WHY CHANGE FROM PCM? CASE STUDY OF THE AIRBUS A380 ETHERNET BASED DATA ACQUISITION NETWORK

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ABSTRACT

The adaptation of ubiquitous Ethernet technology to airborne FTI systems is a relatively recent development, offering multiple advantages to FTI applications, including a high data throughput and ability to integrate COTS equipment with ease.

For large-scale FTI applications – such as on the Airbus A380 - the use of traditional PCM based data acquisition systems results in enormously complex system architectures, with difficulties in system design, implementation, commissioning, test and maintenance. However, on the A380, the use of the Ethernet-based, IENA protocol alleviated these problems, in addition to offering several additional advantages.

This paper explores the theoretical and practical implications of using Ethernet-based data acquisition in an FTI application, with direct comparison to an equivalent PCM based system.

KEYWORDS: Data acquisition, FTI, A380, network, distributed, Ethernet, PCM

1. INTRODUCTION

For several decades now, FTI data acquisition systems have used PCM as the standard mechanism for the transmission and recording of data [1]. PCM has proven itself to have many advantages, including robustness and reliability. PCM is also a deterministic means of transmitting data, as most PCM standards are based on a fixed PCM frame containing a fixed placement of data words, repeated continuously. This allows system designers to calculate system data throughput and bandwidth usage with 100% certainty during FTI system design. Thus, data acquisition strategies can be optimised to meet the available bandwidth for telemetry via PCM frame design, making IRIG-106 PCM the best method of transmitting FTI data via RF links at present.

There is a large and growing interest in the FTI community in the use of COTS equipment. The motivation behind this interest is the desire to migrate from a being a high-cost, niche-market sector to one which can take advantage of commercially available products - thereby reducing cost and capitalizing on the abilities of COTS systems to provide scalable architectures and use open standards, thereby alleviating inter-operability issues.

Ethernet is one such COTS technology, which has been used in state-of-the-art FTI system designs, including on the Airbus A380 [2]. While offering all of the advantages of COTS equipment – such as ease of availability, attractive cost, well-defined maintenance and upgrade paths, Ethernet has some additional advantages over PCM. Firstly, the use of PCM for system data transmission implies a link between the acquisition of a parameter value and transmission of that parameter value in the PCM stream. Ethernet, on the other hand, transmits data as packets – and decouples the link between sampling of a parameter and transmission of that parameter. Furthermore, the maximum bitrates quoted for state-of-the-art PCM-based data acquisition systems are approximately 20Mbps today, while Ethernet supports 100Mbps and 1Gbps as standard, with 10Gbps Ethernet products also available.

This paper explores the differences between PCM and Ethernet based data acquisition system architectures, and presents a brief case study of the A380 FTI system.

2. CONSTRAINTS OF PCM SYSTEM ARCHITECTURES

2.1 DATA TRANSMISSION BY PCM

Traditional PCM systems have strict rules for the transmission of data through the data acquisition system itself. Consider a chain of DAUs, as illustrated in Figure 1.

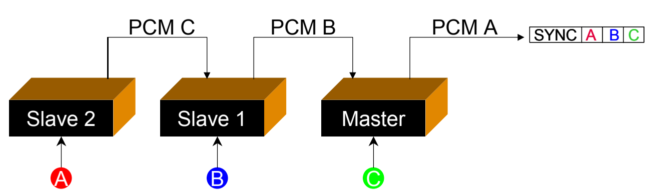

Figure 1

Three parameters A, B and C are sampled in Slave 2, Slave 1 and in the Master DAU, respectively. These three parameters are transmitted in a PCM stream from the Master DAU in real time. Consider the timing model of the three DAUs, as illustrated in Figure 2.

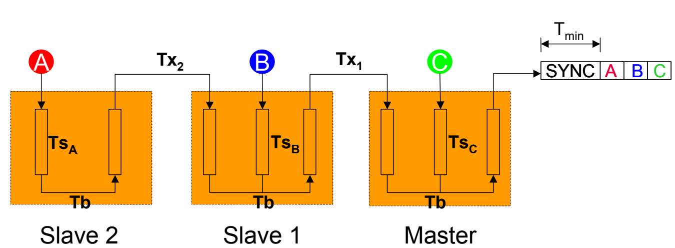

Figure 2

where:

Tmin = Earliest possible time which a parameter can be placed in a master PCM frame
Tb = Time required to transfer data across a chassis backplane

Tx_n	= Time required to transfer a parameter between two chassis
Ts_x	= Time required by sourcing constraints

From Figure 2, the earliest time which parameter A can be placed in the PCM frame shown is given in Equation 1.

(Equation 1) $$T \min \geq (Ts_A + Tb) + (Tb + Tx_2) + (Tx_1 + Tb)$$

Note that parameter A must be sourced from the acquisition module (hence the Ts_A term) in Slave 2, must pass through three system backplanes (hence 3 x Tb terms) and must be transmitted through two inter-chassis cables (hence the Tx_1 and Tx_2 terms).

To put some real-life figures to the above equation:

Tb	= 500ns (which is typical for a KAM-500 system)
Tx_1	= 70ns (10m of cable between slave 2 and slave 1 with 7ns per meter of delay in that cable)
Tx_2	= 70ns (10m of cable between slave 1 and the master chassis with 7ns per meter of delay in that cable)
Ts_A	= 10µs (determined by the convert delay of the ADC)

Hence,

(Equation 2) $$T \min \geq (10\mu s + 500ns) + (500ns + 70ns) + (70ns + 500ns)$$

(Equation 3) $$T \min(A) \geq 11.64\mu s$$

Note that if the master PCM bitrate is 5Mbs, that 11.64µs is equivalent to the time taken to transmit 59 bits from the start of the PCM frame out of the master chassis. By similar calculations, parameters B and C are limited to the following minimum placement times in the master PCM Frame:

(Equation 4) $$T \min(B) \geq 11.07\mu s$$

(Equation 5) $$T \min(C) \geq 10.5\mu s$$

which is equivalent to 56 bits and 53 bits after the start of PCM frame out of the master chassis, respectively. Thus, due to the requirement to transmit parameters A, B and C in a PCM frame, they are limited to the above placement restrictions in the PCM frame from the master chassis. These constraints apply to each occurrence of every parameter in the PCM frame, and in practice impose complex limitations on when parameters can be placed in PCM frames. These constraints become even more stringent with higher PCM bitrates.

Note that a star architecture instead of daisy chain will alleviate many of the difficulties detailed above, such as delay in transitting parameters through several chassis in series, in addition to delays in cabling between slave chassis. However, star architectures will still have timing constraints eminating from the time to transfer parameters through each slave chassis backplane

(Tb), the time to source a parameter from an acquisition unit (Ts_x) and the time to transmit a parameter between slave and master chassis (Tx_n).

2.2 WIRING COMPLEXITY IMPOSED BY PCM

State-of-the-art FTI designs often contain up to thousands of parameters from a diversity of locations throughout the aircraft [3]. This implies that up to several tens of DAUs are required to be networked together to meet the FTI requirements.

The need to network multiple PCM-based DAUs implies the challenge of design, installation and commissioning of the wiring necessary to achieve this. This wiring must provide scope for DAU reprogramming (where DAUs can be configured remotely via software), inter-DAU synchronization and inter-DAU transmission of data, as illustrated in Figure 3.

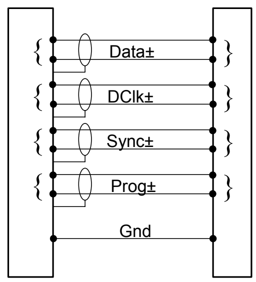

Figure 3

Thus, many PCM based systems use four shielded-twisted-pair (STP) connections between DAUs, along with a ground connection. Some PCM systems use up to 10 wires between chassis. Standards such as CAIS can alleviate such complexity by the use of a four wire interface which supports programming, synchronization and the transfer of data throughout the system [4]. In this respect, CAIS offers many advantages - however, CAIS bus operation (5Mbps max.) is slow by today's standards.

2.3 RS-422 BITRATE LIMITATIONS

The above wiring challenges are compounded by the limits of the RS-422/485 data transmission standard [5], which is the predominant data transmission protocol for the transmission of serial data over wire. RS-422 allows for approximately 1Mbps of error-free data transmission over a distance of 100m. Thus, relaying several tens of megabits of data per second around an aircraft, which is tens of meters in size, can be quite a challenge.

State-of-the-art PCM-based DAUs have typical maximum output bit-rates of 20Mbps [6]. Given that a compressed digital video stream or high bandwidth avionics data parameter may require several Mbps, the limit of 20Mbps means that FTI system designers frequently resort to using complex architectures in order to meet their FTI requirements.

2.4 COMPLEXITY AND LACK OF FLEXIBILITY

Given modern aircraft development and certification schedules, FTI engineers tend not to have time to engage in thousands of calculations like those presented above. Thus, suppliers of FTI DAUs abstract this complexity from the FTI designer, supplying software to schedule for data transfer through the distributed data acquisition system [6]. However, design and maintenance of this software is costly for the supplier and requires considerable effort to address the inherent complexities.

The inherent complexity of data transfer through a network of PCM based FTI DAUs also imposes a lack of flexibility to the FTI engineer, since changes of configuration often need to be re-processed by the DAU software – which can be an iterative process, based on modification of the system configuration according to system design rules.

2.5 DATA RECORDING INTERFACE

PCM is commonly used as a means of relaying FTI data to onboard storage systems such as tape, hard disk and solid state recorders. Due to the bitrate limitations of PCM based systems (≤ 20Mbps typically), many systems use multiple PCM streams to tape (or other) storage media in order to achieve the required system aggregate data storage rates. Such approaches typically complicate the replay and analysis of data, sometimes requiring data multiplexor/output reconstructor interfaces for data replay (such as ARM, ARMOR and mini-ARMOR units).

3. OVERVIEW OF ETHERNET

3.1 BACKGROUND

The term Ethernet implies network implementations that are compatible with the IEEE 802.3 standard. This standard covers the Physical and Data Link layers of a network implementation, as illustrated in Figure 4.

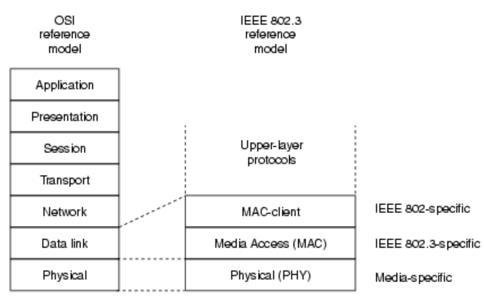

Figure 4

Since Ethernet network devices implement only the bottom two layers of the OSI protocol stack, they are typically implemented as interface cards/modules that plug into a host motherboard. The host device typically uses Upper Level protocols referred to in Figure 4 to control the higher-level flow of data between devices.

3.2 IP, TCP AND UDP

Since the arrival of the internet age, it is now widespread to use the Internet Protocol (IP) to provide a basic delivery mechanism for packets of data sent between devices linked by Ethernet connections, regardless of whether the systems are in the same room or even on different continents [7]. IP provides a "fire and forget" means of transmitting data from a source to a destination, under which data integrity is not guaranteed, nor is the order in which data packets are received at the destination device.

Internet-enabled devices use a combination of Transmission Control Protocol (TCP) and Internet Protocol (IP) to guarantee reception of error-free and correctly ordered data via an Ethernet link [7, 8]. However, although TCP provides higher transmission integrity, it requires large buffers to handle retries and timeouts, and this buffering introduces considerable uncertainty in message latency. This is clearly an undesirable characteristic for real-time data transfer where timely delivery of data is a priority.

Thus, in real time Ethernet systems, the User Datagram Protocol (UDP) is commonly used with IP to manage data transmission from source to destination [9]. UDP does not require much data buffering and does not provide for retransmission of poorly received data (though it does provide the ability to determine errors during the transmission using a checksum). Hence, UDP makes message latency more deterministic, in addition to using less bandwidth on the physical link - since it's a simpler protocol than TCP.

3.3 IENA – THE AIRBUS UDP PACKET STRUCTURE

Airbus use UDP over IP (as illustrated in Figure 5) to manage the transmission of FTI data from DAUs on the A380 to the onboard data storage units, RF data transmitters and onboard groundstations [2].

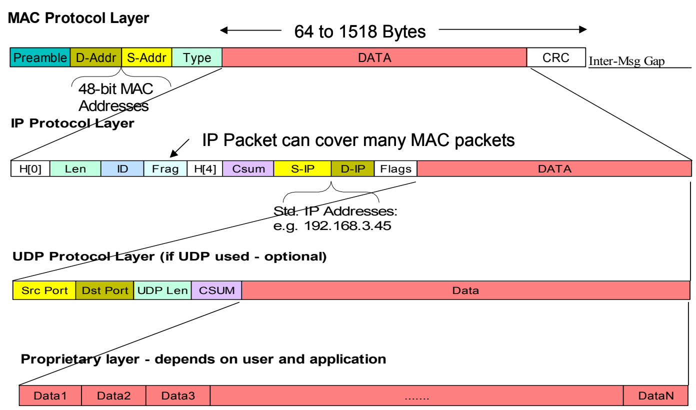

Figure 5

Airbus have developed a packet structure, called IENA [10], within UDP to carry the data on their UDP/IP network. This packet structure is illustrated in Figure 5. (Note that each word is a 16-bits).

KEY	SIZE	TIME	STATUS	SEQ_NUM	DATA	END
(1 word)	(1 word)	(3 words)	(1 word)	(1 word)	(1 to 65,527 words)	(1 word)

Figure 6

where:

Key = Unique identifier for each packet type
Size = Number of words in the packet, Key to End words inclusive
Time = Microseconds elapsed since 0h00 on the 1st Jan of current year
Status = Status value (Synchronous/Asynchronous)
Seq_Num = Packet counter (counts instances of packets of each key type)
Data = up to 65,527 data words (fixed per key)

End = End word (typically 0xDEAD)

4. ETHERNET DAUS

4.1 FEWER DATA TRANSMISSION RESTRICTIONS

The operation of the IENA packet structure over UDP/IP is significantly different to the operation of a PCM based data acquisition system. Since data is transmitted via Ethernet packets rather than in a PCM frame, the transmission of the data is fundamentally decoupled from the acquisition.

To illustrate this point, consider the system illustrated previously in Figure 1, but this time with an Ethernet output from the Master chassis instead of a PCM frame. Three Ethernet packets are created to carry data from parameters A, B and C, as shown in Figure 7.

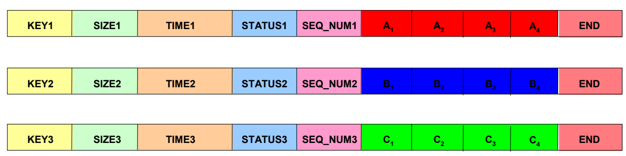

Figure 7

Firstly, since there are several samples of each parameter in the each packet, each packet is not transmitted until the last sample of each parameter is available. This contrasts with the PCM frame, in which each parameter is transmitted soon after it is sampled. This decoupling of data transmission from acquisition gives considerable relaxation to the timing restrictions of a PCM system, as described in §2.

As shown in Figure 8, parameter latency is still determined by the inherent ability of the data acquisition system to move data from the acquisition sources to the transmission device, as per a PCM system. However, instead of there being strict timing constraints for the immediate transfer of each sample of every parameter to the PCM frame, all that exists in the Ethernet frame is urgency to transfer the last sample in each Ethernet packet.

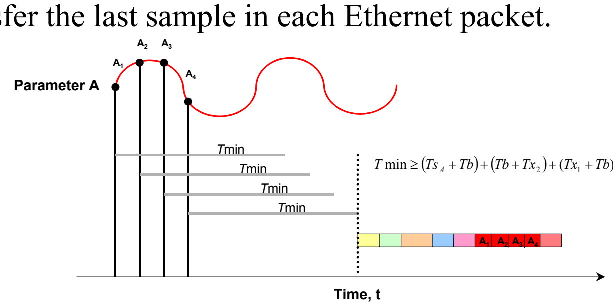

Figure 8

This freedom means that DAUs can proceed to sample data synchronously with the system clock, but are free to transmit their data at any time before the Ethernet packet is transmitted. Previous sample values may be buffered at the source, or buffered in the Ethernet module itself, helping to alleviate data scheduling bottlenecks in the data acquisition system.

This relaxation of timing constraints makes scheduling of data transfers in a complex system a much more manageable task, reducing the complexity for the FYI engineer and DAU supplier alike.

4.2 ETHERNET DAU WIRING IS SIMPLER

Since Ethernet is a full duplex protocol, the use of Ethernet means that DAUs can both transmit data and be reprogrammed/reconfigured via the same Ethernet interface. Thus, rather than having Data±, DClk± and Programming± connections to DAUs (3 x STPs), these can be replaced by one Ethernet cable (which contains 2 x STPs), as illustrated in Figure 9. Note that it may still be necessary to connect a synchronization signal between DAUs to maintain synchronous operation.

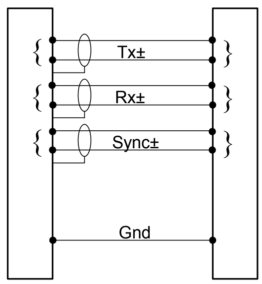

Figure 9

The limits of the RS422/485 data transmission standard do not apply to Ethernet (100Mbps and faster), since these provide for physical signalling rates of ≥100Mbps and over distances of 100m and greater [11]. This alleviates the limits imposed by the necessary wiring lengths and allows the FTI engineer more freedom to choose their desired sample rate throughout the aircraft, regardless of location of the DAU.

4.3 FLEXIBLE ARCHITECTURES WITH ETHERNET DAUS

The use of COTS Ethernet equipment such as switches gives the FTI designer freedom in their system architecture, since individual DAUs may connect directly to Ethernet buses via Ethernet Switches, rather than being connected in a daisy chain or star network with PCM links between DAUs, as illustrated in Figure 10.

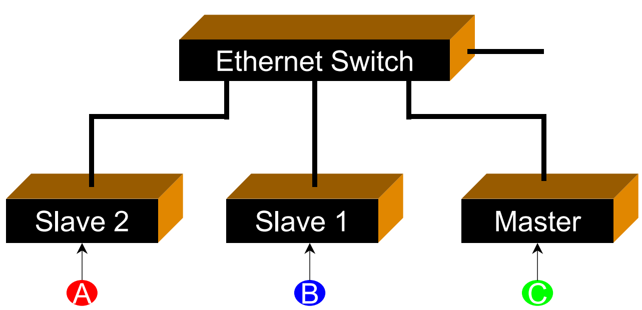

Figure 10

This allows the FTI engineer more freedom when designing for high bandwidth data sources, such as video streams or high bandwidth avionics bus parameters, than was possible using PCM based DAUs.

Ethernet based networks use switches to relay data from individual Ethernet devices. Using switches, it is possible to filter data between various Ethernet devices. For example, a switch can allow data from Slave 2 through to the Master DAU, but can block traffic from Slave 2 being passed to Slave 1. Thus, in this way, system architecture is largely reconfigurable via Ethernet switches rather than being hardwired in the aircraft installation. This has added benefits for maintenance and service.

4.4 HIGH RELIABILITY

Similar to RS-422/485, Ethernet is an established and well-proven physical interface, which has very high reliability. This reliability can be increased by the use of open source Network and Transport protocols, which can provide checks and guarantees for data integrity and delivery.

4.5 DATA RECORDING INTERFACE

Due to it's higher channel datarate capacity than PCM, Ethernet is now a common interface to onboard storage systems. Furthermore, since one Ethernet link (100Mbps or 1Gbps) can often handle the aggregate system data storage rate, the interface to and from the storage media can be greatly simplified. Instead of handling multiple channels of replayed PCM and possibly also additional hardware for output data multiplexing, Ethernet provides a means for a high capacity datastream to be replayed from a storage unit to a data analysis consumer. The use of COTS Ethernet switches facilitiates such applications, by simplifying system wiring.

5. CASE STUDY – THE AIRBUS A380

The Airbus A380 was the first large FTI program to use a fully Ethernet based data acquisition architecture [2], as illustrated in Figure 11.

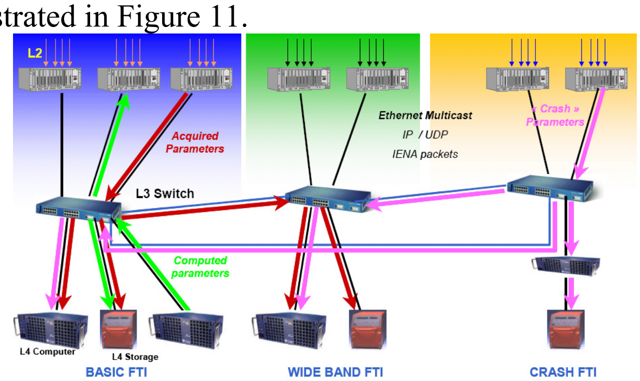

Figure 11

On the A380 aircraft, Basic, Wide-Band and Crash FTI Ethernet data streams were channelled into different Ethernet switches, and directed to specific mass storage, processing and telemetry devices (as appropriate to the type of data being transmitted). The A380 FTI system was designed according to the IENA standard, developed by Airbus [2]. The IENA standard is based upon a hierarchical structure, as summarized below:

> <u>Level 1:</u> Sensor Level. This is where each physical parameter being measured is converted into an electrical signal (i.e. voltage or current).

Level 2: Acquisition Level. This is where each electrical signal is conditioned, digitised, time-stamped, included into an Ethernet packet and transmitted on the Ethernet FTI bus.
Level 3: Concentration Level. This level is where Ethernet switches filter data and direct data to the appropriate receiving device.
Level 4: Recording and Analysis Level. This level covers data storage, analysis and transmission via RF.

Significantly, the use of Ethernet for the FTI network simplified the overall A380 wiring installation. FTI Ethernet devices used the same connectors and wiring standard as AFDX (ARINC 664) – the Ethernet based aircraft control bus [12]. As this was the first Ethernet based FTI system to be used by Airbus, the first A380 aircraft was installed with two identical Ethernet networks, providing a redundant path for data from DAUs as backup in case of problems on the main FTI bus [2].

The use of Ethernet based FTI systems provided Airbus with a 15-fold increase in system data capacity for standard FTI parameters (up to 512sps), and a 35-fold increase in data throughput capacity for wideband parameters (up to 2.5ksps).

6. CONCLUSIONS

The use of Ethernet based protocols for transmission of data from DAUs offers many advantages over traditional PCM. Whereas PCM is mainly a point-to-point protocol, with half-duplex operation, Ethernet is a full-duplex protocol which can support a wide range of freely-configurable architectures, from point to point through to complex star and bus based networks.
The use of PCM for data transmission imposes several constraints on the FTI engineer, since there are limitations on bitrates (due to cable lengths and RS-422 limitations), limitations on the placement of parameters in PCM frames (due to the time taken to transfer data through the network of PCM DAUs), in addition to a complex and expensive wiring design, installation and commissioning effort.

On the other hand, Ethernet supports considerably higher bit-rates than are possible with PCM (≥100Mbps as standard 'off the shelf') and gives far greater freedom in the data transmission – since transmission of parameters is decoupled from their acquisition. The use of Ethernet as the DAU interface simplifies the task of the FTI system designer, as DAUs from different vendors will support a common interface.

The use of Ethernet in data acquisition units is consistent with developments in other spheres of the FTI community, for example the iNet initiative [13] – which is pushing for data acquisition systems to provide more interactive features such as quality of service and data retransmission upon demand, features which are already available using Ethernet with higher level protocols.

The use of Ethernet implies upgrade paths to Gigabit data transfer and storage area networks, as the ability of DAUs to output data at these rates becomes available.

Finally, the use of Ethernet gives the FTI system designer a large degree of protection against system obsolescence – since Ethernet is a ubiquitous technology, with a clear evolutionary path as technology develops.

7. ACKNOWLEDGEMENTS

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9. GLOSSARY

AFDX: Avionics Full Duplex (ARINC 664)
CAIS: Common Airborne Instrumentation System
COTS: Commercial off the shelf
DAU: Data Acquisition Unit
FTI: Flight Test Instrumentation
IENA: Test Installation for New Aircraft
iNET: Integrated Nework Enhanced Telemetry
IP: Internet Protocol
LAN: Local Area Network
Mbps: Mega bits per second
OSI: Open Systems Interconnection
PCM: Pulse Coded Modulation
STP: Shielded Twisted Pair
TCP: Transmission Control Protocol
UDP: User Datagram Protocol