DOI 10.5162/ettc2022/2.4

From Automotive to Flight Test Instrumentation: Wiring Reduction Using New Ethernet Standard.

Joaquín Antonio Pablos Palomino[1],
[1] Airbus Defence and Space, San Pablo Sur FTC, Seville, Spain,
joaquin.pablos@airbus.com

Abstract:
The electric car has required the development of a new vehicle architecture , use of new sensor technologies (cameras, UWB, radar,) and networking extension (cloud gateways) to support new requirements of connectivity, safety, security and reliability, enabling not only current but future services (infotainment and communications). Supporting this architecture has been possible thanks to a new Ethernet standard that will reduce significantly the wiring needed: Ethernet over a single pair cable.

This article introduces the main features of the new Ethernet standards related with single pair Ethernet and how Flight Test can make use of them. Currently most of FTI components have Ethernet interfaces (acquisition systems, sensors, cameras …) so the adoption of the new standard in current architecture can be done smoothly at different paces. The proposal of new FTI architectures for some use cases are presented to show major improvements from this standard. Finally, future expected advantages for FTI components are analyzed as the adoption of Ethernet for new sensors, the use of AI devices at the edge and the co-existence with wireless and IoT technologies

Key words: Single Pair Ethernet (SPE) , Flight Test Installation (FTI)

1. Introduction: Ethernet Role in FTI

Ethernet has become the backbone solution for communications in Flight Test Installations in the last 20 years. The movement has allowed to benefit of all the new advances in this technology such as time synchronization, traffic priority and segregation or easy upgrade to new speeds.

One of the main benefits of Ethernet is to simplify the installation of remote acquisition units near measurement zones (wing, engines), reducing the wiring to the zone to power supply and Ethernet communications channels.

Since the first use of Ethernet in flight test for acquisition systems, more FTI equipment are adopting Ethernet standard such as cameras or pressure scanners. This is increasing the use of Ethernet wiring and the complexity of installation of Ethernet harnesses.

In addition flight test campaigns are being developed more often in customers' aircrafts. This is requiring to design flight test installations more compact and pushing to reduce harnesses to avoid impact in customers' aircrafts.

Keeping all the functionality of Ethernet and reducing the wiring needed for it would simplify installations. This article introduces a new Ethernet technology named Single Pair Ethernet (SPE) developed for automotive sector that uses single pair cable for full-duplex Ethernet communications. This means to reduce from two pairs to one for 100 Mbps and four pairs to one for 1Gbps. This technology has been created and standardized thanks to automotive sector as it will described to show the origins in first place.

Second a description of the different standards developed is introduced. Third the current status of technology supporting the technology is shown. Fourth the results of some tests carried out internally will be presented. These tests have been done using standard FTI equipment, single pair Ethernet converters and standard flight test wiring. Finally use of SPE in current and future flight test installations are analyzed.

A previous study of Time Sensitive Networks and Ethernet over Single Pair Cable was done for avionics use when the standards were in development [1]. This article also completes this analysis with all recently published standards related with Single Pair Ethernet and the application to flight test.

2. Automotive Network Evolution

The automotive sector is living a revolution pushed by electric car and new systems as Advanced Driver Assistance System (ADAS) and Infotainment (information and entertainment). For supporting these technologies a problem raised to transmit the volume of data required. Just upgrading the firmware of all the systems was becoming a problem. This was the initial use of standard Ethernet in cars though pins of OBD port (On-board diagnostics). The first use of Ethernet had as objective to reduce the time required to upgrade the car systems from 16 hours using Controller Area Network (CAN bus) interface [2]. This application detected a problem of use of standard Ethernet UTP (Unshielded Twisted Pair) cables in automotive sector, emissions were higher that allowed by automotive normative radiated emissions limits [3]. So standard Ethernet over UTP was right because the car was in a garage for the specific flash upgrade function but could not be used when car was in the runtime.

Considering this problem an innovation program leaded by BMW [2] was launched and had good results to develop an Ethernet physical transceiver based on an unshielded single pair cable that met the emissions required by automotive sector.

This new network technology is key to support the evolution of architecture in cars currently based on several automotive protocols LIN, CAN, MOST or Flexray with lower data rates (see Table 1).

Table 1 – Main automotive buses

Protocol	Speed	Distance	Physical Media
LIN	19.2 Kbit/s	40m	Single wire
CAN	125kbps/5 Mbps	500m/40m	Twisted pair
MOST	25/50/150Mbps	-	Fiber/UTP/Coax
Flexray	10 Mbps	24 m	1 or 2 UTP

The volume of SPE nodes in a car is expected to grow exponentially. This need has led to semiconductors companies to develop physical transceivers compatible with SPE.

Finally the technology developed has become a standard published by IEEE. This is very important in automotive sector, to allow the integration of equipment from different vendors avoiding proprietary solutions for intra communication in the vehicle. In this way a car manufacturer can choose independently the best sensor and the best processing unit for processing the sensor data. The standardization by IEEE has become important also for the use in other sectors as industry.

3. IEEE Standards

Initially Single Pair Ethernet was developed by Broadcom that provided the required modifications for owned technology to support automotive sector. This technology is known as BroadR-Reach.

The interest in standardization led to a group of automotive and semiconductors' companies to create a group called OPEN Alliance SIG in 2011 (more than 300 members now).[4] This group has developed the Ethernet specifications related to automotive [5].

As other sectors as industry considered this technology useful, at the same time IEEE started to develop the IEEE 802.3 related standards. The standards that have been developed so far are:

- 100Mbit/s specification: IEEE Std 802.3bw™-2015 [6]
- 1000Mbit/s specification: IEEE Std 802.3bp™-2016 [7]
- 10 Mbps/s specification: IEEE 802.3cg-2019 [8]
- 2.5 Gb/s, 5 Gb/s, and 10 Gb/s: IEEE 802.3ch-2020 [9]
- Power over Data Lines (PoDL) : IEEE Std 802.3bu™-2016 [10]

These standards describe the functions of the physical layer (named PHY).

The specification IEEE 802.3bw [6] (100Mbps) defined for each copper port a single balanced twisted-pair link segment connection of up to 15 m in length. For supporting full-duplex communications over a single balanced twisted-pair it uses echo cancellation. The 100BASE-T1 PHY leverages 1000BASE-T and 100BASE-TX PHY technologies in operation at 100 Mb/s adopting Pulse Amplitude Modulation 3 (PAM3) to provide trade-off between bandwidth and EMI performance.

The PHY converts the stream of 4-bit words at 25 MBd to a stream of 3-bit words at 33.333 MBd. The bits are then scrambled and converted through PCS encoding to a stream of code-groups (pairs of ternary symbols).These ternary symbol pairs are then multiplexed to a serialized stream of ternary symbols at 66.666 MBd

The link segment defined in the standard supports up to 15 m single balanced twisted-pair cabling with up to 4 in-line connectors and two mating connectors

The standard [6] defines the characteristics of the cable up to 66 MHz (impedance, insertion/return loss…). As we will see later physical transceiver developed are capable of longer distances than defined in the standard.

The standard IEEE 802.3bp [7] (1 Gbps) operates using full-duplex communications over a single twisted-pair copper cable with an effective rate of 1 Gb/s in each direction simultaneously.

It supports operation on two types of link segments:

a) An automotive link segment supporting up to four in-line connectors using a single twisted-pair copper cable for up to at least 15 m (referred to as link segment type A)

b) An optional link segment supporting up to four in-line connectors using a single twisted-pair copper cable for up to at least 40 m to support applications requiring extended physical reach, such as industrial and automation controls and transportation (aircraft, railway, bus and heavy trucks). This link segment is referred to as link segment type B.

The 1000BASE-T1 PHY utilizes 3 level Pulse Amplitude Modulation (PAM3) transmitted at a 750 MBd rate. A 15-bit scrambler is used to improve the EMC performance. To maintain a bit error ratio (BER) of less than or equal to 10e–10, the 1000BASE-T1 PHY uses Reed-Solomon Forward Error Correction.

The standard IEEE 802.3cg [8] (10 Mbps) defines two different physical layers:

- 10BASE-T1L: specification for a 10 Mb/s Ethernet local area network over a single balanced pair of conductors up to at least 1000 m reach. The 10BASE-T1L PHY is a full-duplex PHY specification, capable of operating at 10 Mb/s. The PHY supports operation on a link segment supporting up to ten in-line connectors using a single balanced pair of conductors for up to at least 1000 meters. The 10BASE-T1L PHY utilizes 3-level Pulse Amplitude Modulation (PAM3) transmitted at 7.5 MBd on the link segment.
- 10BASE-T1S: specification for a 10 Mb/s Ethernet local area network over a single balanced pair of conductors up to at least 15 m reach. It is specified to be capable of operating at 10 Mb/s in several modes. All 10BASE-T1S PHYs can operate as a half-duplex PHY with a single link partner over a point-to-point link segment (four in-line connectors and up to at least 15 meters in reach), and, additionally, there are two mutually exclusive optional operating modes: a full-duplex point-to-point mode over the link segment, and a half-duplex shared-medium mode, referred to as multidrop mode, capable of operating with up to 8 stations (bus length of 25 m). The 10BASE-T1S PHY utilizes two level Differential Manchester Encoding (DME). A self-synchronizing scrambler is used to improve the EMC performance.

The IEEE 802.3ch-2020 [9] define the 2.5GBASE-T1 PHY, 5GBASE-T1 PHY, and 10GBASE-T1 PHY that operate using full-duplex communications over a single balanced pair of conductors with an effective rate of 2.5 Gb/s, 5 Gb/s, or 10 Gb/s in each direction simultaneously while meeting the requirements (EMC, temperature, etc.) of automotive environments. The PHY supports operation on an automotive link segment supporting up to four in-line connectors using a single balanced pair of conductors for up to at least 15 m. The 2.5GBASE-T1, 5GBASE-T1, and 10GBASE-T1 PHYs utilize 4-level pulse amplitude modulation (PAM4) transmitted at 1406.25 MBd, 2812.5 MBd, and 5625 MBd rates, respectively.

The IEEE 802.3bu [10] describes the specification for providing a device with a unified interface for both data and power it requires (see Figure 1). The standard defines the electrical characteristics of two power entities: a PoDL Powered Device (PD) and PoDL Power Sourcing Equipment (PSE) for use with supported single balanced twisted-pair Ethernet Physical layers (see Table 2).

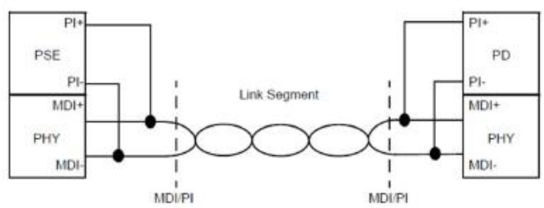

Figure 1 - PoDL block diagram [10]

The total resistance through two conductors looped at one end of the link (direct current loop resistance) shall be less than 6 Ω for 12 V unregulated classes. The direct current loop resistance shall be less than 6.5 Ω for 12 V regulated, 24 V regulated and unregulated, and 48 V regulated classes.

DOI 10.5162/ettc2022/2.4

Table 2 -PSE classification [10]

	12 V unregulated PSE		12 V regulated PSE		24 V unregulated PSE		24 V regulated PSE		48 V regulated PSE	
Class	0	1	2	3	4	5	6	7	8	9
Pmax (W)	0.5	1	3	5	2	3	5	10	30	50

The use of power over data line can raise EMC problems to be analyzed. The use of power over data line will also increase the size of the gauge required.

Finally an important standard related with single pair Ethernet and aeronautics was published in 2020. This document specifies the ARINC 854 Cabin Equipment Network Bus (CENBUS) [11] utilizing a new, serial communications protocol based on IEEE 802.3 Clause 96 (100BASE-T1) operating at 100 Mbps.

4. Technology Maturity

As introduced before, although technology was developed by one manufacturer (Broadcom) the creation of OPEN group later led to several semiconductor companies related with automotive sector to develop physical layers IC for the different standards that cover Single Pair Ethernet. Currently the most available PHY IC is the 100BASE-T1. The following table show the ICs provided by the main manufacturers.

Table 3 - Physical layer transceivers for Single Pair Ethernet

	Manufacturers				
Standard	Broadcom	TI	Marvell	Microchip	NXP
100BASE-T1	BCM89820	DP83TC81x	88Q120xM 88Q111x 88Q1010	LAN8770	TJA1101BHN TJA1102AHN
1000BASE-T1	BCM89882 BCM89880	DP83TG720			
10BASE-T1L		DP83TD510			
10BASE-T1S				LAN8670/1/2	
10G/5G/2.5GBASE-T1	BCM89890		88Q4364		
100BASE-T1/ 1000BASE-T1	BCM89881 BCM89883		88Q222xM 88Q211x		
Switch 100BASE-T1, 1000BASE-T1 PHYs	BCM89571 (8 ports) BCM8956X				
Switch 100BASE-T1	BCM89559 BCM8954X BCM8955X BCM8953X BCM89549		88Q5072 88Q5050 88Q5030		SJA1110 (PREPRODUCTION)

Most of the physical layer transceiver ensures that that length for 100BASE-T1 is at least 15 m but others like TI with DP83TC814R-Q1 and DP83TC811R-Q1 announces maximum cable lengths of 49 m and 60 m. It has to be considered that this length is for an unshielded single pair cable, if we use a better cable the distance can be longer. A distance of 40 m for 100Base-T1 is considered to be reachable with a cable with enough quality.

The physical layer integration in the electronics design is simple, it has a typical MII (Media Independent Interface), RGMII (Reduced Gigabit MII) or SGMII (Serial Gigabit MII) interface depending on the link speed. Any existing physical Ethernet transceiver could be replaced by minor changes in software driver to configure it.

The external components required between phy and the external connector of the 100BASE-T1 phy are (see Figure 2): ESD protection, common mode termination, DC block capacitors, common mode choke and low pass filter (it can be integrated in the PHY). Transformers are not used in the automotive application so isolation is different of standard Ethernet. The transformer is replaced by a Common Mode Choke (CMC) to meet EMC in automotive sector.

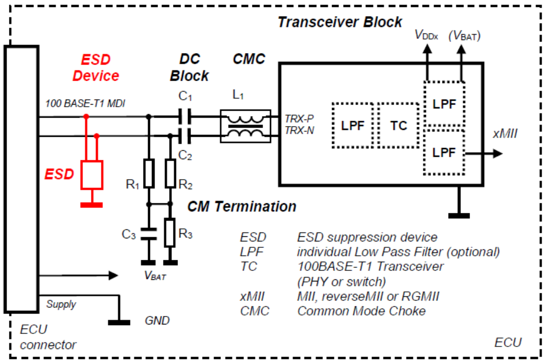

Figure 2 - External components of Phy for 802.3w[5]

For keeping isolation of standard Ethernet some application notes treat how to modify the automotive solution [12].

In addition to the electronics components needed for updating or designing new equipment, commercial/industrial equipment are also available.

Test equipment manufacturers [13] have developed products to analyze OPEN Alliance requirements of 10BASE-T1S, 100BASE-T1, 1000BASE-T1 and 2.5G/5G/10GBASE-T1 (see Figure 3).

Figure 3 - Oscilloscope with SPE test capabilities

In the market there are also available [14] converters for testing and validating applications/equipment with automotive Ethernet connections (like MATEnet or

DOI 10.5162/ettc2022/2.4

Molex/mini50) for 100BASE-T1 and RJ45 connection for 100BASE-TX (see Figure 4).

Figure 4 - Ethernet converters

Ethernet switches supporting SPE that are a key element in deployment of new standard are also available [15].

The main manufacturers of connectors/cables are developing products for automotive, but also for other sectors interested in single pair Ethernet as industry or aeronautics [16].

Therefore we can conclude that all the elements of this technology are ready to be used.

5. Testing with FTI Wiring and Equipment

Previous studies have analyzed the use of Single Pair Ethernet for aerospace application performing EMC tests with CAT 5 cable [17,18] and cabin existing wiring of an A321 [19].

As an approach to single pair Ethernet technology some tests connecting FTI equipment have been done using two typical FTI wiring.

As converter module to connect 100Base-Tx equipment using 100Base-T1 standard an evaluation board from TI has been used. The DP83TC811EVM [20] supports 100-Mbps speed and is IEEE 802.3bw compliant. This evaluation board is a media converter to enable bit-error rate testing, interoperability testing and PMA compliance.

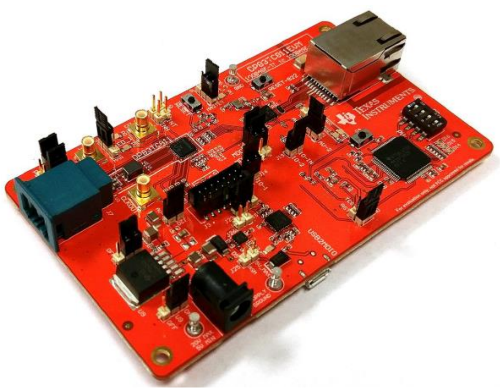

Figure 5 - Evaluation board used as converter

FTI equipment used were a rugged Ethernet PTP master switch, a recorder and two different remote acquisition units.

The wiring used during the tests have been a standard FTI Ethernet cable and a standard two-cores FTI cable [21]:

- KD24: 100 ohms shielded quad core cable, used for high speed data transmission (Ethernet networks) 100 Mbit/s and in-flight entertainment application.
- ASNE 0411 TV: 2 core shielded cable used mainly for connecting sensors to remote acquisition channels. The use of this cable is not expected to pass EMC tests and it is done only for testing robustness of physical layers with non-qualified Ethernet standard wiring.

The following test have been performed:

- Test 1: Connection of a FTI recorder to a remote acquisition unit with 16 meters of KD24 (using one of the two pairs for bidirectional communications). The bit rate of the link was 5 Mbps working without errors (see Figure 6 & 7).

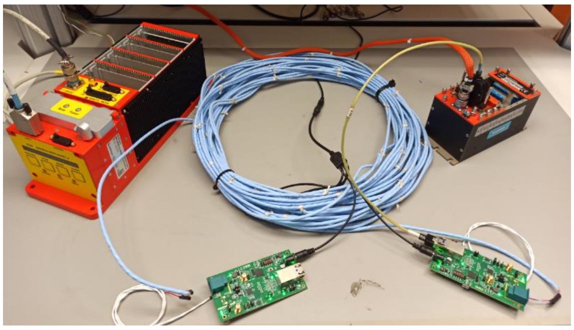

Figure 6 – Test 1 set-up

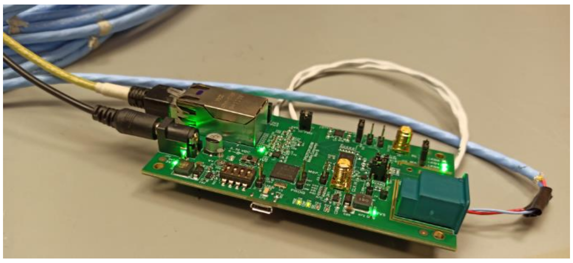

Figure 7 – Detail of test 1 set-up

- Test 2: connection of a FTI switch to a remote acquisition unit with 16 meters of KD24 (using one of the two pairs for bidirectional communications, see Figure 8). The bit rate of the link was 6.5 Mbps working without errors.

DOI 10.5162/ettc2022/2.4

Figure 8 - Test 2 set-up

- Test 3: connection of a FTI switch to a remote acquisition unit with 20 meters of TV (see Figure 9). The bit rate of the link was 6.5 Mbps working without errors.

Figure 9 - Test 3 set-up

- Test 4: connection of a FTI switch to a remote acquisition unit with 50 meters of ZTV. The bit rate of the link was 6.5 Mbps working without errors.
- Test 5: connection of two PCs with 16 meters of KD24. For this test a software tool "iperf" was used to check performance of the link. Using a traffic of 90 Mbps no packet was lost during the test. If the traffic is configured to 95 Mbps some errors are detected (maybe produced by converters).

As performed tests show, existing technology is very promising, even with a not considered "Ethernet wiring" as the TV, in the end it seems to provide a good communication link.

6. FTI Architecture with SPE

FTI architecture rely on Ethernet infrastructure for the main functions (see Figure 10): data acquisition, recording and monitoring. It has become the backbone that connect most of the FTI systems [22].

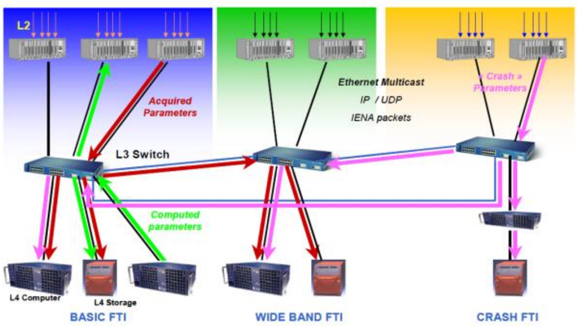

Figure 10: A380 IENA FTI LAN (Acquisition mode)

Remote acquisition units has reduced the wiring of sensors but has increased Ethernet wiring. Other FTI equipment as cameras are moving to Ethernet technology, so Ethernet wiring is growing and being one of the main problems. Ethernet growth implies additional connectors, increase of pressure seals occupation and new need of drilling holes in normal installation (see Figure 11).

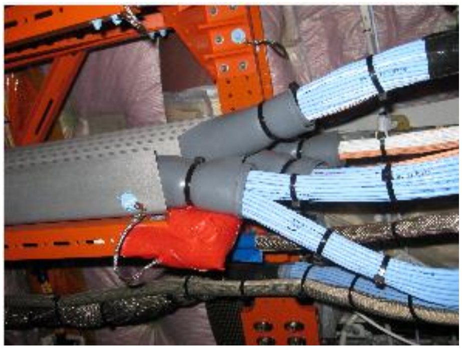

Figure 11 - Ethernet wiring in Flight Test

The benefits of using Single Pair Ethernet is clear: we can reduce the size/weight and cost of wiring of the current installation by a half. In addition the building of the installation is simplified because less connectors have to be assembled.

The following figure shows a typical A400M light FTI architecture:

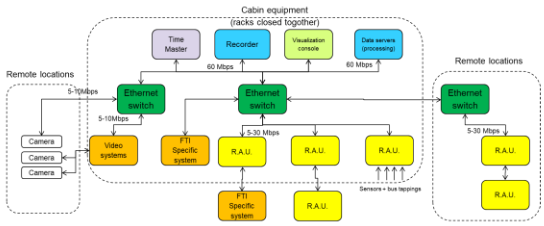

Figure 12 - A400M Light FTI

In one of the A400M prototypes with a light FTI the use of SPE would reduce the Ethernet pairs from 86 to 27, so only one third of the number of existing pairs would be needed and less connectors used. In the case of heavy FTI where many racks are interconnected with Ethernet wiring the savings taking into account cable length and weight would be even more noticeable. One of the main cable manufacturers claims [16] that specific SPE cable would save 14 % of weight compared with standard cable (2 pairs) required for 100Base-Tx and 62 % compared with standard cable (4 pairs) required for 1000Base-Tx

The main problem to adopt SPE is that none of the existing equipment have network interfaces that support it. FTI Ethernet switches should support SPE as a first step for future growth. New ARINC 854 standard will help to have this kind of device available and qualified for aircraft with standard connectors and wiring [25].

Current installations can benefit of SPE technology using converters and existing Ethernet wiring to avoid modifying installation in not accessible zones. These converters would simplify the update when a higher speed for a connection is needed or the number of Ethernet channels has to be increased. As a typical case we can consider to increase the number of remote acquisition units in an engine or a POD without needing to increase the Ethernet wiring from Cabin to the remote acquisition zone (see Figure 13). We would need two converters in each end and the same KD24 wiring would support the increase of channels.

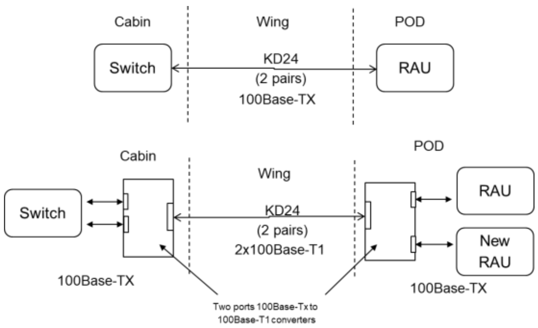

Figure 13 - Use of converters in current FTI

One of the advantages of supporting SPE in FTI is that will allow to make use of new devices developed for automotive that could have application in flight test such as cameras or other kind of sensors/devices.

As Ethernet cameras and micro acquisition systems (6-8 inputs) are recent FTI elements that have a promising future (see Figure 14), supporting SPE can make more attractive the use of these elements. Not only data but power could be provided through a single pair for this kind of elements as they don't have a high power consumption.

Figure 14 - Examples of micro acquisition system and Ethernet camera

Integrating this technology in existing and new devices will simplify flight test installations. The technology for 100 Mbps and 1 Gbps is available and is currently being used in automotive sector. The technology for 10 Mbps and PoDL will allow to integrate new equipment with only one pair cable and longer distances. Use of this technology by automotive and industrial sectors will ensure that it will be supported and updated.

One of the first documented uses of SPE technology in flight test has been a Flight Test Pod on board a Panavia Tornado [1] with good performance even when technology was not mature (2014).

7. Future Applications of SPE in FTI

The main elements required to support the evolution to SPE in FTI architecture are the following (see Figure 15):

- Ethernet switches supporting 100 Mbps/1Gbps communications and PoDL.
- Ethernet Cameras supporting 100 Mbps / 1 Gbps communications and PoDL.
- Micro data acquisition units supporting: 100 Mbps / 1 Gbps communications and PoDL.
- Remote acquisition units with support of 100 Mbps / 1 Gbps communications.
- Specific Ethernet FTI equipment (pressure scanners, specific sensors …) using most convenient SPE speed and PoDL.
- Access points for wireless technologies with SPE support for communications and PoDL.

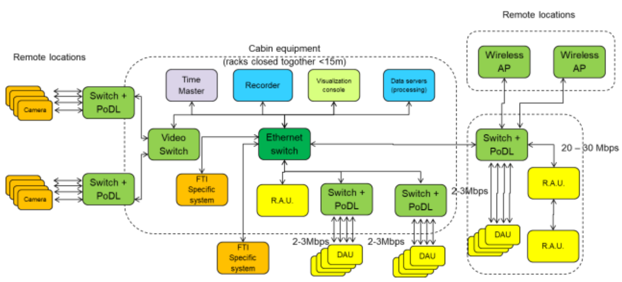

Figure 15 - Future SPE FTI architecture

SPE use for FTI in drones can be key to maximize the autonomy range optimizing size and weight while keeping support of high bandwidth (1 Gbps).

Although SPE can be seen as a reason to avoid use of wireless technology, it can help to power and communicate with the access points simplifying the routing to the best place for radio coverage.

Currently many aircraft and FTI equipment make use of protocols such as CAN, LVDS, … that can have now an easy migration to Ethernet using reduced wiring and enhancing the speed if needed. This process has been done in automotive and industry sectors to replace the use of old field buses. In the industry a group of leading suppliers and standards development organizations are working in the development of Ethernet advanced physical layer (Ethernet-APL [23]) based on 10 Base-T1L to meet the requirements for the field of process plants.

Every new FTI device / sensor should consider SPE for data transmission to reduce the wiring impact in aircraft and to avoid dependencies or other communications protocols.

Finally future use of IoT devices with new microprocessors & tools that will provide intelligence at the edge will need a way to transmit information. Although wireless technology is being considered in many use cases [24], the use of SPE can be an alternative for these applications, especially when communications reliability and data rate are important. The power over data line feature is another advantage of SPE standards to become an advanced platform for Internet of Things. The use of SPE will simplify use of Ethernet for digitalization at the edge.

8. Conclusions

In this paper the main IEEE standards related with Single Pair Ethernet has been introduced. The technology is ready to be used and several tests have been done with FTI equipment. Automotive sector has been the main developer of this technology and new sectors as aviation and industry are adopting it, defining related standards.

The main technological advance is to support from 10 Mbps to 10 Gbps Ethernet based on a single pair cable in harsh environments, reducing weight and installation of Ethernet networks. Flight Test Installations make use currently of 100 Mbps and 1 Gbps Ethernet interfaces, so it could benefit from this technology to reduce wiring and harnesses as in the use cases described.

The FTI systems that will take the most advantage of the new standard have been analyzed to define a future FTI architecture. Use of SPE for communications with remote locations are the main application in transport platforms. For small platforms as drones the use of SPE can help to reduce the FTI footprint.

The main advantages that justify the use of SPE for FTI are reduced cost, easier and faster installation, and higher bandwidth if needed. This simplification of Ethernet will facilitate the use of new emerging devices with capabilities of machine learning in flight test.

9. References

[1] Wilfried Steiner, TTTech Computertechnik AG, Vienna, Austria, Peter Heise and Stefan Schneele, Airbus Group, Munich, Germany - “Recent ieee 802 developments and their relevance for the avionics industry” - *2014 IEEE/AIAA 33rd Digital Avionics Systems Conference (DASC)*

[2] Kirsten Matheus, Thomas Königseder: “Automotive Ethernet” 2nd Edition, Cambridge University Press

[3] Donovan Porter: “100BASE-T1 Ethernet: the evolution of automotive networking” – Texas Instruments whitepaper April 2018

[4] OPEN Alliance (One-Pair Ether-Net) - https://www.opensig.org/

[5] OPEN Alliance Automotive Ethernet Specifications : http://www.opensig.org/Automotive-Ethernet-Specifications/#

[6] IEEE 802.3bw-2015 - IEEE Standard for Ethernet Amendment 1: Physical Layer Specifications and Management Parameters for 100 Mb/s Operation over a Single Balanced Twisted Pair Cable (100BASE-T1)

[7] IEEE 802.3bp-2016 - IEEE Standard for Ethernet Amendment 4: Physical Layer Specifications and Management Parameters for 1 Gb/s Operation over a Single Twisted-Pair Copper Cable

[8] IEEE 802.3cg-2019 - IEEE Standard for Ethernet - Amendment 5: Physical Layer Specifications and Management Parameters for 10 Mb/s Operation and Associated Power Delivery over a Single Balanced Pair of Conductors

[9] IEEE 802.3ch-2020 - IEEE Standard for Ethernet--Amendment 8:Physical Layer Specifications and Management Parameters for 2.5 Gb/s, 5 Gb/s, and 10 Gb/s Automotive Electrical Ethernet

[10] IEEE 802.3bu-2016 - IEEE Standard for Ethernet--Amendment 8: Physical Layer and Management Parameters for Power over Data Lines (PoDL) of Single Balanced Twisted-Pair Ethernet

[11] ARINC Specification 854 - https://www.aviation-ia.com/products/854-cabin-equipment-network-bus

[12] SPE Industrial Partner Network – “Single pair ethernet for industrial applications (application note)” - https://single-pair-

ethernet.com/sites/default/files/2021-03/202103speapplikationnotespe-integrationv10en_anp085.pdf

[13] Rohde-schwarz – "Excellence in automotive Ethernet solutions" : https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/Automotive_Ethernet_fly_en_5216-0267-32_v0100_120dpi.pdf

[14] Keysight – "Automotive Networking Tools" - https://www.keysight.com/es/en/assets/3120-1066/data-sheets/Automotive-Networking-Tools.pdf

[15] Technica Engineering – 100BASE-T1 Products - https://technica-engineering.de/en/product-category/100base-t1/

[16] Martin Cullen, Robert Moore, Clint Schlosser, Mark Benton:" Connecting the future of flight" – TE whitepaper

[17] A. Thain, F. Le Sergent, C. Marot, B. Pasquier: "Suitability of 2-wire ethernet solutions for aerospace applications" - *2016 ESA Workshop on Aerospace EMC (Aerospace EMC)*

[18] R. Perraud , C. Marot, G. Martins, V. Kretzschmar,, B. Theillaumas , J. Sperandio : "EMC Investigations on Ethernet Link for Avionic Application" - *2019 ESA Workshop on Aerospace EMC (Aerospace EMC)*

[19] Alexandros Elefsiniotis, Sebastian Hahn: "Aircraft harness measurement campaign and investigations on introducing one pair Ethernet" - *Telecommunications Network Strategy and Planning Symposium (Networks), 2016 17th International pp.207 - 212*

[20] DP83TC811 100BASE-T1 to 100BASE-TX automotive Ethernet PHY media converter evaluation module https://www.ti.com/tool/DP83TC811EVM

[21] Nexans catalogue - A complete range of wire & cable solutions for aerospace applications Issue 9 - June 2013

[22] Natalie Revaux – Frédéric Abadie: "A380 Flight Test Architecture : Switched IENA from Pulse Code Modulation to Ethernet LAN", ETTC 2003

[23] Ethernet APL - Two-Wire Ethernet For Process Automation - https://www.ethernet-apl.org/about-moksha

[24] P. Durand Estebe, V. Boitier, M. Bafleur, J-M. Dilhac : "Power Supply for a Wireless Sensor Network: Airliner Flight Test Case Study" - *The 2014 International Power Electronics Conference*

10. Glossary

SPE: Single Pair Ethernet

IEEE: Institute of Electrical and Electronics Engineers

FTI: Flight Test Installation / Instrumentation

UWB: Ultra Wide Band

IoT: Internet of Things

AI: Artificial Intelligence

ADAS: Advanced Driver Assistance System

CAN: Controller Area Network

UTP: Unshielded Twisted Pair

LIN: Local Interconnect Network

MOST: Media Oriented Systems Transport

SIG: Special Interest Group

PoDL: Power over Data Lines

PHY: Ethernet physical layer

PAM: Pulse Amplitude Modulation

BER: Bit Error Rate

EMI: Electromagnetic interference

EMC: Electromagnetic compatibility

PD: PoDL Powered Device

PSE: PoDL Power Sourcing Equipment

CENBUS: Cabin Equipment Network Bus

ARINC: Aeronautical Radio, Incorporated

ESD: electrostatic discharges

CMC: Common Mode Choke

MII: Media Independent Interface

RGMII: Reduced Gigabit MII

SGMII: Serial Gigabit MII

DME: Differential Manchester Encoding

LVDS: Low Voltage Differential Signaling