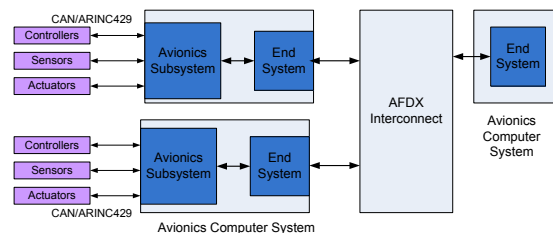### A. Current Avionics Communication Architecture

Fig. 1. Current Avionics Communication Architecture

As shown in Figure 1, the current avionics network consists of a full redundant backbone network, based on the AFDX, to interconnect the avionics End Systems, while keeping some legacy systems connected to low rate data buses, e.g., CAN [12] or ARINC429 [13]. Although this architecture simplifies

the design process and reduces the time to market, it leads at the same time to inherent *heterogeneity* due to the necessary applicative gateways.

The AFDX [1] network is based on Full Duplex Switched Ethernet protocol at 100 Mbps, successfully integrated into new generation civil aircraft like the Airbus A380. This technology succeeds to support the important amount of exchanged data due to policing mechanisms added in switches and the Virtual Link (VL) concept. The latter gives 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 1 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. Unlike some old data buses, the AFDX implements an event-triggered communication paradigm to enhance the system's flexibility and modularity, which decreases the (re)configuration effort. However, to guarantee a high availability level, this network is used in a fully redundant way, which induces high installation and deployment costs.

Hence, an ultimate avionics communication architecture has to keep the low (re)configuration effort and high availability level, guaranteed by the current AFDX-based architecture, while reducing the complexity of wiring. Furthermore, this new architecture must fulfill a set of key requirements. These requirements concern both technical and costs aspects:

- **Predictability**: The network must behave in a predictable way and appropriate proofs to guarantee its determinism have to be provided by the network designer. For example, the communication latencies of each traffic type have to be bounded on the AFDX network;
- **Reliability and Availability**: The network must be fault-tolerant and fulfill required safety levels to prevent failed nodes from affecting the normal operations. For instance, redundancy mechanisms are implemented for the AFDX network to recover packet losses and faulty nodes during operation time;
- **Modularity**: This requirement is related to the flexibility and exchangeability of software and hardware components. An important step towards enhancing the avionics system modularity has been fulfilled with the adoption of the IMA approach [14], i.e., common elementary components can be configured to fit different avionic applications. This feature aims to minimize the (re) configuration and readjustment effort to facilitate system's maintenance and its progress over the years. In the specific case of the AFDX, the implementation of an event-triggered paradigm is favoring such a requirement;
- **Costs**: The flexibility and configurability of components reduce development cycle duration, and ease incremental design process and maintenance operations. Furthermore, the use of commercial off-the shelf (COTS) technolo-

gies and components infers development and deployment costs reduction.

These requirements will be considered in the rest of the paper to benchmark the most relevant RTE solutions from an avionics perspective.

B. Ring-based RTE solutions for Avionics

Nowadays, RTE solutions supporting ring topology have progressed and introducing them for avionics has become feasible, but also advisable for the following reasons:

- the high communication speed of Ethernet technology, i.e., 1Gbps, will favor the transmission of mixed criticality-data on the same physical links; thus decrease the heterogeneity and installation costs of the global architecture;
- the ring topology will decrease the cabling complexity, in comparison to the switched one, thus an inherent weight reduction and an increase of system's efficiency, e.g., less fuel consumption;
- the high availability level offered by the ring topology due to the various redundancy solutions, which have been specified in the documents IEC62439-1/7.

However, the main challenge for RTE solutions supporting a ring topology is reconciling the different avionics requirements, and especially predictability and availability, while reducing the reconfiguration effort and deployment costs.

III. RING-BASED RTE SOLUTIONS VS AVIONICS REQUIREMENTS

A. Taxonomy and Classification

During the last two decades, a wide range of RTE solutions have been proposed by industrials and academia. The most relevant ones have been cited in [4], [15], [16].

In [15], an interesting classification of the main RTE solutions has been detailed based on the implementation level of each proposed solution. Hence, a first class with an implementation at the network layer has been identified, e.g., P-NET, V-NET and Modbus-RTPS. These solutions are usually easier to implement and configure, but they lead at the same time to important latencies (about 10ms), which makes them more effective for soft real-time applications. Then, a second category has been defined, which provides a realization on top of the MAC layer while keeping the IEEE802.3 compatibility, e.g., TCNET, Ethernet/IP with Device Level Ring (DLR) and PowerLink, or modifying the standard implementation, e.g., EtherCAT and Profinet IRT.

In this paper, we introduce a different classification to identify the most relevant RTE solutions from an avionics perspective. This classification is based on the following characteristics:

(i) *Communication paradigm*: is of utmost importance to quantify the reconfiguration effort needed by the alternative RTE solution, in comparison to the AFDX-based one. This indicator conditions the modularity level offered by

the selected solution, a key requirement in avionics. We consider the two main paradigms, i.e., event-triggered and time-triggered. The event-triggered paradigm is known as highly flexible and facilitates the system's reconfiguration, but it infers at the same time an indeterminism level and needs further proofs to verify the predictability requirement. On the other hand, the time-triggered paradigm is highly predictable, but presents some limitations in terms of system reconfigurability;

(ii) *Redundancy solution*: impacts especially the availability level of the communication network, but also the deployment costs to support the introduced redundancy level. We mainly identify two classes of redundancy solutions, static and dynamic. The former is generally based on a fully duplicated network, where both networks are used in parallel to increase the fault detection coverage. This solution offers a zero switchover time when a failure occurs, through guaranteeing two redundant paths for each transmitted data. This fact infers a high availability level, but also high deployment costs. The most relevant static redundancy solutions for a ring topology are the Parallel Redundancy Protocol (PRP) [17] and High-availability Seamless Redundancy protocol (HSR) [17]. With PRP, most of the devices are attached to both parallel networks, and each data is duplicated at the transmission and filtered at the reception; whereas the HSR protocol achieves the same purpose through a daisy-chain ring topology and sending duplicated data on both directions, then the destination consumes only the first valid one. On the other hand, the dynamic redundancy solutions have been introduced to decrease the installation costs, through using a backup path in case of failures, but they need to offer a bounded switchover time to guarantee availability. The most relevant protocols in this category of solutions are the Distributed Redundancy Protocol (DRP) [18] and Ring-based Redundancy Protocol (RRP) [19]. The DRP implements local fault detection mechanisms, where each equipment can check the status of its neighbors by sending a link test frame *LinkCheck* to detect failures. Then, in addition to these local mechanisms, DRP implements a centralized fault detection mechanism to check the ring status in a cyclic manner, i.e., during each cycle, only one equipment can check the ring status via a ring test frame *RingCheck*, gather and broadcast the information to the rest of equipments. On the other hand, the RRP implements distributed mechanisms to build the routing tables within equipments. Moreover, RRP consists in transforming the ring topology into line topology to avoid infinite packet looping, through selecting two adjacent devices, called Ring Network Managers (RNMs), which disable one of their ports.

The different combinations of these characteristics lead to four classes of RTE solutions supporting ring topology, as illustrated in Fig. 2:

- Event-triggered with static redundancy: this class represents the current avionics network based on the AFDX standard, which implements an event-triggered paradigm and a fully duplicated network. This solution reduces the
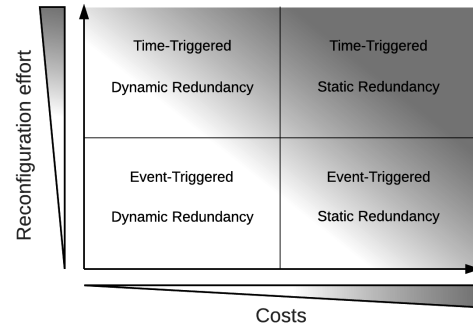

Fig. 2. Classification of RTE solutions based on Communication paradigm and Redundancy mechanisms

reconfiguration effort, while increasing the deployment costs. Hence, it is considered as a reference for the benchmarking of the most relevant RTE solutions. It is worth noting that the current avionics network has been proved as predictable [20] and guarantees a high availability level thanks to its static redundancy solution, similar to the PRP [17];

- Time-triggered with static redundancy: a representative solution in this class is the Time Triggered Ethernet (TTE) [9], which implements a time-triggered paradigm and a static redundancy solution. This solution offers a high predictability and availability levels, but it increases at the same time the deployment costs and the reconfiguration effort. Therefore, this solution will not be detailed in this paper;

- Time-triggered with dynamic redundancy: two interesting solutions can be identified in this class, EtherCAT and Profinet/IRT. These RTE solutions implement actually a master/slave mechanism based on a time-triggered paradigm, and dynamic redundancy solutions, such as the Media Redundancy Protocol (MRP) [21] for Profinet/IRT. This class of solutions will definitely decrease the deployment costs thanks to the standby mode on a ring topology, but increase at the same time the reconfiguration effort. Hence, to better assess the effectiveness of such solutions, we will detail in this section the characteristics of both candidates and discuss their pros and cons vs the avionics requirements. Furthermore, their performance evaluation will be conducted to quantify their predictability and availability levels;

- Event-triggered with dynamic redundancy: there are two interesting candidates in this class, Ethernet/IP with DLR [7] and AeroRing [11]. Both solutions implement the event-triggered paradigm, which induces a similar reconfiguration effort to the AFDX solution, while implementing a dynamic redundancy solution to reduce the deployment costs. From a practical point of view, this class should actually contain the best solution for the new generation avionics in terms of modularity and costs, but it is also the one introducing the most challenging issues to guarantee predictability and availability. Hence, to introduce such a solution in avionics, one needs to verify these key requirements.

Therefore, we detail herein a qualitative benchmarking of the most relevant classes of RTE solutions in the avionics context: time-triggered with dynamic redundancy and event-triggered with dynamic redundancy. A quantitative analysis of their performances will be conducted in the next section.

B. Time-Triggered Solutions with Dynamic Redundancy

1) EtherCAT: EtherCAT has been defined by Beckhoff GmbH and supported by the EtherCAT Technology Group (ETG). It implements a master/slave mechanism on top of Fast Ethernet (100Mbps). The main particularity of EtherCAT is the on-the-fly forwarding technique, which allows the slaves to insert the requested data in the frame crossing the couplers step by step. It is worth noting that this technique requires a specific implementation within the slaves, but allows at the same time collecting data from several slaves to be transmitted within the same frame. Therefore, this technique allows reducing the overhead of EtherCAT to one header for many collected data, instead of one header per data in classic Ethernet.

Furthermore, to guarantee the reliability requirements, EtherCAT supports the master redundancy due to the hot standby method, and implements a dynamic redundancy solution based on a ring topology. In the case of a link or node failure, first, the slave detecting the failure returns immediately the EtherCAT frame to the master to avoid losing the communication with the rest of the nodes. Afterwards, the master activates its ports and sends the frame on both to be received by all slaves. Furthermore, the master can determine the failure location through analyzing the slaves error counters.

EtherCAT provides interesting timing performance and availability levels due to the on-the-fly mechanism. The latter induces actually short communication latencies, thus a fast failure detection. Furthermore, it implements a specific redundancy mechanism to enhance the reliability level. However, the main drawbacks of this technology are mainly related to: (i) the specificity of its devices, which increases the implementation costs; (ii) the use of a master/slave mechanism, which reduces its compatibility with the AFDX standard and increases its reconfiguration effort.

2) PROFINET IRT: PROFINET/IRT (*Isochronous Real-Time*) is an extended version of PROFINET, which supports real time communications on top of Fast Ethernet (100Mbps). It is a master/ slave network, based on cyclic communication handling two communication channel types: isochronous and asynchronous. These channels are used by slaves to transmit real-time and non real-time data, respectively. The data is relayed using the Cut-through mechanism to reduce the processing time. It is worth noting that the isochronous channel requires an accurate synchronization protocol to guarantee packet transmissions according to a predefined schedule. Furthermore, PROFINET/IRT implements a slipstream method to transmit data, which consists in sending the packets following the physical order of the nodes from the master point of view: the first packet is for the farthest node and the last packet is for the nearest node. This method inherently decreases the communication latencies.

Profinet/IRT supports reliability features through implementing the MRP [21], based on a ring topology. The MRP is based on a manager, called Media Redundancy Manager (MRM), that monitors the status of the network and the other nodes, called Media Redundancy Clients (MRCs). Each equipment integrates an internal switch with two ports, and supports three status: *disabled*, when the port is down; *blocked*, the forwarding function is disabled; *forwarding*, the port can receive and forward messages. In the nominal case, the ring is closed and all MRCs are forwarding the data, except the MRM which blocks one of its ports to avoid the infinite message looping. Furthermore, the MRM monitors the status of the network by sending periodically *Test* frames on both ports, and if the frames are received on the opposite ports, then the ring is closed. However, if at least one of the frames is lost, then the MRM concludes that the network is faulty, activates both ports to transmit data and informs the MRCs about the topology change by sending *TopoChange* frames.

Profinet/IRT favors predictability and availability requirements thanks to the cut through mechanism and the slipstream method, which infer short communication latencies and fault detection time. Moreover, it implements the MRP to manage redundancy and enhance reliability. However, it has mainly the same drawbacks than EtherCAT in terms of reconfiguration effort, because of the synchronization protocol and the master/slave paradigm. Finally, Profinet/IRT should be more interesting than EtherCAT in terms of deployment costs since it does not require specific devices.

C. Event-Triggered Solutions with Dynamic Redundancy

1) Ethernet/IP with DLR: Ethernet/IP (for Industrial Protocol) is a 100Mbps network developed by Rockwell Automation in 2001 and supported by the Open DeviceNet Vendor Association (ODVA). Ethernet/IP uses CIP (Common Industrial Protocol), which allows the use of off-the-shelf products that are compatible with the TCP-UDP/IP stack. Ethernet/IP is based on CIP connections, which define the type of packet that will be produced on the network. Two categories of connections are defined: Explicit Messaging and Implicit Messaging. The former is used for generic communications between two nodes, whereas the latter is specific to I/O applications and uses UDP rather than TCP.

To favor the real-time communication on top of Ethernet/IP and support safety requirements, OADV have introduced in 2008 the Device Level Ring (DLR) mechanism, based on ring topology. The DLR mechanism is based on a ring controller, called active ring supervisor, which collects data from the other interconnected nodes on only one port to avoid infinite traffic loop, except some specific frames, i.e., beacons. Each equipment has two Ethernet interfaces and an integrated switch, which implements Store & Forward mechanism and Static Priority service policy. Moreover, fault detection and reconfiguration mechanisms are handled within the controller via specific messages, i.e., beacon and announce, similar to the MRP.

Ethernet/IP with DLR has interesting features in terms of reliability due to the fault detection mechanisms within the controller, and of its reduced costs due to standard devices. However, the non-nominal case needs the reconfiguration of the supervisor, which increases the configuration effort. Furthermore, integrated switches based on Store & Forward mechanism induce high transmission latencies, which decrease the offered real-time performance and availability levels.

2) AeroRing: AeroRing [11] has been specified in 2015 during a collaborative project between academia and industrials funded by a European grant[1], to fulfill avionics requirements using a ring-based gigabit ethernet solution. AeroRing allows any "Ethernet-compliant" equipment to transmit its data via a specific end-system, called T-AeroRing, following an event-triggered paradigm similar to the AFDX standard. The T-AeroRing is a specific 3 ports Full Duplex Ethernet switch having the following main characteristics: (i) Cut-Through forwarding technique to guarantee short forwarding latency; (ii) Static Priority service policy to manipulate four priority classes, e.g., control, hard real-time, soft real-time and non real-time; (iii) Traffic policing to control each traffic class compliance with its predefined contract to avoid the network saturation. Each traffic exceeding its associated contract may be discarded to guarantee the communication determinism; (iv) QoS-aware routing based on two routing modes to transmit the generated packets depending on their priorities, i.e., sending on both ring ports for high priority traffic classes to enhance reliability, and sending on the port corresponding to the shortest path for medium and low priority traffic classes to enhance delay; (v) a Frame redundancy management mechanism to detect redundant frames generated by the first routing mode, and to determine whether to deliver the packet to the final destination or drop it because its replica has already been received. In practice, all packets sent on both ring ports are provided with a 2-bytes sequence number field that occurs just before the FCS field, which will be checked at the destination; (vi) Filtering Function to avoid infinite packet looping as a result of broadcast communication or erroneous header information, where each T-AeroRing eliminates all its generated packets sent on one port and received on the other port or all received packets with erroneous source address.

AeroRing implements a specific distributed redundancy solution. Any T-AeroRing has to consider a connection as down with a neighbor, if it does not receive any message from its neighbor during a certain period called "detection period". This detection period can be easily tuned by the network designer. In practice, if a T-AeroRing has no data to transmit to its neighbor, then it announces periodically its status to that neighbor through sending control messages. These control messages to announce the status to neighbors are sent periodically when at least one of the following conditions is satisfied: (i) The *T-AeroRing* does not have any data to send on this port during a period called "*announcing period*" (this period is less then the *detection period* that covers in general

the reception of more than one control message);(ii) The *T-AeroRing* did not receive any data or control message from this port for a duration equal to the *detection period*. In this case, the T-AeroRing indicates to its neighbor through a control message that the connection is considered as down. When a connection is considered as down by one of the interconnected T-AeroRing, the latter sends a first control message to inform the other T-AeroRings, followed by a second control message to update the routing tables. Afterwards, a down connection is considered operational again, if the T-AeroRing starts receiving frames (data or control) from its neighbor. In this case, it sends a control message to update the routing tables of the other nodes. Hence, unlike DRP, AeroRing implements a completely distributed redundancy protocol, based only on local fault detection mechanisms. Furthermore, unlike RRP, the T-AeroRings build autonomously their routing tables with a low induced overhead, and messages can be sent on both directions or only on the shortest path, according to the message class.

The event-triggered paradigm of AeroRing will definitely guarantee a reduced configuration effort, similarly to the AFDX network. Furthermore, the predictability and availability requirements are favored due to the cut-through mechanism and the QoS routing algorithm implemented within the T-AeroRing, which infers short communication latencies. Moreover, it supports interesting redundancy mechanisms to cope with reliability features. Finally, the use of COTS devices will decrease the deployment and installation costs.

D. Benchmarking and Discussions

The summary of the main characteristics of described RTE solutions is illustrated in Table II, and the benchmarking of the described RTE solutions supporting ring topology vs the main identified requirements in Section II-A is illustrated in Table I. EtherCAT and Profinet/IRT imply higher costs due to the specificity of the implemented devices and synchronization protocol, and lower reliability due to the master/slaves mechanism, than Ethernet/IP with DLR and AeroRing. The latter are based on standard devices and implement fault detection and reconfiguration mechanisms, which enhance costs and reliability. Concerning predictability and availability, EtherCAT, Profinet/IRT and AeroRing allow short latencies due to on-the-fly and Cut Through mechanisms, whereas Ethernet/IP with DLR induces high latencies because of the Store & forward one. Moreover, these transmission latencies have a direct effect on the fault detection time, and consequently the availability level. Hence, the offered predictability and availability levels of EtherCAT, Profinet/IRT and AeroRing are higher than Ethernet/IP. Finally, concerning modularity, Ethernet/IP and AeroRing offer higher modularity level thanks to the implemented event-triggered paradigm, in comparison to EtherCAT and Profinet/IRT due to the master/slave mechanism.

As we can notice, each RTE solution satisfies some selected requirements better than others, but there is no best solution in terms of all the avionics requirements detailed in Section

Protocols	Reliability	Availability	Predictability	Modularity	Costs
EtherCAT	Medium	High	High	Low	High
PROFINET/IRT	Medium	Medium	Medium	Low	High
Ethernet/IP with DLR	High	Low	Low	High	Medium
AeroRing	High	Medium	Medium	High	Low

TABLE I
BENCHMARKING OF RTE SOLUTIONS SUPPORTING RING TOPOLOGY

Characteristic	EtherCAT	PROFINET IRT	Ethernet/IP	AERORING
Rate (Mbps)	100	100	100	1000
Topology	Bus or ring	Bus or ring	Daisy-chain ring	Daisy-chain ring
Media	100Base-TX	100Base-TX	100Base-TX	1000BASE-TX
Control Mechanism	Master/slaves	Master/slaves	Event-triggered with SP policy	Event-triggered with SP policy
Robustness management	centralized (specific)	centralized (MRP)	centralized (DLR)	distributed (specific)
QoS management	no	no	yes	yes
Standardization	Open standard	Open standard	By OADV	Open specifications
Pros	On-the-fly transmission Short transmission cycle	Cut-through transmission Short transmission cycle	Efficient faults detection QoS Management	Cut-through transmission Short transmission cycle QoS Management Distributed Fault Management
Cons	Specific devices Central point of failure	Specific devices Central point of failure	Complexity due to integrated switches High latency	Not standardized yet

TABLE II
SPECIFICATIONS COMPARISON OF RTE SOLUTIONS SUPPORTING RING TOPOLOGY

II-A. However, it is worth noting that AeroRing bridges the gap between these aforementioned RTE solutions, through guaranteeing similar reliability level, costs and modularity than Ethernet/IP with DLR, while enhancing the predictability and availability levels to be comparable to EtherCAT and Profinet/IRT. This benchmarking based on qualitative criteria will be consolidated through performance evaluation of quantitative performance indicators in the next section.

IV. PERFORMANCE EVALUATION

The document IEC 61784-2 [4] has introduced a set of Performance Indicators (PIs) to evaluate the RTE networks abilities. In this section, we first describe the most effective PIs in an avionics context. Then, we describe a representative avionics case study, considered as a reference to assess the PIs of the different RTE solutions described in Section III. Finally, we detail and discuss the obtained results for each solution.

A. Performance Indicators

The main PIs to compute have been defined in [4] and the most relevant ones in avionics are:

- Maximum Delivery Time: indicating "the time needed to convey an APDU containing data (message payload) that has to be delivered in real-time from one node (source) to another node (destination)" when considering the worst-case scenario. This PI is of utmost importance in avionics to conclude on the network *predictability*, since we need to guarantee that the maximum delivery time of any type of traffic is lower than its associated temporal deadline;
- Maximum number of end-stations: in [4], this indicator represents the maximum number of stations that can be supported by the RTE solution. In the avionics context, such an indicator has to give an idea on the network

scalability, while respecting the time constraints, i.e., the maximum number that still respects the temporal deadlines of any type of flow exchanged on the network;
- RTE Throughput: it "shall indicate the total amount of APDU data (in bytes) on one link per second". This parameter allows assessing the resource utilization *efficiency* of the alternative solution, thus to evaluate its maintainability during the long lifetime of an avionics system (about 20 to 30 years), which needs an easy incremental design process for adding functions along this duration.
- Non-RTE Bandwidth: it "shall indicate the percentage of bandwidth, which can be used for non-RTE communication on one link". This parameter can be considered complementary to evaluate the effectiveness of the alternate solution, in terms of resource utilization efficiency;
- Redundancy recovery time, indicating "the maximum time from failure to become fully operational again in case of a single permanent failure". This indicator is essential to evaluate the network *availability*, a key requirement in avionics.

In order to compute these identified PIs for each described RTE solution, we identify herein the main interesting work in this area. For EtherCAT, Profinet/IRT and Ethernet/IP, we mainly use the analytical results detailed in [22] concerning the maximum delivery time and [4] for the rest of the indicators. For AeroRing, we have applied the main results in [23] to compute the delivery and recovery times.

B. Reference Case Study

The considered case study is a representative avionics communication network setup, which supports three types of flows: the I/O data initially transmitted on the CAN and ARINC 429,

the legacy AFDX flows and audio data for cabin management. Furthermore, we consider the following assumptions:

- The network topology is a ring;
- The links speed is $C = 1Gbit/s$ (we enlarge the capacity of EtherCAT, Profinet/IRT and Ethernet/IP to 1Gbps to conduct fair comparative analysis with AeroRing solution);
- The network size varies from 5 to 100 nodes;
- All devices are similar and send the same traffic in broadcast mode;
- Each equipment generates one flow of each type of traffic, described in Table III. It is worth noting that the different traffic classes are handled with FIFO policy for the RTE solutions with no QoS management, and Static Priority for the rest.

TABLE III
TRAFFIC CHARACTERISTICS

	Priority	MFS (byte)	BAG (ms)	Deadline (ms)
I/O data	High	8	2	2
Legacy AFDX	Medium	1300	10	4
Audio	Low	160	20	20

C. Numerical Results

Fig. 3 illustrates the maximum delivery time of the different RTE solutions supporting the ring topology. There are mainly two interesting observations through this figure. The first one confirms the qualitative benchmarking in Section III-D in terms of predictability requirements. Ethernet/IP has actually the highest delivery time, in comparison to the rest of the solutions, which have quite similar performance for I/O data. The second observation concerns the network scalability, where the maximum number of RTE end-systems respecting the most constrained deadline, i.e., I/O deadline of 2ms, is about 8, 70, 76 and 81 for Ethernet/IP, EtherCAT, Profinet/IRT and AeroRing, respectively. This result shows the high scalability of AeroRing and Profinet/IRT, a key requirement for avionics.
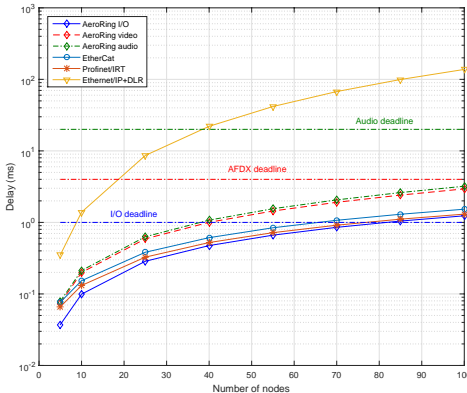

Fig. 3. Maximum Delivery Time of Ring-based RTE solutions

Concerning resource efficiency of the different RTE solutions, we can observe Figures 4 and 5 illustrating the RTE throughput for the different types of traffic and the Non-RTE bandwidth, respectively. The obtained results show the

high efficiency of EtherCAT, Profinet/IRT and AeroRing, in comparison to Ethernet/IP. Furthermore, we can notice a better RTE throughput for I/O data and non RTE bandwidth with AeroRing than EtherCAT and Profinet/IRT. This fact is mainly related to the QoS management within AeroRing, which enhances the highest priority performance, while degrading the medium and lowest priority ones.
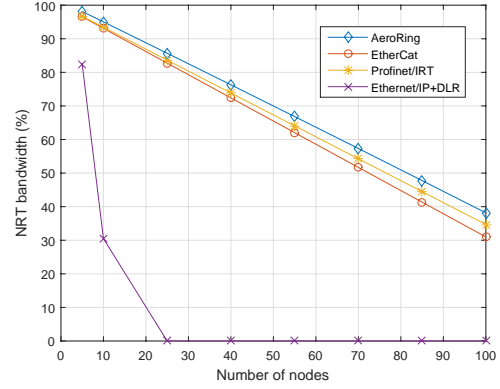

Fig. 5. Non-RTE Bandwidth of Ring-based RTE solutions

Finally, to assess the availability level of the different RTE solutions, the maximum recovery time is shown in Fig. 6. The results confirm again the first qualitative conclusions in Section III-D, where EtherCAT, Profinet/IRT and AeroRing have similar availability levels, which are much better than the one offered by Ethernet/IP.
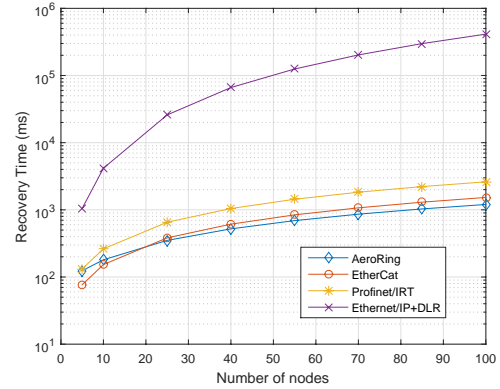

Fig. 6. Redundancy Recovery Time of Ring-based RTE solutions

Based on this quantitative analysis of the most relevant PIs, we can adjust the conclusions of Section III-D concerning the expected behavior of each described RTE solution vs the predictability and availability requirements. For predictability, we can notice that AeroRing offers the lowest delivery time for the most constrained traffic, i.e., I/O, which upgrades its predictability level from medium to high. Furthermore, under 1Gbps, Profinet/IRT offers better performance than EtherCAT. This fact is mainly due to the slipstream method of Profinet/IRT and the impossibility of grouping many large-sized data in one frame for EtherCAT. Therefore, we also upgrade the predictability level of Profinet/IRT from medium to high. For availability, we have exactly the same observations
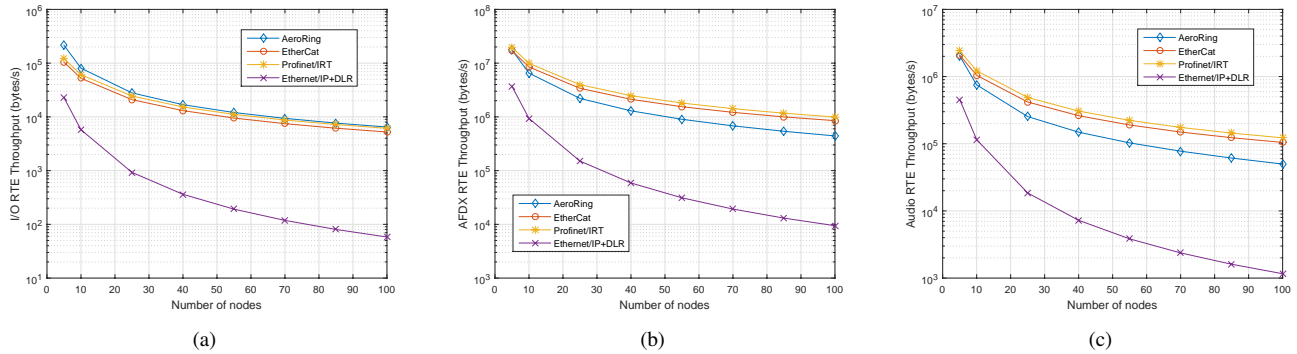
Fig. 4.   RTE Throughput of Ring-based RTE solutions: (a) I/O traffic; (b) AFDX traffic; (c) Audio traffic

Protocols	Reliability	Availability	Predictability	Modularity	Costs
EtherCAT	Medium	High	High	Low	High
PROFINET/IRT	Medium	High	High	Low	High
Ethernet/IP with DLR	High	Low	Low	High	Medium
AeroRing	High	High	High	High	Low

TABLE IV
UPDATED BENCHMARKING OF RTE SOLUTIONS SUPPORTING RING TOPOLOGY

based on the redundancy recovery time. Hence, we obtain the updated Benchmarking Table IV. The latter shows that the best RTE solution, supporting ring topology, for avionics is AeroRing, since it offers a high modularity level thanks to its event-triggered scheme and a low deployment costs due to its dynamic redundancy solution, while guaranteeing a high availability, reliability and predictability level thanks to its QoS-aware routing and Cut Through mechanism.

V. CONCLUSIONS

To handle the emerging requirements of new generation aircraft in terms of decreasing the wire complexity and integration costs, the Real-Time Ethernet profile supporting a ring topology has been revealed as an interesting solution. The effectiveness of the most relevant solutions in this domain vs the main avionics requirements has been assessed in this paper, through the computation of the main PIs on a representative avionics network setup. The quantitative benchmarking has shown the high predictability, availability, scalability and resource efficiency of EtherCAT, Profinet/IRT and AeroRing, in comparison to Ethernet/IP with DLR. However, EtherCAT and Profinet/IRT induces lower reliability and modularity levels than AeroRing due to the master/slave mechanism. These facts make AeroRing the most relevant RTE solution for new generation avionics.

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