Fibre Channel is being implemented as an avionics communication architecture for a variety of new military aircraft and upgrades to existing aircraft. The Fibre Channel standard defines various network topologies and multiple data protocols.

This paper provides an overview of a Fibre Channel avionics network and protocols being used for avionics. The paper also discusses a practical implementation of avionics-level testing and testing challenges associated with these applications.
ABSTRACT

Fibre Channel is being implemented as an avionics communication architecture for a variety of new military aircraft and upgrades to existing aircraft. The Fibre Channel standard defines various network topologies and multiple data protocols. (Refer to the T11 website at www.t11.org.)

Some of the topologies and protocols (ASM, 1553, RDMA) are suited for avionics applications, where the movement of data between devices must take place in a deterministic fashion and needs to be delivered very reliably. All aircraft flight hardware must be tested to ensure that it will communicate information properly in the Fibre Channel network. The airframe manufacturer needs to test the integrated network to verify that all flight hardware is communicating properly. Continuous maintenance testing is required to ensure that all communication is deterministic and reliable.

This paper provides an overview of a Fibre Channel avionics network and protocols being used for avionics. This paper also discusses a practical implementation of avionics-level testing and testing challenges associated with these applications.
INTRODUCTION

New advanced avionics programs and applications have an increasing need for bandwidth while maintaining the traditional values of low latency, determinism, and reliability as hallmarks of military-avionics requirements. During the past decade, Fibre Channel has emerged as a winning solution from several competing technologies, for example, Scalable Coherent Interface (SCI), and Gigabit Ethernet. One characteristic that all competing technologies share with Fibre Channel is that they are all based on high-speed serial transmissions placed in routed switched architecture.

This “shared characteristic” places two important stress points on incumbent testing methodologies and strategies. First, the shear volume of the data makes it impossible to hold onto a practice of logging all data on the network so as to not miss something of importance for post-run or post-flight analysis. Secondly, in a switched topology there is no single tap point in the system where all the data may be seen. Equally important is the fact that since shared media transports have been abandoned for the increased system bandwidth offered by switched networks, there is no single link that can possibly contain all the network traffic.

Although relatively new to the avionics marketplace, Fibre Channel is already a high speed digital data bus for avionics. For example, it is already being implemented on major programs such as the F18, F16, E2C, B1B, and others. Although Fibre Channel is largely not understood, it must fulfill the military-avionics market requirements for speed, reliability, determinism, and fault tolerance. Speed, reliability, and determinism issues are relatively easy to address. However, fault tolerance turns out to be dependent on a combination of architectural issues, Upper Level Protocol (ULP) features, and Fibre Channel transport characteristics.

FIBRE CHANNEL BASICS

Fibre Channel is an accepted international standard. Within the American National Standards Institute (ANSI) is a group call the International Committee for Information Technology Standards (INCITS), which has a committee called the Fibre Channel Protocols Task Group (T11). Defining Fibre Channel is the responsibility of the T11 task group. The High Performance Parallel Interface (HIPPI) committee and the Fibre Distributed Data Interface (FDDI) committee are sister sub-committees to T11. In addition, the T11 committee works with the T10 committee on Small Computer System Interface (SCSI) issues.

This means that Fibre Channel is a Commercial-off-the-Shelf (COTS) technology enjoying all the benefits of a three to five billion dollar commercial marketplace referred to as the Storage Area Network (SAN) market. Although military-avionics requires special environmental packaging and support for deployed architectures greatly exceeds the eighteen months of the commercial marketplace, there are great benefits derived from a marketplace which tests, deploys, and supports the basic
technology. Even in the commercial marketplace, deployed Fibre Channel systems more closely match military-avionics systems because the commercial world greatly values the integrity of their core corporate data files and reliable access with ultra-high availability. Witness the Wall Street and banking industry requirements for Six Sigma availability and 100% reliability of data. The billions annually invested into this commercial marketplace accrue directly to the military-avionics market.

Fibre Channel was designed to be a communication protocol between host processors and secondary storage elements, like disk drives and tape drives. This means that Fibre Channel has been designed with all the real-time requirements of speed and reliability characteristic of the Input/Output (I/O) market and shared with the military-avionics market. Additionally, Fibre Channel has been designed with the concepts of connectivity and interoperability that mark the general networking marketplace. Finally, Fibre Channel has been designed to be a universal carrier of information. The result is that Fibre Channel has been crafted to easily map other protocols. The idea was to allow existing software written for legacy protocols to be easily ported to Fibre Channel. In fact, Fibre Channel does not have a native command set of its own. For an application to utilize Fibre Channel physical and logical transport layers, someone much map an existing command set to it, like SCSI or 1553, or invent one of their own like the Anonymous Subscriber Messaging (ASM) protocol used on some advanced avionics programs.

Fibre Channel is described in the standards as a stack of architectural levels. Although the stack pictured in Figure 1 illustrates seven levels, we will only briefly discuss four of them here.

**Figure 1 – Architectural Levels – Simple Node**

FC-0, the bottom level, describes the Physical Interface for Fibre Channel. This level specifically defines the speeds, transceivers, connectors, and cabling. Currently there are three baud rates shipping in commercial and military avionics Fibre Channel products: 1.0625 Gigabytes (GB), 2.125 GB, and 4.25 GB. These baud rates translate to duplex user data rates of 200 MBps, 400 MBps, and 800 MBps respectively.

Although the technology is called “Fibre Channel,” the physical media variants include copper along with long-wave and short-wave optics utilizing both single mode and multimode cabling. Fibre Channel systems are flexible enough that every physical link may be chosen based on that link’s requirements
and not on the presence of other media types elsewhere in the system.

The second level, FC-1, together with the FC-0 level, completes what the OSI 7-layer network architectural model describes as the “physical layer.” On the transmit side of a link, the FC-1 level prepares the data package to be sent by the FC-0 level. On the receive side of a link, the FC-1 level converts bit streams into recognizable data packages for FC-2 level processing. Responsibilities include serialization and de-serialization of the bit stream, encoding and decoding of eight-bit bytes into and from ten-bit transmission characters, as well as basic link initialization protocols like bit and word synchronization.

The FC-2 level describes how Fibre Channel manages the flow of information between two ports. This level was designed by the standards body to allow ease of mapping to ULPs through an intermediate mapping level, FC-4.

Fibre Channel supports three pure topologies – point-to-point, arbitrated loop, and switched fabric (as illustrated in Figure 2) – and one hybrid. The hybrid topology supported is arbitrated loops attached to switch ports. Note that in all topologies, a Fibre Channel port’s transmitter is only ever physically attached to one other port’s receiver. This simplification of the link allows for highly-reliable transmissions lowering the system error rate even in ultra-high-speed links to acceptably low rates.

Figure 2 – Fibre Channel Basic Topologies

A simple solution for higher availability and greater fault tolerance using any of these topologies is to have redundant physical ports on a node attach to redundant topologies.

For example, Figure 3 depicts a single node with four Fibre Channel physical port connections. Two of the connections can be to two redundant switches and two can be tied into two redundant arbitrated loops. This would be a very fault tolerant system.

Figure 3 – Fault Tolerant Node

The figure also illustrates that a single physical Fibre Channel link is comprised of two independent fibers: a dedicated transmit and a dedicated receive. This means that the protocol is full-duplex capable of receiving and transmitting concurrently. In fact, in a switched
topology, a port can be receiving data from a source port while sending data to a completely different destination port.

To the attached Fibre Channel ports – called N_Ports or Node-Ports – the switched fabric looks like a cloud that handles all destination routing. This can be seen in Figure 4. The N_Port is uninvolved in the process of routing since packets of data, called Frames, are routed on a network assigned address.

Figure 4 – Fabric Cloud

Figure 5 illustrates the Fibre Channel data hierarchy. A ULP command represents an operation. For example, a 1553 Remote Terminal (RT) to Bus Controller (BC) transfer command represents an operation comprised of several movements of data, beginning with the BC sending a command to the RT. Then the RT sends a status message to the BC followed closely by the RT sending the data to the BC. In Fibre Channel this operation is called an exchange. The importance of this is that exchanges are Fibre Channel’s mechanism for mapping half-duplex protocols like 1553, SCSI, and others to what is inherently a full-duplex capable architecture.

The individual movements of data like 1553 commands, status, and data – which from the ULP’s point of view are typically called information units – are represented in Fibre Channel by sequences. Exchanges are comprised of one to many sequences. Sequences are comprised of one to many Fibre Channel frames. The maximum Fibre Channel frame size is limited to 2,148 bytes, where 2,112 bytes are user-defined data. If the information unit to be transferred is larger than 2,112 bytes, the sequence must be comprised on more than one Fibre Channel frame. Finally, frames are comprised of transmission words and transmission words are comprised of four transmission characters. Each transmission character is ten bits; Fibre Channel utilizes an eight-bit to ten-bit transmission encoding.

Another valuable Fibre Channel feature relates to user classes of service that Fibre Channel offers. There are four user classes of service defined in Fibre Channel; however, only Class 2 and Class 3 are widely deployed. Classes of service relate to the Quality of Service (QoS) with which data is sent across the media. QoS features include guaranteed bandwidth, guaranteed latency,
acknowledged delivery, notification of non-delivery, end-to-end flow control, and guaranteed in-order delivery of frames within a sequence.

Class 3 is the dominant user-class of service deployed in both the commercial and military-avionics markets. It is a best effort packet-switched service that resembles a datagram service with no attendant QoS features. Class 2 has been implemented by some vendors of Fibre Channel hardware with a view to the future. It also is a packet-switched services, but it has end-to-end flow control with acknowledged delivery and notification of non-delivery. It does not guarantee bandwidth or latency of messages.

To learn more about Fibre Channel or to become an expert, you can obtain the appropriate ANSI Standards from Techstreet in Ann Arbor, Michigan. You can contact Techstreet by email at techstreet.service@thomson.com, or by calling (800) 699-9277. Draft versions of the standards are available for download from the T11 website at www.t11.org/index.html.

OVERVIEW OF A FIBRE CHANNEL AVIONICS NETWORK

Figure 6 illustrates one possible avionics architecture. Redundancy for fault tolerance and high-availability is secured by each node containing three ports. One port attached directly to a Fibre Channel switch and the other two ports attach to Fibre Channel arbitrated loops connected in reverse directions. With this configuration, a switch port fails, then the loops (which are independently connected) will support the avionics traffic. Even if one loop fails, the other loop is present.

Figure 6 – Fibre Channel Avionics Architecture

Loop topologies are inherently lacking in fault tolerance because the failure of a single port can cause the entire loop to become inoperable. In commercial as well as military implementations, Fibre Channel loop ports may be made fault tolerant by connecting them with bypass elements that allow a failed port to be bypassed.

POPULAR AVIONICS PROTOCOLS

Within the T11 Fibre Channel Standards group is a technical committee dedicated to the definition of profiles for the military-avionics community. Three of the profiles published to date include a mapping of the 1553 Command Set to Fibre Channel, a totally new protocol called Anonymous Subscriber Messaging (ASM), and Remote Direct Memory Access (RDMA), which is a SCSI light protocol.

One way for those already familiar with a legacy protocol like 1553 to think about this is to mentally separate the command set from the means of the
transport. Features deemed beneficial for their deterministic or fault tolerant value may be mapped to Fibre Channel with dynamic equivalents. For example, the timeout for an RT to respond to a BC command – although not functionally necessary when implemented in Fibre Channel – can be implemented. Mapping the 1553 bus command set to Fibre Channel has some instant benefits including much larger message sizes, orders of magnitude more bandwidth, orders of magnitude more allowed network/bus connections, and even allowances for multiple active bus controllers.

Also, 1553 bus features like BC timeouts on responses to commands from RTs are not necessary to carry over to Fibre Channel. In a similar manner, the limitations of the 1553 bus, like allowing only one active BC at a time and the small message sizes of 1553, do not need to be carried over to Fibre Channel.

Once again, the fault tolerance of a system is derived from a combination of the architecture, the topology, they physical transport protocol, and the application protocol. For example, a loop topology guarantees in-order delivery by virtue of its single path for all frames. In a complex switch topology where multiple paths are possible, the topology does not guarantee in-order delivery; in-order delivery of frames must be handled by other means, such as a routing protocol.

**Figure 7 – Example 1553 BC-RT Operation**

Figures 7 and 8 are ladder diagrams that illustrate two common 1553 commands as Fibre Channel exchanges. Generally, the industry uses Class 3, which is the unacknowledged datagram service. Since Class 3 is a best effort delivery, there is no indication provided by the Fibre Channel transport that a frame has been lost. In time, the RT will send a status sequence in response to the received data sequence.

**Figure 8 – Example 1553 RT-BC Operation**

The 1553 command set is a self-acknowledging protocol from the ULP level. Since the ULP level is higher up on the protocol stack than the network
transport level, it is a more reliable means of acknowledgment than if Fibre Channel Class 2 service was used and the network sent an acknowledgment frame for every frame received. If the BC does not receive the status sequence from the RT, then it can choose some recovery mechanism.

Addressing determinism in a switched fabric is difficult. Critics point out that with any number of random messages from different sources headed to the same destination port will result in network traffic congestion. The fallout of unknown traffic congestion is all bad. Periodic messages will arrive in time and perhaps not at all.

The traditional MIL-STD-1553 bus solved this problem by virtue of its half-duplex nature. Only one message was active on the system at a time and each message was scheduled by the BC. One way to solve the problem on a full-duplex switched fabric system like Fibre Channel is to allow only one network controller to schedule all the traffic. Then if the switch is a non-blocking switch, it should be an easy matter for the network controller to ensure that no two network terminals send messages to the same destination at the same time. In this way, the value of the switched fabric allowing many messages to flow in a full-duplex fashion is preserved, making more efficient use of system bandwidth while at the same time providing determinism in message traffic with very low jitter.

Figure 9 illustrates the ASM protocol that was invented for use of modern avionics programs. It is a very simple Producer-Consumer paradigm. The idea is that avionics applications are designed to be run at periodic rates. Applications, by design, expect to consume certain data elements at well-known periodic rates. They will also generate data elements at well-known rates. These applications do not need to be instructed by a master controller when to consume and generate data; they will do it by design. Also inherent in the design is that both the producers of data and the consumers of data are anonymous. As Figure 9 illustrates, the ASM exchange is a very simple single sequence.

Figure 9 – Example ASM Exchange

Figure 10 illustrates the RDMA protocol. RDMA is really exactly like the commercial SCSI Fibre Channel protocol with only slight modifications to enable low latency transfers. In terms of fault tolerance and determinism, the protocol is similar to the 1553 mapping to Fibre Channel already discussed.

Figure 10 – Example RDMA Protocol

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TESTING CHALLENGES

Avionics systems designed around Fibre Channel present some new challenges to those tasked with maintaining, testing, and validation. For 1553 bus testing, it is not uncommon to log all network traffic. Consider carrying that practice over to a Fibre Channel-based system. A single Fibre Channel link operating at 1.0625 Gbps will generate 200 MBps of data. To log one hour of traffic amounts to collecting and storing just under seven TB of data. Further complicating the situation is that Fibre Channel topologies are not shared in the sense of offering a single point in the system where all traffic may be monitored. So in a typical avionics system utilizing a 24 port switch, there are 24 links to monitor, meaning the total system data capability is just under 168 TB of information in one hour.

Another challenge is the notion that testing and instrumentation should be completely unobtrusive. Unobtrusiveness is achievable in 1553 systems designed around multi-drop buses; but in fibre optic systems with point-to-point and switched fabric topologies it is not possible. There are three options for tapping into a Fibre Channel switched fabric topology:

1. You can optically tap into a fibre optic link at the cost of power to the destination.
2. You can schedule traffic to be routed to a test system, but this means the test system is no longer in-line with the destination.
3. You can insert an instrument between the source and destination on a link causing the data to the destination to be delayed and retimed.

TESTING STRATEGIES

There are three basic types of test instrument apparatus useful in testing Fibre Channel systems: two-channel pass-through protocol analyzers, data or pattern generators, or emulators.

The two-channel pass-through protocol analyzer is useful in debugging the correctness of the Fibre Channel transport protocol on the physical links as well as assisting in debugging the user applications running on the link. It can also be used to stream data to secondary storage for post run analysis.

Data or pattern generators are used to stimulate avionics modules under test. A pattern generator should be able to stress the link’s ability to handle data, send legal and illegal user application data, and perform illegal Fibre Channel

Figure 10 – Example RDMA Read Operation
operations. Since avionics systems have a large component of periodic data, it would be useful if the data generator had the ability to schedule periodic data transfers.

Building onto the data generator the ability to respond to link inputs in real-time makes a useful tool for hosting applications under test or for emulating systems to other Devices-Under-Test (DUT). In short, this “emulator” can provide a complete, flexible lab environment in which to stimulate and test a DUT.

AIT is the leading supplier of Fibre Channel testers for military-avionics market. Our PCI Fibre Channel tester card, APG-FC2/4, meets and exceeds all the requirements for each of the three test apparatus.
REFERENCES