Network Technologies Investigation NASA/GSFC High Speed Fiber Optics Test Bed

4 October 1998

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1 Introduction

1. Purpose

The need for higher speed (>1Gb/s) communication on spacecraft data networks is increasing. Instruments involving large array CCDs which generate pixel-per-bit data are capable of generating 10e7-10e8 Mbit/sec data streams. Simultaneously, other instruments are generating lower data rates capable of being transmitted over conventional wiring media. The ability to use wideband optical media capable of integrating the data and command transmission requirements for the entire spacecraft databus, could provide advantages in weight, power, signal routing, reliability and overall spacecraft/payload interface design.

Generally, spacecraft have utilized low speed interfaces such as RS-422, MIL-STD-1553 or MIL-STD-1773 for data communications. These basic systems are usually limited to bandwidths of 1 Mbps or less. Recent advancements in network technologies have dramatically increased available bandwidth for data communications; newer technologies can scale up to 2 Gbps and more. These improvements have a significant impact on the High-Speed Fiber Optics Test Bed (HSFOTB) architecture in terms of performance and cost. The HSFOTB network design will utilize new technology and provide for an easy migration path to faster data rates as technology matures.

The purpose of this investigation is fourfold:

1. Present an overview of the selected network technologies
2. Compare and contrast the capabilities of each
3. Assess the general requirements of a network of payload instruments capable of transmitting Gb/s data rates; either aggregate data rate or individual data rates.
4. Make recommendations for the elements of the HSFOTB architecture

1. General Requirements

Ground-based commercial fiber optic networks have existed for some time. These networks provide reliable connector-based and connector-less data transmission for a large number of users with heterogeneous (voice, data, video, high speed, low speed, etc.) data streams. The requirements for a spacecraft network system differ significantly from those of a commercial network. Table 1 below highlights the key differences.

Table 1

Category	Ground, commercial	Space, science

Cost	Cost dictated by revenue stream and business model. Ability to make in-situ upgrades to capabilities is important	No revenue stream. Science data needs are paramount. Design re-usability important. Initial design costs, manufacturing costs and availability of space qualified parts are drivers
Quality of Service	Function of competitive environment and customer ability to pay. Packet losses, loss of service and outage times are major factors which at times may be tolerated by the customer	Function of science and mission priorities. Data loss is not tolerable. Overall end-to-end reliability and availability are main factors.
Data	Voice, data, video. Classes of variable bit rate data. Traffic prioritization and bandwidth management are key factors.	No voice. Fixed number of users with fixed data rate requirements. Serial data from RS-422 type interfaces required. Available bandwidth will have margin over worst case traffic load.
Media and protocol	Mixed media and protocols. ATM, Ethernet, FDDI, Fiber Channel, etc. may be accommodated.	Connection-oriented, fiber network with a single protocol is possible.

Based upon these generalizations, the following top-level requirements for a high-speed fiber optic test bed for space applications can be defined.

a. A connection-oriented network consisting of a small number of nodes and switches.
b. Fixed traffic priorities with constant bit rate data.
c. Full duplex operation for data acknowledgement, retransmit and status
d. Local Area Network type operation
e. High priorities on low-error rate and high-speed data transfer
f. Low priority on bandwidth utilization and traffic management
g. End-to-end fiber solution
h. High priority on hardware modularity and low power

1.3 Technologies Covered

This paper covers four network protocols: (1) ATM, (2) Fibre Channel, (3) Gigabit Ethernet, and (4) FDDI as candidate technologies for onboard data communications. An overview of each protocol is presented, including protocol architecture and services provided by each. While technical details are presented, this paper is not intended as a tutorial in the technologies covered, nor is this paper intended to be an exhaustive survey of available network technologies. The identified protocols were selected based on two simple criteria; support of gigabit bandwidths and commercial availability.

Recommended sources describing industry standards include the Internet Engineering Task Force (IETF) Request For Comments (RFC) documents, and the various IETF working group drafts. The interested reader is referred to the appropriate sources listed in the bibliography for further information.

1.4 Executive Summary

This study recommends ATM over Fibre Channel as the network technology for the High Speed Bus. This conclusion is based on several factors. ATM can scale to gigabit speeds, supports a variety of interfaces (fiber optic as well as twisted pair), and can operate in both local and wide area networks. Moreover, ATM has been successfully tested over satellite links. While still relatively new, ATM is a proven technology, with many commercial vendors, thus enabling lower development costs. Fibre Channel provides a flexible network topology capable of supporting both ATM and other networking approaches. This flexibility will prove useful in evaluating competing network approaches.

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3. Fibre Channel

The Fibre Channel (FC) specification is another set of standards being developed by ANSI and is intended to provide high-speed, inexpensive data transfer between all levels of computers and/or storage devices and other peripherals. [21]

Early efforts started with the Fibre Channel Systems Initiative (FCSI), a joint program supported by HP, IBM, and Sun. The FCSI is a closed organization, focused on interoperability between the three members' products. In 1993, the Fibre Channel Association (FCA), now a consortium of over 80 organizations was formed. The FCA is an open organization, with the objective of providing a forum for system integrators, manufacturers, etc. who develop FC products, and to complement the activities of the ANSI X3T11 committee which is developing the FC standards. At the Fall '95 InterOp conference, FCSI announced that it had finished its charter and would dissolve, leaving the advancement of Fibre Channel technology to the FCA.

Another organization, the Fibre Channel Loop Community (FCLC) is a smaller group focused on the use of Fibre Channel Arbitrated Loop (FC-AL) technology, one of the three topologies the Fibre Channel supports. The primary users of FC-AL are peripheral storage manufacturers.

3.1 Fibre Channel Overview

Fibre Channel (FC) defines a high-speed protocol originally intended for superworkstations, large array storage media and high performance desktop applications. It has found application usage in applications originally built using the SCSI (Small Computer System Interface) standard. Fibre Channel supports multiple data rates up to 4 Gb/s, in switched and shared architectures, in connection-oriented and connection-less modes. The physical media of FC will support ATM.

Data communications may be categorized into two types; channels and networks. Channels are point-to-point links between communicating devices. Channels operate at hardware speeds, with minimal software overhead, and interconnect only a small number of devices over short distances [22]. Examples of channel data communications include both SCSI and HiPPI.

Networks, on the other hand, provide low to moderate speed connections. Networks interconnect many devices, some of which may be physically distributed over long distances. While networks have a higher software overhead, they are more flexible in supporting a variety of applications.

Basically, channels are hardware intensive while networks are software intensive. Channels are simple, provide higher performance and guaranteed delivery, whereas networks are more flexible at the cost of lower throughput. Fibre Channel combines the desirable attributes of each. [23]

3.1.1 Fibre Channel Architecture

Fibre Channel provides a high-speed serial link and supports higher level protocols such as SCSI, HiPPI, ATM, and IP. Figure FC-1 illustrates the Fibre Channel protocol architecture. There are five layers, FC0 - FC4, which are briefly covered below. The first three layers are specified in the FC-PH document. [21]

Figure FC-1.

Fibre Channel Layers

Fiber Channel can support both high-speed I/O block transfers and packet-oriented network protocols.

3.1.1.1 FC-0 Layer

FC-0 specifies the physical characteristics of the interface and media, including cables, connectors, transmitters/receivers etc. Currently, there are products available for the 133 Mbaud rate, up to the 1 Gbaud speed. The higher rates have been approved as standards, however no products are available yet. Copper media (coax and twisted pair) is also supported for limited distances.

3.1.1.2 FC-1 Layer

FC-1 defines the 8B/10B encoding/decoding scheme. FC transmits 10 bits for every 8 data bits. Therefore the actual *data* rate is approximately 25% less (i.e. 100 Mbps data rate with the 133 Mbps signaling rate). IBM, which gives a royalty-free license for its use, has patented the 8B/10B encoding scheme.

3.1.1.3 FC-2 Layer

FC-2 is the core of the Fibre Channel specifications and serves as the transport mechanism of Fibre Channel. FC-2 defines the framing structure for Fibre Channel frames, the signaling protocol, the flow control, as well as the service classes that Fibre Channel supports. To support all these functions, FC-2 defines several message formats: Ordered Set, Frame, Sequence, and Exchange. The Fibre Channel service classes are discussed in the next subsection.

3.1.1.4 FC-3 Layer

FC-3 defines common services necessary for the higher level capabilities. While the FC-2 layer deals with individual N_Ports, the FC-3 layer covers functions that span multiple N_Ports. Among the advanced features envisioned are:

(1) Striping across multiple FC ports to transmit data in parallel (i.e. inverse multiplexing)

(2) Hunt groups to associate multiple ports with the same address (to improve efficiency in networks with centralized servers)

(3) Multicasting support across a fabric

3.1.1.5 FC-4 Layer

FC-4 defines the upper layer protocol mapping to the Fibre Channel services. The FC-4 layer is analogous to the ATM SSCS layer. Each mapping is called a "protocol profile" and provides guidelines for implementing a specific protocol over Fibre Channel. Several protocol profiles are defined including SCSI, IPI-3, HiPPI, and IEEE 802.2 LLC for legacy LAN data.

3.1.2 Fibre Channel Topologies

Fibre Channel supports three topologies, point-to-point, arbitrated loop, and switched. All three topologies are fully interoperable, so the topology is transparent to the attached devices. Figure FC-3 illustrates the three topologies.

Figure FC-3

Fibre Channel Topologies

In Fibre Channel parlance, the switch topology defines a Fabric that interconnects each end-station. Switch ports are called Fabric or F_Ports, while end-station ports are referred to as Node or N_Ports. Ports in the loop topology are generically called L_Ports. Loop ports are further distinguish by whether the device is a node or fabric port. (FL_Port/NL_Port)

Both point-to-point and loop topologies require all nodes communicate at the same data rate. However, with a fabric topology, dynamic rate conversion is supported, so that a 266 Mbps device could communicate with a 1.062 Gbps device.

3.1.3 Fibre Channel Classes

Presently, Fibre Channel supports three classes of services, and a fourth which is a combination of classes 1 and 2. (Additional classes are specified in FC-PH enhancement proposals) Much like the service classes supported by ATM, these different classes allow Fibre Channel to support a variety of communication needs. [23]

3.1.3.1 Class 1

The FC Class 1 service, analogous to ATM Class A, provides a circuit-emulation service for time-sensitive applications such as video teleconferencing. Class 1 service is designed for dedicated, non-bursty links between supercomputers. Class 1 traffic is circuit-switched.

3.1.3.2 Class 2

The FC Class 2 service provides guaranteed delivery for connectionless traffic. Class 2 traffic is switched on each frame rather than on a connection. An acknowledgment from the destination provides an end-to-end guarantee of delivery. There is no corresponding ATM class since ATM does not guarantee delivery.

3.1.3.3 Class 3

The FC Class 3 service offers a best-effort connectionless service. Class 3 is similar to Class 2, except that no guarantee is given for delivery. Class 3 service is closest to ATM Class Y service, which is also a non-guaranteed, connectionless service with flow control mechanisms.

3.1.3.4 Intermix Class

The FC Intermix class is a combination of Class 1 and Class 2 services. Intermix reserves the full bandwidth of a dedicated connection, but also allows connectionless traffic within the fabric to share the link while the Class 1 connection is idle.

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4 Gigabit Ethernet

Not to be outdone by ATM or Fibre Channel, Ethernet aficionados are pushing Ethernet to even higher speeds. Ethernet originally ran at 10 Mbps. The 100Base-T and 100VG-AnyLAN Ethernet standards run at 100 Mbps. The Gigabit Ethernet Alliance is an industry consortium that has developed the specifications for Gigabit Ethernet, working closely with the Institute for Electrical and Electronic Engineers (IEEE) which formed a working group, 802.3z to develop the Gigabit Ethernet standard. In June 1998, the IEEE 802.3z working group approved the Gigabit Ethernet standard.

Gigabit Ethernet uses the same 802.3 frame format, and access protocol (Carrier Sense, Multiple Access with Collision Detection, CSMA/CD) to remain backwards compatible with standard 10 Mbps and 100 Mbps Ethernet. The packet format is variable length (64-1514 byte) packets, unlike ATM, which uses a fixed length cell.

The Gigabit Ethernet CSMA/CD algorithm has been improved so operation at gigabit speeds is possible. Otherwise, minimum sized Ethernet packets could complete transmission before the sending stations sees a collision, which violates the CSMA/CD rules. Basically, the CSMA/CD extensions have increased the carrier time, from 64 bytes to 512 bytes. For frames smaller than 512 bytes, the carrier signal is extended to assure that only one small frame at a time can be on the shared wire. Like 100 Mbps Ethernet switches, both full and half-duplex operation is supported. In non-switched devices, (e.g. hubs) the media is shared, so half-duplex mode must be used. Full-duplex devices will continue to use the regular 96-bit interframe gap and 64-byte minimum packet size.

The 802.3z working group has drawn heavily on the Fibre Channel specification FC-0 and FC-1 for the physical layer. This permits the same integrated circuits to be utilized for lower cost and quicker time to market. Initial products will use fiber for connectivity. Work is still in progress to define support for twisted pair cabling.

Typical Ethernet networks have throughput of approximately 70% of the wire speed. Early simulations of Gigabit Ethernet show improvement over 100 Mbps Ethernet by an order of magnitude [24]. Other advantages as well as disadvantages of the Gigabit Ethernet specifications are listed below.

Advantages:

- same frame format as 10/100 Mbps standards
- full duplex with switching devices (802.x standard)
- backwards compatible in shared mode using carrier extension
- extension of a well understood, well characterized network approach.
- LAN oriented
- wide range of hardware and software available
- Highly modular hardware approach.

Disadvantages:

- Products are not yet available
- Gateway device necessary to interface to wide area link protocol
- Ethernet does not support time-sensitive data

Because of the large installed base, costs are expected to be lower than competing technologies such as ATM or Fibre Channel. The primary disadvantages are due to the immaturity of the technology, though that will of course change with time.

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5 Comparison Analysis of ATM, Fibre Channel, Gigabit Ethernet

Figure Comp-1 illustrates a communication technology tree, which categorizes the various data communication standards. The diagram gives an overall view of where the technologies discussed in this paper relate to each other as well as other data communication standards. The classification of Fibre Channel is somewhat arbitrary since it also supports LAN environments.

Figure Comp-1.

Data Communications Technology Tree (note 4)

5.1 Bandwidth

Typical Ethernet networks have throughput of approximately 70% of the wire speed. Early simulations of Gigabit Ethernet show improvement over 100 Mbps Ethernet by an order of magnitude. The Gigabit Alliance claims that with full-duplex operation, close to the theoretical limit of 2 Gbps will be achieved [24].

Currently the fastest ATM products available run at the OC-48 rate of 2.48 Gbps. Fore Systems offers a OC-48c switch module on their ASX-4000 switch.

The fastest Fibre Channel products available now run at 800 Mbps (1.062 Gbaud). ANSI has approved the 2.134 Gbaud and 4.25 Gbaud standards in 1995, however the optic technology is still immature. The 2 Gbps products are becoming available now, but the 4 Gbps products will be a few more years until available.

If higher layer protocols are employed, the actual data throughput will be significantly less and latencies higher than the raw speeds given in Table Comp-1. The difference is primarily due to protocol overhead in moving data from the application to the wire, and the efficiency of the host network adapter.

In particular, TCP/IP traffic over a wide area, T3 (45 Mbps) ATM link may be as low as 2 Mbps [25]. Actual performance is dependent on the system in use. Therefore each system should undergo benchmarking tasks to obtain realistic performance statistics

	ATM	Fibre Channel	Gigabit Ethernet
Bandwidth	1.5 M - 2.48 G	100 M - 4 G	1 G
Latency	100+ usec (est.)	10-30 usec	N.A.
Cost per switch port	$1000 and higher	$1500 and higher	$1800-2800
Cost per adapter	$500-$3000	$1200-$3000	N.A.
Topologies	pt-pt switch	pt-pt switch loop	pt-pt switch
Connectivity	serial simplex	serial duplex	serial half/full duplex
Maximum distance	unlimited	100 m STP 10 km SM fiber	100 m UTP 5 km SM fiber
Maturity	third generation	second generation	emerging
Products/application	switches, routers, frame buffers	switches, routers, frame buffers, mass storage i/f	switches, buffered repeaters

Table Comp-1

Network Comparison Chart

5.2 Latency

Because Fibre Channel can also support dedicated channels, it can provide low delay links for large data transfers. Comparatively, ATM has much higher latencies, on the order of hundreds of microseconds. Note, the measured latency is highly dependent on the size of the transfer. A University of Minnesota study reported similar latencies (500 usec) for ATM and Fibre Channel when transferring only 4 Kbytes [26]. Latencies for Gigabit Ethernet were unavailable at the time of this writing.

5.3 Ability to Scale

5.4 Error Detection/Recovery

ATM provides single bit error correction over the cell header, and only error detection over the payload. It is up to the higher layer protocols to handle error correction for multiple bit errors or payload errors. Fibre Channel provides error correction as an option. Applications may request Class 2 service, which provides guaranteed delivery. For Ethernet, error detection is defined in the CSMA/CD algorithm. The sending station re-transmits upon detecting a collision.

5.5 Multicasting/Broadcasting

Traditional IP multicasting may also be done over ATM using LAN Emulation (LANE). The IETF has published several RFCs on multicast support over ATM using Classical IP. Fibre Channel supports multicasting within its switched topology. The FC-3 Fibre Channel layer provides the capability to send a single transmission to all or a subset of N_ports. The FC Class 3 service (unconfirmed datagram service) is used for multicasting. Broadcast is inherently supported in Ethernet, since it is a shared medium.

5.6 Traffic Management

The ATM Forum published the Traffic Management version 4.0 specification April 1996, which defined many of the necessary parameters and algorithms for traffic management. These include the QoS parameters for each class of service, traffic contract specification and conformance, and functions such as connection admission control.

The FCA has not addressed traffic management in as much detail. Fibre Channel simply returns a "Busy" frame when congestion is encountered, providing a sliding window flow control mechanism.

Ethernet does not provide any traffic management services.

NOTES:

4. Original diagram from "Networks and their Architectures", C. Smythe, Electronics & Communication Engineering Journal, Feb. 1991 pp. 18-28. The original version was modified to include channel technologies.

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7 Summary

Direct comparisons are always difficult since the different technologies often focus on different niche markets. Early ATM development was based on the B-ISDN standards and was intended as a wide area network protocol. Fibre Channel supports both peripheral communications and isochronous applications such as video. Both of these technologies have evolved to encompass switched local area networks.

ATM is flexible, provides an easy interface between local and wide area networks, and there is significant support for ATM in the marketplace. However, ATM is also very complex, and the standards are incomplete. Fibre Channel is versatile, and supports almost every application. However, Fibre Channel is very complex and the standards and available products are not as mature.

In the battle for the desktop network interface, there will not be a clear winner. ATM will not be ubiquitous, given that not all applications require such capabilities, and there will continue to be cheaper alternatives, i.e. Ethernet. Between the technologies covered in this report, Ethernet will have the largest share of the market, followed by ATM. Fibre Channel will have a niche market. Fibre Channel is becoming the next generation interface for mass storage systems. Fibre Channel is also utilized as a physical layer for other technologies (e.g. Gigabit Ethernet).

This paper has presented a technical overview of several network technologies for possible use in the HSFOTB program, including ATM, Fibre Channel, and Gigabit Ethernet. While each technology has both advantages and disadvantages, the recommended technology is ATM over Fibre Channel. This conclusion is based upon several factors:

1. ATM can scale to gigabit speeds.
2. ATM Supports a variety of interfaces (fiber optic as well as twisted pair).
3. ATM can operate in both local and wide area networks.
4. ATM has been proven to operate over satellite links
5. The anticipated development costs are lower for ATM due to its wide commercial availability.
6. Fibre Channel provides for a LAN topology that is easily adaptable to the spacecraft environment.
7. Fibre Channel provides the best solution for gigabit speed transfer of large data sets (50-150Mb).

Neither Fibre Channel by itself nor Gigabit Ethernet are designed for wide area communications such as satellite links and therefore would require a gateway (e.g. CSU/DSU) to interface between the on-board LAN and the downlink. If ATM is used as the downlink, no gateway device is required, thus providing seamless integration between the on-board network and the ground segment. However, the issue of integrating the data downlink into a WAN beyond the spacecraft is beyond the scope of the current effort.

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