

General Requirements for WDM Backbone Networks

RATIONALE

It is desirable to architect a new standard Wavelength Division Multiplexed (WDM) fiber optic network architecture for aerospace platforms that will not only supplement current aircraft system, but can enable replacement of applicable legacy interconnects to maximize the benefits of fiber optic network technology and revolutionize networking in aerospace platforms through the use of a flexible, scalable and high capacity networking infrastructure. One of the objectives of a WDM-based solution is to enable migrating these legacy communications needs over to a lighter weight, optically multiplexed WDM network. In this manner, the weight of the typically heavy electrical cable harnesses can be eliminated, justifying the introduction of optical communications, while enabling new applications that can be supported by the available optical fiber bandwidth. This document describes network interfaces and requirements a WDM Optical Backbone network (WDM OBN), a transparent optical network which contains optical components and optical interfaces to perform optical transport, optical add/drop, optical amplification, optical routing, and optical switching functions.

AIR6005 has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This document (AIR6005) provides the framework for the specifications of a WDM OBN within the SAE AS5659 WDM LAN Specification document family, in particular, the Transparent Optical Backbone Network Specification. This framework includes potential requirements, technical background, investigation and context to support the writing of SAE's WDM LAN specifications documents. The SAE's AS6005 WDM OBN document describes a transparent optical network which contains optical components and optical interfaces to perform optical transport, optical add/drop, optical amplification, optical routing, and optical switching functions. The conforming **optical** signal interfaces for the data plane of the WDM OBN are defined. The conforming signal interfaces for the control and management planes of this network are also defined. The control and management plane signals may be either electrical or optical. If successful, a WDM LAN standard is anticipated to include multiple variants that may get created either as separate documents (e.g. a multimode and single-mode specification) and additional documents may be needed to specify the components from which a WDM LAN and OBN will be built.

The WDM OBN specification is to be established in a future document, SAE AS5659. This AIR document is a requirements document that provides input regarding the WDM OBN to the AS5659 Aerospace Standard. Additional documents are anticipated to specify aggregation of access for multiple systems that interface to the OBN. The transition from electrical communications links to optically multiplexed networks, is anticipated to involve aggregation of slower speed signals as necessary part of a cost effective transition.

2. REFERENCES

The following publications for a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS5603	Digital Fiber Optic Link Loss Budget Methodology for Aerospace Platforms
ARP5061	Guidelines for Testing and Support of Aerospace, Fiber Optic, Inter-Connect Systems
AS5370	Multi-Transmitter Bidirectional Fiber-Optic Data Bus for Distributed Aircraft Control Systems
AIR5271	A Guideline for Application of High-Density Fiber Optic Interconnects to Aerospace Platforms
AIR5601	A Guide for Application of Rf Photonics to Aerospace Platforms
AIR5667	Fiber Optic Wavelength Division Multiplexed (WDM) Singlemode Interconnect and Component Standards Mapping for Aerospace Platform Applications - Device Level Specification
AIR6004	Optical Networking Glossary Terminology
AIR6006	Modeling and Simulation Capabilities for Aerospace WDM LAN Applications

2.2 ANSI Publications

Available from American national Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

Z136.1	American National Standard for Safe Use of Lasers, 2007
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2.3 IEC Publications

Available from International Electrotechnical Commission, 3 rue de Varembe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +44-22-919-02-11, www.iec.ch.

IEC 61290-3-1 Optical Amplifiers – Test methods – Part 3-1: Noise figure parameters – Optical spectrum analyzer method, copyright 2003

2.4 U.S. Government Publications

Available from the Document Automation and Publication Service (DAPS), Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

MIL-STD-810F RTCA D0-160E, Environmental Conditions and Test Procedures for Airborne Equipment

2.5 Applicable References

Avionics Architectures Incorporating Optical Fiber Technologies; Andrew Lee, Sept. 12. 2006, IEEE/AVFOP conference, Annapolis, MD

The Theory of Networking and Architectures, Casey Reardon, Oct. 26, 2006, SAE WDM LAN task group meeting, Jacksonville, Florida

Virtual Prototyping of WDM Avionics Networks presentation by Casey B. Reardon, Ian A. Troxel, and Alan D. George; HCS Research Laboratory, University of Florida; September 2005, IEEE/AVFOP Conference Presentation.

High Performance Single Mode Fiber Optic Cable for Aerospace Applications, by Géraldine Trouillard and Aurélien Bergonzo

RONIA Results: WDM-based Networks in Aircraft Applications, Sarry F. Habiby and Michael J. Hackert, IEEE/AVFOP 2008 Conference, October 2008, San Diego, CA.

“Open System Interconnection –Model and Notation” ITU-T Recommendation X.200, July 1994.

“Impact of filter concatenation on the performance of metropolitan area optical networks utilizing directly modulated lasers”, Ioannis Tomkos, Robert Hesse, Neo Antoniadis, and Aleksandra Boskovic, OFC 2001 Conference, WBB4.

Khrais, N., Elrefaie, A., Wagner, R., and Ahmed, S., IEEE Photonic Technology. Letters., vol. 7, p. 1348-1350, 1995.

Khrais, N. N., Elrefaie, A., and Wagner, R. E., Electron. Lett., vol. 31, p. 1179-1180, 1995.

Zhensheng Jia, Jianjun Yu, Lei Zong, and Gee-Kung Chang, “Transport of 8x2.5-Gb/s Wireless Signals over Optical Millimeter Wave through 12 Straight-Line WSSs and 160-km Fiber for Advanced DWDM Metro Networks,” in Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference, OSA Technical Digest (CD) (Optical Society of America, 2008), paper OMO3.

3. INTRODUCTION

3.1 Motivation

The purpose of this document is to define requirements for optical networks in aircraft applications and understand the rationale behind them. The specifications derived from these requirements will enable aerospace network engineers and designers to design and use wavelength division multiplexed (WDM) systems and technology to implement a flexible, scalable and upgradeable optical network supporting the systems and subsystems aboard an avionics platform. While the physical plant definition will differ from platform to platform, the method for network access and transport across a backbone single-mode fiber network can be standardized, e.g. as in access and transport across an Ethernet or fiber channel Local Area Network (LAN). Additional context in terms of scope and purpose are provided in Sections 1 and 3.5. This document provides inputs (requirements) for the AS5659 Specifications document being developed by the SAE AS-3A1 WDM LAN Development Subcommittee.

WDM technology is viewed as a basis for the desired networking solution as it enables support of many different legacy and novel applications (through transparency); it provides optical layer scalability, both in terms of overall bandwidth and the number of provisioned applications, through the assignment of wavelengths or shared wavelengths. Many WDM commercial telecom and datacom systems exist that incorporate a number of existing, commercially supported standards, yet there are technology challenges (e.g. integration, packaging outlined below) to overcome before WDM components and networks can be adopted for the targeted applications. By developing a WDM LAN standard we expect to define the critical parameters that can facilitate deployment of standardized systems. These standards will insure interoperability between the optical equipment network elements within these systems. The commercial industry is motivated to utilize these standards to minimize the amount of tailored development of engineered systems.

The development of a WDM LAN standard is expected to have similar broad applicability for avionics and ship-board applications. The main focus of this document is on the optical backbone network (OBN) portion of a WDM LAN based on single mode fiber to enable a scalable optical network aboard aircraft, hereafter referred to as a WDM Optical Backbone Network or WDM OBN. Nonetheless, we also provide a taxonomy (Sec. 3.5.2) that delineates a range of cable plant, application and optical network architectures that can be specified using this document as a baseline. As such, this document is intended to have a broad scope and enable an “inclusive” standard that can be applied to airborne as well as ship-board and other mobile network systems. The various platforms envisioned include those depicted in Table 1.

Additional networking categories of interest include:

- a. On Board access networks (to WDM LAN OBN)
 - 1. Passive Optical Networks
 - 2. Point to Point Links
- b. Interfaces to external networks

Consequently, the set of optical backbone network requirements identified in this document will provide the framework for an upgradable cable infrastructure network over time.

TABLE 1 – POTENTIAL WDM LAN PLATFORMS

Military	Aircraft	Ships
	1) Transport 2) Tactical 3) Rotorcraft 4) UAVs	5) Aircraft Carriers 6) Destroyers 7) EW Ships 8) Small Boats
Commercial	9) Transport (Passenger & Cargo/freight) a. Large transport b. Regional airplanes 10) Rotorcraft	
Other Military and commercial Applications	Terrestrial	Subsea
	11) Local Area Networks 12) Long Distance Systems	13) Local Area Networks 14) Long Distance Systems

While initial applications expect to be driven by high performance end users who can afford the initially high costs incurred by early adopters using single mode fiber, potentially viable upgrade alternatives are envisioned. For example, a future implementation of legacy multimode fiber based networks might provide a cost effective alternative to the costly, obvious upgrade path of stripping out the existing media to install single-mode fiber.

3.2 Network Abstraction

A WDM Optical Backbone Network (WDM OBN) can offer another level of network abstraction beyond that available on existing avionic platforms, as shown in Figure 1. Current platforms support applications through dedicated static point-to-point networks or legacy bus networks. These networks may be formed using existing electronic bus standards, or with a set of overlay links (electronic or fiber optic links). Major current practice limitations include significant cost and added weight associated with network upgrades; it is challenging to manage the life cycle cost of numerous unrelated networks which use different standards and different connection methods, while they all are tightly packed into the same physical platform. An important part of installation and maintenance of equipment aboard military platforms has to do with space, weight, and access. For example, replacement of wire and cable infrastructure aboard a fighter aircraft can be invasive and expensive, causing unintended collateral effects on other aircraft subsystems. Diversity of protocols typically exists with these systems resulting in incompatibility and the need for cable plant upgrades when interconnection of system elements is required. Developing a network layer that can provide novel functionality aboard an aircraft, such as through a WDM OBN, can provide a transparent optical layer that enables the connectivity and performances desired, while still offering a level of network layer scalability and flexibility.

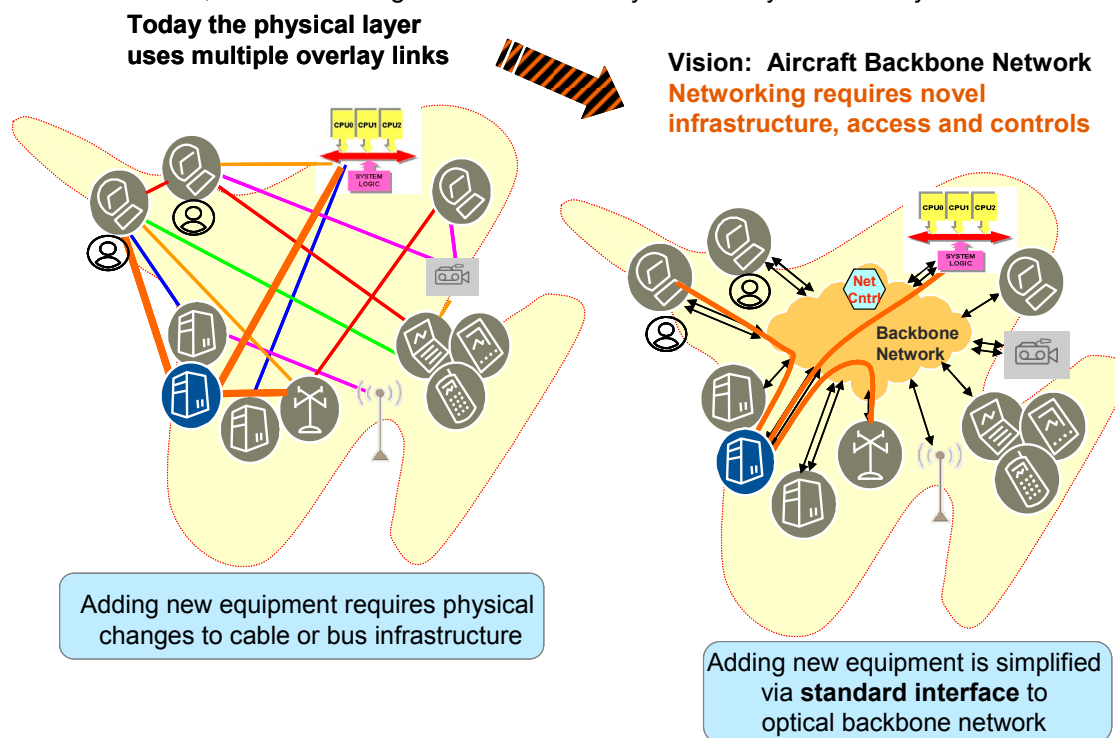


FIGURE 1 - WDM LAN OBN: NETWORK ABSTRACTION; EVOLUTION OF AIRCRAFT NETWORKS

The primary basis for introducing a WDM LAN into any platform is to group future-proof parts of the wire and cable infrastructure, dedicated to data communications, into a single entity. The intent is that an OBN within the WDM LAN will be designed and installed once, and provides connectivity directly to all subsystems which require high bandwidth communication. (Signals from low bandwidth devices may be multiplexed together before the aggregated signals access the backbone network). The WDM OBN will be operated and maintained as a separate system, providing networked communication services to devices that are connected to it. Health monitoring and problem diagnosis can be performed with simple network algorithms, so the need to physically access remote nodes would be done only as necessary. Future upgrades of the systems and applications aboard aircraft will be achieved by connecting equipment to the backbone's Optical Network Elements (ONE) and Optical Fiber Interconnects (OFI) defined in more detail below. The client equipment nodes are connected to the OBN using standards-based Network Access Interfaces (NAI), without invasive and costly wire or optical cable upgrades. The ONE and OFI are interconnected to each other through standards-based optical Backbone Network Interfaces (BNIs). Additional details regarding the WDM OBN interfaces (NAI and BNI) of the ONEs and OFIs are provided in Section 5 of this document.

Fundamental requirements exist to ensure that evolving demands for improved efficiency and throughput on aircraft networks can be met. Creation of a network-centric configuration is the logical approach in meeting the requirements. Understanding the systems and application performance requirements is a precursor to the design of a general purpose WDM LAN that supports present and future device communication.

A WDM LAN and the OBN within it are expected to provide improved flexibility in supporting new services on the network while reducing the complexity associated with physical reconfiguration with the addition or removal of network elements. It also provides a potential for accommodating security (such as Multiple Independent Levels of Security, MILS) as a managed network function.

3.3 System Applications

In avionics systems the allocation of network resources are typically required for the following systems (these systems are defined in Section 4.1):

- Communication, Navigation and Traffic Identification/Surveillance
- Vehicle Management System
- Mission/Flight Plan Processing
- Core Computing
- Displays and Sensors
- Cabin Systems
- Electronic Warfare
- Stores Management Systems

As shown in Figure 1, the system applications are currently implemented as a collection of data links rather than through a networked approach; by migrating to an optical fiber infrastructure and introducing WDM technology that enable provisioning of the large number of wavelengths (bandwidth resources) available in optical fiber, it is expected that a significant improvement in overall system capacity, latency, redundancy and reliability can be achieved.

3.4 WDM LAN Challenges and Rationale

The use of a WDM LAN introduces a set of physical layer and operational challenges and requirements that need to be addressed. These challenges point to specific topics and technical areas where standardization is needed. These include specification of the WDM OBN network interfaces (i.e. BNI and NAI), as well as network operations and management/control. Also, at the optical data plane layer, the wavelength allocation and inter channel performance requirements (e.g. interference or crosstalk) need to be defined. Since the aerospace industry makes a direct correlation between weight and cost, reduction in overall system weight translates into valuable payload that a platform can carry, the loiter or mission time that an aircraft can maintain, and the amount of fuel a platform requires to first get aloft and then to stay aloft. Therefore, minimizing size, weight, and power (SWAP) is a critical metric for the aerospace industry. In turn, SWAP drives the highest degree of integration for optoelectronic devices. While critical to aerospace applications, weight reduction has a lesser priority for terrestrial datacom and telecom networking. Component development for these commercial applications is driven more by cost reduction and performance, respectively. Although not obvious, packaging of currently available discreet commercial components incurs a high packaging cost (to survive the harsh aerospace environment) which is weight and space prohibitive. Consequently, an enabler for a low cost OBN within a WDM LAN is the component miniaturization and integration of the multiple functions needed to create the network connections within an OBN. Thus, a number of new technologies which provide the possibility of this integration (e.g. silicon photonics) could in fact make OBNs and WDM LANs a viable reality.

The contrast between commercial data communications and aerospace application also can be drawn by comparing the importance of reliability and maintainability. Between the complexity of the system (which might be compared to the telecommunications grid) and the harsh environment in which an aircraft functions, avionics equipment reliability is critical to keep an aircraft available and flying. Based on current experience, reliability and maintainability can be improved by

reduced pin count on fiber optic connectors, through the introduction of a networked infrastructure (e.g. OBN) rather than a collection of point-to-point links that replace the existing copper/electrical infrastructure. Reliability directly relates to the amount of time an asset is available to fulfill its mission. The military wants its aircraft flying to fulfill the needs of their fleet, and the airlines want aircraft that are in the air flying passengers from which they are making money.

An additional weight savings can be achieved by the multiplexing of multiple connections currently carried over slower speed copper interconnects. Historically, system after system has been added to aircraft, each requiring further addition of the copper connections as well as overlay of single wavelength optical fiber links. This has resulted in a large number of huge-size cables with corresponding large weight penalties. One of the objectives of wavelength division multiplexed solutions is to enable translating these legacy communications needs over to a lighter weight, optically multiplexed WDM network over one or few fibers. Thus, the weight of these huge cable harnesses can be eliminated, justifying the change to optical communications, while enabling new applications which the added bandwidth of the fiber can support.

Both the military and commercial aerospace markets share sensitivity to the cost of new technology. While the airlines see their margins tied to the purchase and maintenance costs of their aircraft, at the end of day, the military issues a request for proposal for an aircraft to the lowest cost bidder. Fortunately, both markets can benefit from development activity which enables low cost capability. Once the development cost has been incurred to develop WDM LAN capability using low SWAP hardware, all can benefit from it.

Further rationale for developing a WDM LAN standard includes:

- Defining network interfaces is important in a transparent optical network as it enables transmission of multiple wavelengths on the same fiber network in the presence of impairments (loss, crosstalk, etc.). Specific performance criteria at the input and output of backbone, access and aggregation network elements will be an important part of any WDM LAN specification.
- Definition of a "Minimum point of entry" – there is a need for an agreed method or approach for connectivity onto and off of the WDM LAN, including connectivity onto and off of the WDM OBN. Any optical signal source driven by an information source connected to the OBN such as an antenna, sensor, video source, computer, or database, will have to meet or satisfy the defined network access interface and a (simple) optical layer media access protocol.
- Availability of a standard helps put in place metrics to evaluate and compare candidate architectures, providing an objective perspective on the various merits of each and the associated complexities and challenges.

In addition to the rationale for a WDM OBN developed by the SAE ASD effort, similar issues, challenges and benefits were considered by the Future Optical Networking Distribution for Aerospace group (FONDA), a UK Department of Trade and Industry funded project. FONDA is devising similar conventions for aerospace fiber optics, and has analyzed the usefulness of fiber optics technology for use aboard aerospace platforms. Use of high bandwidth applications for situational awareness, network centric warfare, and video distribution is driving the need for higher data transmission speeds, greater flexibility, and increased adoption of commercial standards. Unfortunately, the historical pattern of system segregation for functional (and certification) isolation is not sustainable.

The technical advantages of fiber optics are acknowledged, i.e. high point-to-point bandwidth, decreased EMI susceptibility, and ability to handle secure traffic. Additional physical advantages include reducing connection complexity, reduced weight, and component count. A network can reduce radio and microwave co-location issues. A common physical layer can also simplify management, control, upgrades, health monitoring, and problem diagnosis.

The following network metrics were identified by FONDA:

- Mass.
- Flexibility.
- Installed cost.
- Required development effort (Manufacturing Readiness Level, MRL).
- Cost of ownership.
- Reliability.
- Power.

The FONDA project analysis of present and future data transmission requirements drew some interesting conclusions:

- Systems that used bandwidth efficiently performed the best.
- The best performing systems were not the lightest.
- Bandwidth is a key driver for cost.
- WDM systems provided the best performance for low connectivity networks and for legacy protocols.
- TDM aggregation uses bandwidth efficiently for multiple low bandwidth environments.
- WDM (single-mode) and ribbon (single-mode and multimode) provide the best future proof interconnect methods.
- WDM systems perform best in support of legacy protocols.
- Standardization and incremental development will bring best chance of success.

3.5 Purpose

Future avionics transport networks (such as WDM LANs) must be designed to meet a set of end user requirements. The requirements to be defined in the corresponding LAN standard drive the scope and capability of the systems defined. Characteristics of the proposed WDM LAN infrastructure include:

- Extensible to full capacity of the optical medium
- Certified / qualified for future upgrade
- Open architecture / industry standard
- Provide minimum requirements to ensure interoperability (to the extent that different vendors can properly connect to the network without exchanging any information beyond that which is defined in the standard).
- Define common media (e.g. standard step index single-mode fiber)
- Application transparency
- Capable of supporting overlaying legacy as well as new applications, including digital and analog optical signals
- Support real time applications
- Provide low latency for applications that need it
- Support dedicated links and deterministic communications
- Maintainable in service
- Capable of Built-in-test
- Enable easy addition of new applications and / or new nodes to the optical layer (e.g. "plug-and-play")
- Able to be implemented today, yet upgradeable tomorrow
- Fault tolerant and redundant, supporting the application redundancy requirements

In the remainder of this document, specific requirements, conditional requirements and objectives are identified, that reflect most if not all the above desired characteristics.

The various models, concepts, and application codes defined already in telecom WDM and datacom standards communities are used as a baseline framework that is a practical tool in helping define the requirements for a WDM OBN. The standards followed include ITU, Telcordia, IEC and TIA efforts, while also taking into consideration the various commercial datacom standards such as Ethernet standards (on which current aircraft systems such as AFDX are based) including IEEE 802, IETF, Fibre Channel, and specific ARINC ethernet-based standards, to establish and draw on the key features of complementary standards efforts, where practical.

3.5.1 Requirements Format:

In this document we present requirements as a running numerical sequence using the following format:

R-xxx:	Requirement or threshold that is to be met per the ensuing specifications of the future SAE AS5659 standard document.
CR-yyy:	Conditional requirement that is to be met under identified conditions per the ensuing specifications of the future SAE AS5659 standard document.
O-zzz:	Objective that is to be met per the ensuing specifications of the future SAE AS5659 standard document; this is a desirable feature or goal rather than a requirement.

The requirements are embedded within the various remaining sections below, and also collected as a running list at the end of this document in Appendix A.

Please note that the scope of this document is defined within the context of an overall taxonomy described in Section 3.5.2. Future variations are expected to appear in accompanying documents within the documentation tree.

3.5.2 Taxonomy

Taxonomy is the science of classification and can be used to identify all of the elements of “black boxes” of a system, their transfer functions and specifications, and also their characteristics and interfaces. This methodology is valuable in architecting a new system concept and describing and establishing requirements for the system elements. A taxonomy provides method of tracking the elements of a system and decisions about the element characteristics. Often, taxonomy is used as the point of departure for a system design that starts out with a “blank sheet of paper” and requires analyses and trade-offs to identify the system block diagram and their characteristics. In the case of this SAE requirements effort and the ensuing standards, some of the analyses and trade-offs have been pre-empted by the selection of “WDM” and “LAN”, specifically to leverage the extensive telecom and datacom investments and technology. However, the resulting document will remain sufficiently flexible for other, future, systems and applications by virtue of establishing a set of generic architectural building blocks. The desired network infrastructure is one in which new applications as well as legacy systems can be accommodated.

At the highest level, the problem of developing a new WDM LAN, and specifically the optical backbone network of such a LAN, can be subdivided into a few key elements following the taxonomy depicted in Figures 2 and 3:

- Transmission media and components
- A means of multiple access
- Environment
- Signaling
- Carrier(s)

The first and probably the easiest to understand are the physical elements from which the network is made. Consequently, it is easy to see where its name comes from, specifically the physical layer. This term refers to the lowest or first layer in the ISO networking protocol stack. While this document only considers standard all glass single-mode (SMF) and multimode (MMF) fiber, the transmission media alternatives include:

- Single-mode fiber (SMF)
- Multimode fiber (MMF)
- Free Space Optical
- Planar Lightwave Circuit (PLC)
 - Silica
 - InP
 - Silicon
 - Optical Polymer
- Plastic optical fiber (POF)

While the physical implementation eventually has to be defined and constrains the potential implementations (and ability to provide a low cost solution providing a value proposition with low SWAP), the desired connectivity is a strong driver to the ultimate solution. In the case of connectivity, there is a difference between the physical implementation (or where the physical interconnects are placed) and the logical implementation (how the network routes information over the physical connections). Connectivity alternatives include point-to-point (Single point to single point, point to multi point, including broadcast, and multicast), as well as star, bus, ring and mesh networks. Therefore it is expected that the optical backbone network within a WDM LAN enable these connectivity alternatives. Details are identified in the following set of OBN requirements and objectives.

R-001: Service capabilities provided by an optical backbone network (OBN) shall support a minimum connectivity of at least one point to one or more other points. The following are a representative set of connectivity types supported:

- Point to point
- Point to multi point
 - Broadcast
 - Multicast

O-002: It is desirable that the WDM OBN support the following logical, signal and physical topology alternatives:

- Star
- Bus
- Ring (including ring interconnection)
- Mesh

Note, logical signal and physical topologies are defined in Table 2. as OBN features that apply to connectivity rearrangement, using the functions performed by the ONEs within an OBN that describe interactions with the physical infrastructure that can impact physical, signal and logical connectivity.

TABLE 2 – TOPOLOGY DEFINITIONS

<u>Topology</u>	<u>Definition</u>
Physical	Physical interconnection between OBN network elements
Signal	Path taken by signals remaining in their native form such as an optical signal routed through OBN nodes (ONEs) without being converted to electrical signals (the propagation path of signals between the nodes)
Logical	Connectivity established by the wavelength allocation scheme and switches or add/drop multiplexers within the OBN

The focus of this document is on fiber-optic solutions using multi-wavelength single-mode and multimode fiber, with single mode envisioned for the backbone core network, and where practical for access networks connecting to the backbone, and multimode fiber as a possible medium for access networks only.

At this time, all the connectivity alternatives defined above are included in the document scope. We will continue to track technology improvements in the various transmission alternatives and reflect any significant changes and impacts in future updates of this documents and in the AS-5659 specification.

The environment covered by this Standard is specifically Aerospace (aircraft), with possible extensions to shipboard LANs and other mobile platforms. With respect to multiple access, it has been discussed elsewhere in this document that WDM and TDM will be essential transmission and multiplexing technologies including electronic grooming and aggregation that can be used for low data signals. It has also been discussed that analog and digital signals are likely to use different WDM grid carriers. Signaling will generally be based on on-off-keying (OOK) as in telecom, but other coding schemes can also be considered, based on their compatibility with the environmental constraints.

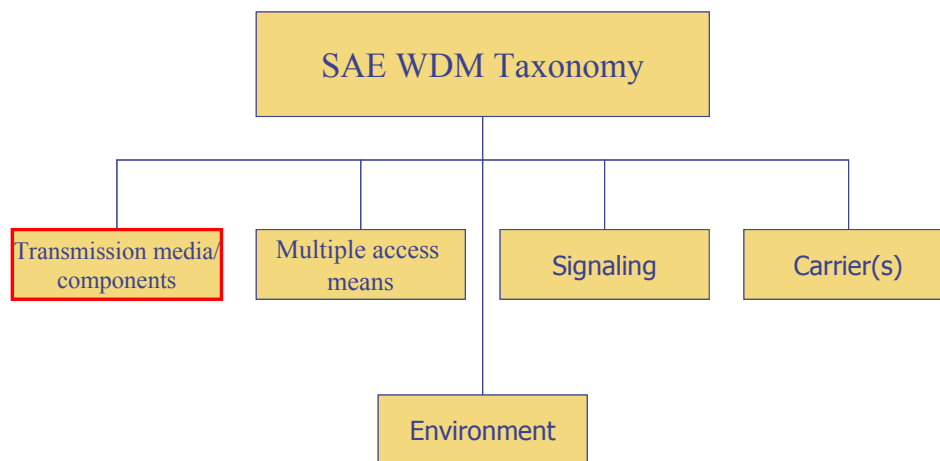


FIGURE 2 - TAXONOMY: OVERVIEW

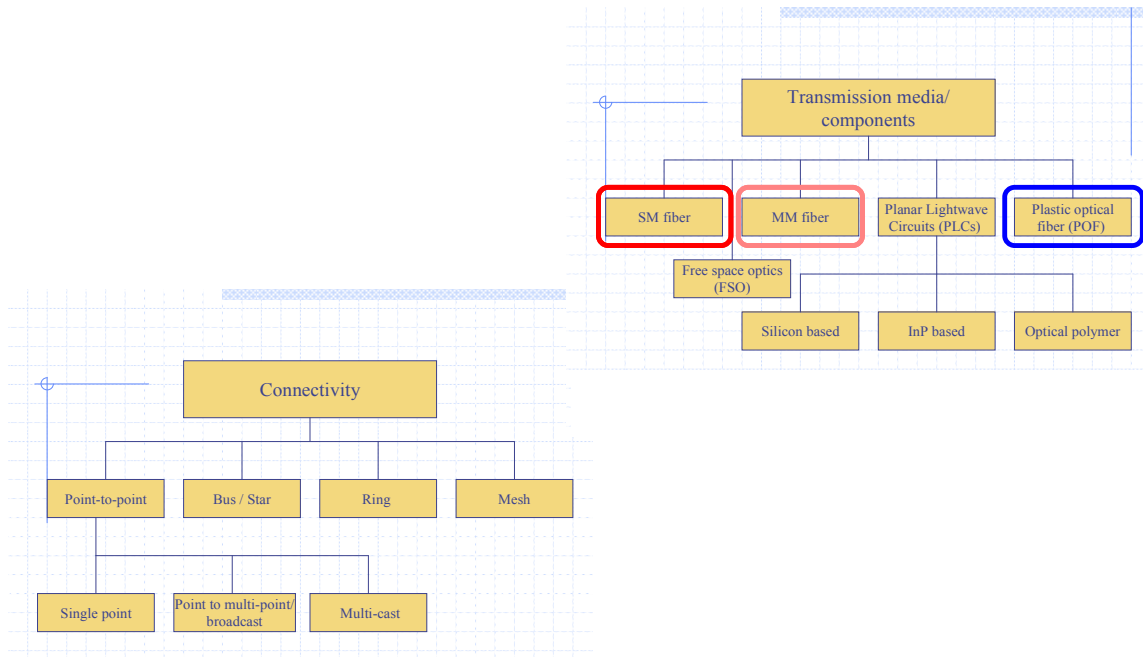


FIGURE 3 - TAXONOMY: TRANSMISSION MEDIA AND CONNECTIVITY

3.5.3 Assumptions

The WDM LAN is intended to support many avionics network suites and applications. Some of the key assumptions regarding the network requirements and the signal types that are expected to be supported include:

- Wavelengths consistent with those defined on the ITU grid, and any appropriate modifications, are to be used.
- Networks can support digital or analog signal formats. This can impact the wavelength plan and wavelength allocation of a WDM OBN. Implementations are likely to result in partitioning of available wavelengths into digital and analog wavelength bands.
- WDM LAN and WDM OBN definitions apply to networking functionality required, not to specific hardware or technology implementations.
- Signal sources used to access the OBN comply with eye-safe transmission guidelines and standards (see Section 5.4.2 for details).
- Signals are generated by equipment that meets environmental constraints defined for the particular application (e.g. for avionics and/or shipboard systems) defined in SAE (and other) standards.
- Network scope includes the optical (WDM) backbone and access networks, including a means to interface with both native high capacity (dedicated wavelength) signal sources and with wavelength aggregation nodes at the network edges, whereby aggregation enables legacy systems and lower bit rate systems to efficiently access and share the wavelength resources in the backbone WDM network.
- The WDM OBN fiber infrastructure uses standardized optical fiber connectors appropriate for the specific media chosen, meeting necessary aerospace environmental and reliability requirements.

3.5.4 Overview of Related Documents

As part of the development process of a next generation optical WDM network for general purpose application, a number of related documents were generated to support the specification of new interfaces and networks. These documents are listed below.

Existing Documents include:

- AS5603 – Digital Fiber Optic Link Loss Budget Methodology for Aerospace platforms.
- ARP5061 - Guidelines for Testing and Support of Aerospace, Fiber Optic, Inter-Connect Systems
- AS5370 - Multi-Transmitter Bidirectional Fiber-Optic Data Bus for Distributed Aircraft Control Systems
- AIR5271 - A Guideline for Application of High-Density Fiber Optic Interconnects to Aerospace Platforms
- AIR5601 - A Guideline for Application of RF Photonics to Aerospace Platforms
- AIR5667 – Fiber Optic Wavelength Division Multiplexed (WDM) Singlemode Interconnect and Component Standards Mapping for Aerospace Platform Applications – Device Level Specification
- AIR6004 – Optical Networking Terminology and Glossary
- AIR6006 – Modeling and Simulation Capabilities for Aerospace WDM LAN Applications

The AIR5667 document was the starting point for the development of a general purpose WDM LAN for aerospace application. The Telecom and Datacom markets have developed relatively extensive sets of standardized optical hardware and industry accepted networking standards. By the time of the "Telecom Bubble" around 2001 optical networking had been brought into prime time application for both long distance Telecommunications as well as short distance data transport. The logical point to start the development of an aerospace implementation was to first learn what mature technology was available from this existing base, and then use that established technology base wherever possible to build a new network.

This document describes the requirements that will lead to the development of the WDM LAN standard, namely AS5659 and the Transparent Optical Backbone Network Specification. It also provides the key definitions (e.g. OBN, ONE, OFI, etc.) and introduces the key interfaces (BNI, NAI, etc.). A basic tenant of project management and system development is to understand the requirements thoroughly enough to feed into the design process. A good understanding of what the design has to deliver is the minimum needed to ensure that a solution will fulfill the intended application. Expectations, while not as concrete as a specific requirement, are also useful to differentiate and clarify what is absolutely necessary versus what provides added value if it can be provided at minimum cost or penalty.

AS5603 is a standard for Digital Fiber Optic Link Loss Budget Methodology for Aerospace Platforms. This SAE document describes methods that can be used to devise a loss budget for a fiber optic link. It is an engineering guide with references that may be used for guidance.

The AS5750 (Loss Budget Specification for Fiber Optic Links) document provides a means for specifying a fiber optic link loss budget and the documentation required for evidence that it has been done.

Development of the modeling and simulation capabilities document, AIR6006, was started in parallel with the AIR6005 requirements document. After the requirements have been defined and a direction set for design, tradeoffs on design decisions need to be evaluated as well as determination of basic design decisions will fulfill the agreed to requirements. At the beginning of this effort, an extensive set of design tools had been developed for the industry. These tended to provide very thorough coverage of most of the physical layer components that are needed for a network design. However, the full suite of design tools for network modeling was not known to be complete. The AIR6006 establishes and documents what those modeling and simulation requirements are in a general way.

The WDM LAN Specification (AS5659) document will be the key result of the development effort and will define the network specification. The AS5659 document family also contains a document that defines the actual networking protocols and management protocols Network Management and Control Specification.

During the course of the development of the WDM OBN and related WDM LAN standards, the formulating committee pulled together a significant amount of material from a number of technical experts with a wide range of disciplines integral to the development of a networking standard. This information was documented into the other standards described above. During the course of this activity, the committee determined that it needed a common set of terms and definitions. Since these terms crossed over all of the documents, this glossary was broken out into a separate standard (AIR6004, Optical Networking Terminology and Glossary)

3.6 Structure of Document

Section 3 (this section) contains an introduction, rationale and motivation, as well as a discussion of purpose and scope for the WDM LAN and WDM OBN standardization. We also address key assumptions and highlight the main sections of the document including availability of a separate document that defines terminology (relevant portions of the terminology document pertinent to this AIR also appear in the glossary section in this document; please refer to Section 10).

Section 4 addresses topics related to optical networks in general and their aviation / aircraft applications. It includes an overview of the basic optical network types.

Section 5 defines WDM OBN network elements and interfaces (access and backbone). A set of Optical Backbone Elements (OBE), including Optical Network Elements (ONEs) and Optical Fiber Interconnects (OFIs) as well as their interfaces are described in this section.

Section 6 defines the WDM OBN Network Interface Application Codes.

Section 7 provides templates that capture the ONE and OFI interface requirements, specifically the Backbone Network Interfaces (BNI) and the Network Access Interface (NAI).

Section 8 introduces the key topics pertaining to managing an optical backbone network. Network Management functions are defined in this section.

Section 9 introduces the key topics pertaining to control plane for an optical backbone network. Optical network control plane functions are defined in this section, including plug-and-play support, platform DNA and client admission control features of a WDM OBN

Section 10 contains an acronym list (alphabetical listing) of terms used in this document.

Appendix A contains a complete sequential list of the requirements, conditional requirements and objectives identified throughout this document.

Appendices B & C summarize two studies of aircraft systems requirements. Appendix B describes key results of the DARPA RONIA project and Appendix C describes key results of a Boeing JSF X-32 Demonstration Aircraft study.

3.7 Terminology

Please refer to Section 8 of this document for a list of acronyms and to AIR-6004 – (Optical Networking Terminology and Glossary) for a glossary containing the terminology pertinent to the WDM OBN and WDM LAN standards.

4. NETWORKS IN AVIONIC APPLICATIONS

In this section, we review market drivers and key functions and features to be supported in next generation, future proof optical networks aboard aircraft (can also extend to shipboard applications). We include an overview of existing avionics network applications and summarize key requirements that future networks must support to establish a scalable, flexible, high bandwidth, reliable and low cost networking infrastructure. This provides the context for the definition of an aircraft backbone network, and in particular the types of cable plant and network elements needed. It also provides a high level overview of the interface types expected (within the backbone network and in and out of the backbone network) to support the set of aircraft systems applications referred to as Avionic Network Applications defined below.

4.1 Existing Avionic Network Applications

4.1.1 Market Drivers

The selection process for an avionics network is driven by a number of key metrics. The selection process ranks these priorities differently for the two major aerospace markets included in the development of this document. These markets are a) military aerospace whose standards are typically supported by SAE, the formulating committee for this document, and b) commercial aerospace which typically utilizes ARINC for its standardization process. Table 3 provides an estimate of how a typical customer for each of these markets rank orders these priorities.

TABLE 3 – METRICS FOR MILITARY AND AEROSPACE APPLICATIONS

Priority	Metric	
	Military Aerospace (Tactical and Widebody)	Commercial Transport
First	Performance	Acquisition Cost (including Life Cycle Cost tradeoff)
Second	Weight (SWAP)	Reliability
Third	Reliability	Performance
Fourth	Acquisition Cost (including Life Cycle Cost tradeoff)	Weight (SWAP)

Acquisition cost is the purchase price of an aircraft. In commercial aerospace, this includes the air frame and flight controls and avionic systems necessary for the aircraft to fly and navigate. It may or may not include the on board networks such as the in-flight-entertainment (IFE) system and / or interior, reconfigurable elements such as the cabin fixtures. In the military market, the acquisition costs include both the first articles meeting the initial capabilities as well as the development costs for a new airframe with the required new capabilities. Commercial aerospace heavily weights its selection process on the initial costs. Military aerospace, while sensitive to costs, tends to be driven instead by performance. Performance gets defined slightly differently in the two markets. The military market tends to create an overall performance definition which includes both airframe capability as well as the full avionics suite of capabilities. The commercial market tends to exclude a significant portion of the overall costs by not including those systems which are added after purchase (e.g. IFE). Reliability translates into how long a system can survive in its intended environment performing its intended functions. Commercial aerospace is very concerned about passenger safety and the liabilities around their transport. Consequently, reliability is its second highest priority, second to only the overall acquisition costs. The last metric is weight; both volume and weight (SWAP) are important considerations in selecting solutions adopted on platforms. Both markets are concerned with this. The military market tends to manage its development programs around weight constraints and consequently translates weight into costs to remove the weight needed to provide the performance. The avionics systems (applications) defined in section 4.1.2 are among the drivers for network performance, in terms of network size, bandwidth, latency, redundancy and upgradeability.

4.1.2 Aircraft Systems

There are many avionic system applications (commercial and military) that are common to a number of military and commercial platforms (the term 'avionics' is used in a general sense in this document to represent the set of applications described and depicted in the figures below). Figure 4 provides an example of the types of systems found on board an aircraft. The diagram represents typical aircraft avionic systems but does not necessarily capture all possible systems on all aircraft platforms. However, it forms the basis for classifying the aircraft systems.

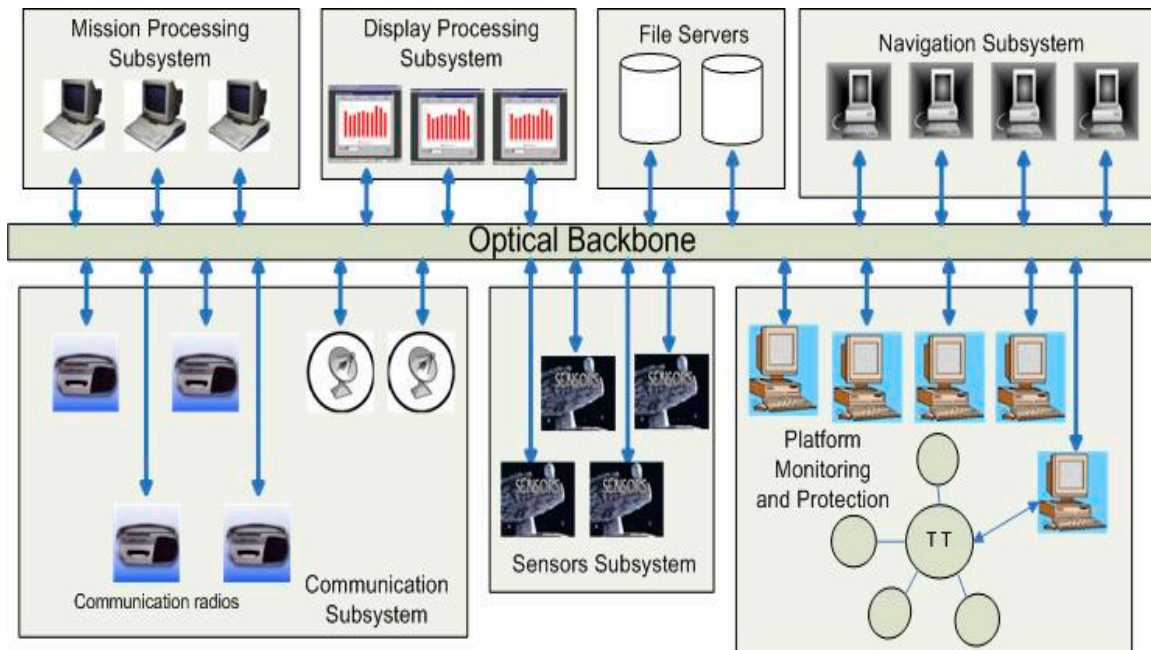


FIGURE 4 - REPRESENTATIVE AVIONIC SYSTEMS CONNECTED THROUGH AN OPTICAL BACKBONE NETWORK

In the next two sections (4.1.2.1 and 4.1.2.2), greater detail is provided on the unique characteristics of military and commercial avionics, to show the similarities and point out the differences between the two. Unless otherwise noted, requirements and objectives contained in these sections apply to all applications, commercial and military.

4.1.2.1 Military Aircraft Systems

The set of systems applications and requirements related to them have been analyzed in several efforts – in section 4.1.4 we highlight the results of two studies, one that resulted from a DARPA effort to document requirements for optical networks in avionics (RONIA) and another by Boeing for the analysis of experimental JSF X-32 applications. Details of the two studies are provided in Appendices B and C respectively.

For the purpose of defining a WDM optical backbone network infrastructure and its requirements, we assume the following list of avionic systems (aircraft systems) is a representative set that can be used to describe many of the significant platform applications that are required to be supported in an aircraft backbone network.

O-003: It is desirable that a WDM OBN support the following aircraft systems:

- Communications, Navigation, Identifications (CNI); (both military and commercial)
- Mission Processing; (military only)
- Platform Monitoring (includes H/VMS: Health Monitoring / Vehicle Monitoring System, and BIT (Built-in Test)); (both military and commercial)
- Sensors (including video / cameras), Radar, Antenna; (both military and commercial)

- File Servers; (both military and commercial)
- Displays; (both military and commercial)
- Electronic Warfare (EW); (military only)
- Stores Management Systems (SMS); (military only)
- Core Computing; (both military and commercial; although IFE is commercial only)
- Cabin Systems; (both military and commercial)

R-004: The OBN shall meet the individually specified reliability and performance requirements (e.g. bandwidth, latency, redundancy, connectivity) for each of the aircraft systems that it supports

Note: Upon completion of the analysis of the diverse set of performance, bandwidth and latency requirements that the above set of applications represent, the set of systems and applications amenable to be supported on a WDM OBN may be revised. If it is more efficient to support a specific legacy application using current copper-based cables or an alternative infrastructure, then that application set above can be updated to reflect such revisions.

The definitions of the avionic subsystems and their applications are provided below (these are also repeated in the glossary/terminology in Section 10):

- Communications, Navigation, Identifications (CNI): The CNI subsystem provides automatic functionality to assist the pilot in navigation to destinations/targets, communication with air traffic controllers, ground stations and other aircraft, and identification of both enemy and friendly aircraft.
- Mission Processing: The Mission Processing subsystem provides a user interface and processing platform for applications that allow the pilot and/or flight crew to plan and execute a mission. This subsystem may manage various sensors and/or weapons and adjust cockpit and flight crew displays as required by the mission.
- Platform Monitoring: The Platform Monitoring subsystem tracks the health of the avionic platform. It monitors for hardware and network failure and initiates failover mechanisms and network rerouting to minimize the loss of capability when a failure is encountered.
- Sensors: The Sensor subsystem are the “eyes and ears” of the aircraft. It provides the pilot and flight crew with information from various sources such as environmental sensors, radars, antennas, cameras, etc. It provides raw data that is analyzed by the flight crew or other subsystems.
- File Servers: The File Server subsystem is a collection of computers that control one or more file systems. The file systems can be used for any information that may be used for flight or mission operations such as weather reports, mission plans, flight plans, intelligence data, maintenance logs, passenger manifests, etc. On air transport airplanes, a file server may be used by passengers for database access or as an internet cache/buffer.
- Displays: The Display subsystem provides the pilot and flight crew with information provided by other subsystems. The subsystem may consist of many different consoles that may operate in various display modes to provide information such as situational awareness, mission objectives, aircraft identification, target identification, intelligence, etc.
- Electronic Warfare (EW): The Electronic Warfare subsystem is a suite of components that use the electromagnetic spectrum for use in one or more of the following applications:
 - Electronic Attack – deny the use of the electromagnetic spectrum to an enemy (e.g. jamming, active cancellation)
 - Electronic Protection – deter an enemies EW attack (e.g. frequency hopping)
 - Electronic Support – gain information about other vehicles

- Stores Management System (SMS): The SMS subsystem controls weapons launch sequences. This includes functionality such as controlling the opening of aircraft bay doors, quantity of weapons to release and timing their release. The SMS may also initiate the firing of countermeasures upon notification from the EW subsystem.
- Core Computing: The Core Computing subsystem is a suite of hardware components and computers that provide a majority of the processing power on the aircraft. Components of this subsystem include: general processors, signal processors, image processors and network interfaces.
- Cabin Systems: related to passenger services. Cabin Systems could include but are not limited to crew communications, video/audio entertainment, real time flight information display (from avionics), video supervision of cabin, internet and email access, database access through file server, and general cabin controls.

Tactical aircraft and wide-body aircraft will have different combinations of the above subsystems, as will military and commercial aircraft platforms. The WDM LAN and therefore the WDM OBN defined will need to support all the subsystem types, independent of aircraft and platform type.

4.1.2.2 Typical Commercial Aircraft Systems

Commercial aircraft divide their major aircraft systems into domains, some of which map into the avionics systems listed in 2.1.2.1. Large commercial transport aircraft can have 40-50 subsystems but the major electronic systems can be categorized as follows:

- Aircraft Control Domain: e.g. flight control systems, landing gear systems
- Aircraft Management domain: avionics, display systems, nav/comm /surveillance, flight management systems, health maintenance systems (key systems in 4.1.2.1)
- Aircraft Passenger domain: cabin services system, in-flight entertainment (IFE) system (loosely maps to Cabin Systems in 4.1.2.1 although military aircraft requirements are nothing like the demands created by commercial IFE)
- Aircraft Energy domain: electrical generation system, electrical distribution system
- Aircraft Propulsion domain: engine control system, fuel control system, thrust reverser system

As the commercial platforms evolve, some of these applications can be viewed as virtual systems that share both computing and network resources. As such, future work on WDM LAN (including joint SAE-ARINC work) may need to differentiate among military and commercial aircraft network architectures and identify associated low-cost optical enabling technologies.

The Integrated Modular Avionics (IMA) for commercial airplane is entering its third generation (compared to military avionics which are deploying their fifth generation). As processors, memory and IO becomes smaller and more powerful, two trends that have deeply influenced avionic architecture are:

- a. Integration of many systems within an IMA cabinet.
- b. Smart peripherals with limited computing power but fast local loop processing

The balance of these two trends is the major difference between today's avionic architectures. In both cases, there is more internal computation and exchange of data within the backplane. The result is less and less traffic on the aircraft system backbone data networks for some commercial aircraft. In contrast, military aircraft continue to see an enormous surge in both sensor and EW traffic that is preprocessed remotely and further processed for missions systems within core computer clusters interconnected by backplanes. In the end, both approaches place a growing demand on the aircraft's overall network. The only question is where and when increased demand will be required which drives the need for an effective upgrade strategy.

For example the first generation IMA cabinet in some commercial aircraft platforms, like the Airplane Information Management System (AIMS) cabinet, consists of Primary Display Function, Flight Management Function, Thrust Management Function, Central Maintenance Computing Function, Airplane Condition Monitoring Function, Data Communication Management Function, Data Conversion Gateway Function, and Flight Data Acquisition Function. The following diagram illustrates the key crew interface devices and sensors utilized by the AIMS functions. The following are the acronyms that appear in the diagram: Built in Test Equipment (BITE), Control Display Unit (CDU), Control Panel (CP), Display Select Panel (DSP), Display Unit (DU), Electronic Flight Instrument System (EFIS), Engine Indication and Crew Alert System (EICAS), Multi Function Display (MFD), Navigation Display (ND), Overhead Panel A629 System (OPAS), Primary Flight Display (PFD).

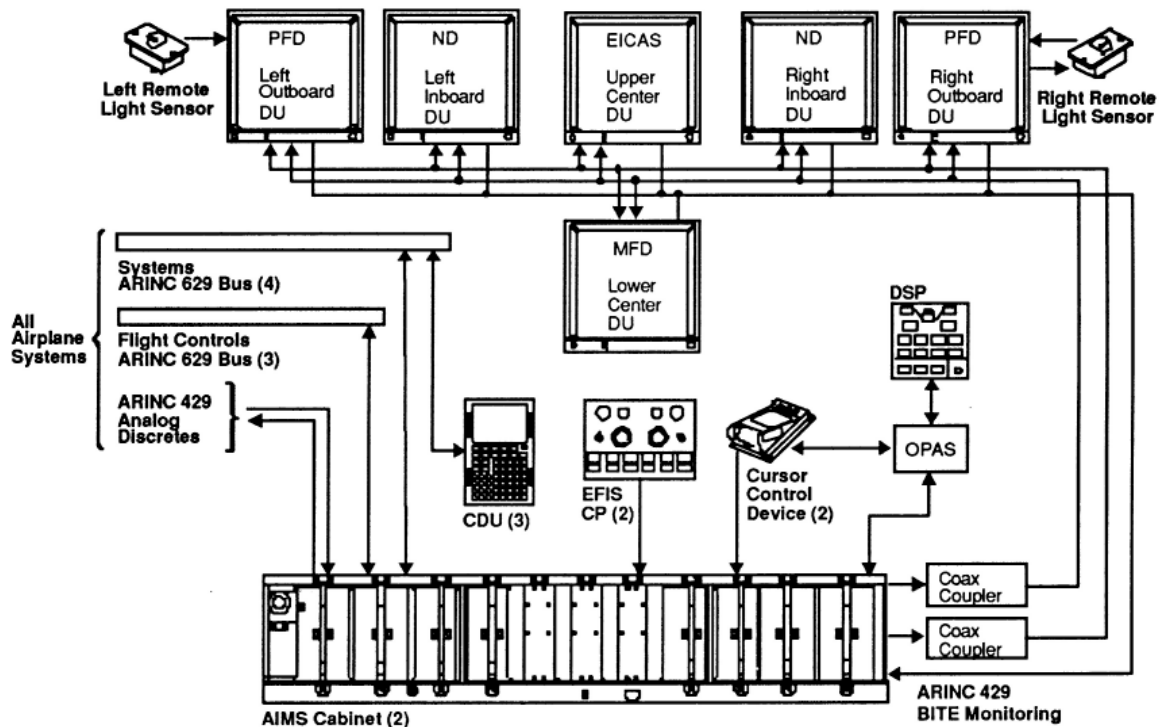


FIGURE 5 - CREW INTERFACE DEVICES AND SENSORS FOR AIMS

In contrast to the estimated 1.4 Tbps capacity anticipated for military aircraft platform networks where all nodes are high speed Gbps nodes and all connected to the backbone network, from a commercial transport aircraft perspective, 90% of all commercial airplane's current data links (as well as current earlier generation military implementations) are less than 10 Mbps for simple sensing and control. High speed data links currently are only needed for network backbone and a few dedicated high bandwidth (between 10 - 100 Mbps) applications such as 3D Navigation and Integrated Surveillance. Because the basic sensing and control functions does not change significantly over the aircraft platform evolution, the future commercial airplane therefore still only have a dozen nodes that need Gbps bandwidth while hundreds of remaining nodes will still be in the 10 Mbps domain. There are hundreds of low speed field buses (CAN, ARINC 429) on the latest Boeing 787 and Airbus A380 commercial aircrafts.

To have any significant reduction in SWAP-C, (C is for cost) more effort is needed to address wiring count reduction of the field buses or access networks that are the 90% of the data links, in addition to the all important backbone network that is the current focus of the WDM LAN effort. Military avionics should also benefit greatly due to wire count reduction such as from aggregation. Due to its low speed, copper access network is low cost, low weight, and it will be important that any glass fiber based WDM solution can demonstrate a good business case in the near term.

The top three issues for deploying fiber optics on commercial aircraft are

- High cost of ruggedized transceivers and connectors in an avionic environment,
- Maintenance logistics of ensuring cleanliness of fiber end faces & repairing of broken fiber, and
- Fiber cable plant integrity (bends, breaks) during installation.

Also, coarse WDM (CWDM) and dense WDM (DWDM) enabled information assurance may be a cost effective alternative to consider in achieving the goal of reducing optical wire count.

The optical fiber core size directly affects these three issues. A one-size fiber solution such as Single Mode Fiber (SMF) may not be able to meet the business case for different applications with different performance requirements on commercial aircrafts. Any viable fiber optics solution for commercial airplanes must be affordable in terms of acquisition cost and the life cycle cost of installation and maintenance.

To achieve the goal of reducing optical wire count both CWDM and DWDM technologies will be considered for transmission over optical fiber. DWDM over single-mode fiber may be a longer term prospect for some of the system integrators (could be >10 yrs for some system integrators) and both multimode fiber and POF may be viable solutions along the path (POF is not likely to find application on military aircraft due to the harsher environment to which they typically are exposed). Nevertheless, the standardization process can start now, in anticipation of TRL maturation and FAA certification processes.

4.1.3 Cable Plant

For a WDM OBN, the fundamental physical layer cable plant is an optical fiber, represented hereafter as a collection of optical fiber interconnects (OFI). There are several options for transporting wavelength over an optical fiber network. While cable plant requirements are not detailed in this document, the AS-5659 specification effort will need to be coordinated with the SAE's ASD task groups to ensure that the network and systems requirements are supported by the defined cable plant. In this document, we define a template for an OFI transfer function (see Section 7.2, Table 6), that identifies key parameters needed for characterization of performance of an OFI. The OFI transfer function can be used in conjunction with ASD AS3 and MIL standards documents to describe performance requirements for an optical fiber cable plant, and in conjunction with the ONE transfer function to describe performance of a collection of Optical Backbone Elements OBEs (namely an interconnected set of ONE and OFI).

The availability of a practical, maintainable and future proof cable plant is a gating item to the development and adoption of the WDM LAN systems and the concepts established in this document. Early adopters of WDM LANs are likely to use simple network architecture and initial implementations of a practical cable plant that ideally would conform to an upgradeable cable plant design. Development of this upgradeable cable plant will be taken up during the drafting of AS-5659 specification.

The following are definitions of some key cable plant concepts:

- Bidirectional Fibers: A single fiber with signals propagating in opposite directions in a single optical fiber.
- Unidirectional Fibers: Optical fibers where signals propagate in one direction per fiber.

Figure 6 depicts some of the key concepts and difference and possible combinations.

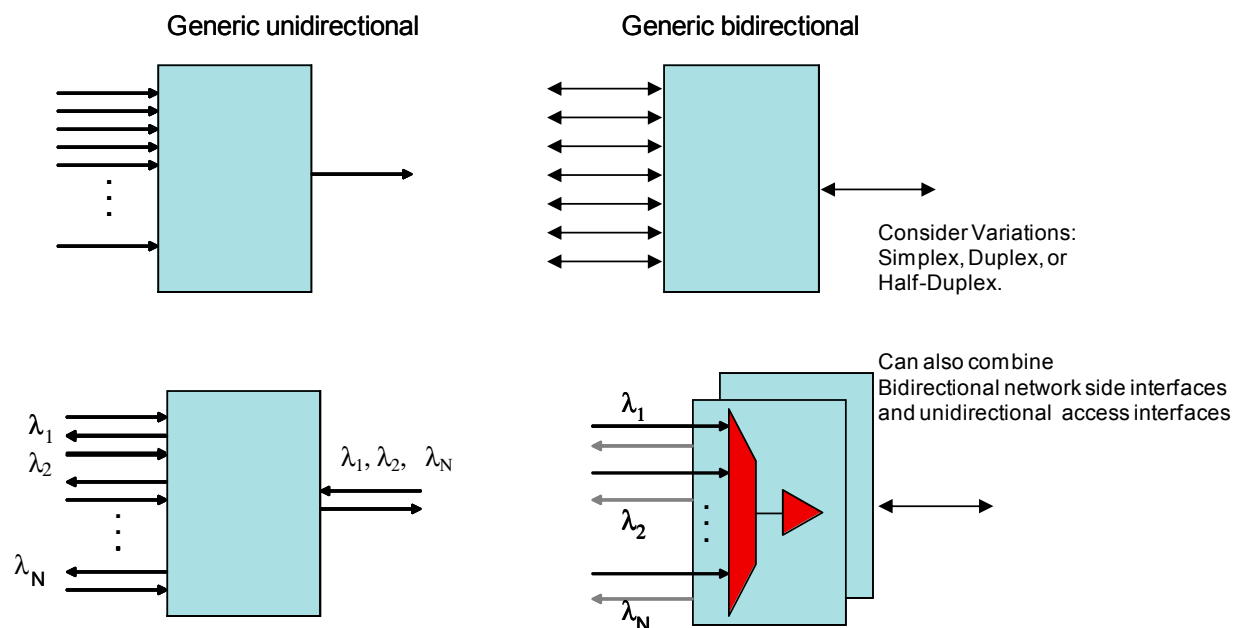


FIGURE 6 - REPRESENTATION OF UNIDIRECTIONAL AND BIDIRECTIONAL FIBER INTERFACES FOR WDM LAN OBN NETWORK ELEMENTS

4.1.3.1 Single mode and Multimode fiber Considerations

As shown in the taxonomy described in Section 5.5.2, the WDM LAN is likely to be composed of single mode fiber in the core backbone network, with potential single mode and multimode fibers used in access subnetworks that provide connectivity to the WDM LAN Backbone. However, in most current avionics installations, multimode fiber is used for point to point links using 850 nm wavelengths. A multimode fiber could also support CWDM architecture with channel separation of 200 GHz or higher at a cost of enhanced insertion losses. Unfortunately, there are no conveniently available multimode optical amplifiers similar to those for single mode fiber to offset this loss. In many avionics applications, CWDM and hence MMF will suffice the needs of the **current** bandwidth. However, the trends and expectations for bandwidth growth in aircraft platforms are for significant increase in demand and applications. Low cost technology paths will need to be considered across military and commercial platforms (as described earlier cost factors often outweigh bandwidth requirements in commercial platforms).

Since the typical lifetime of an aircraft is typically over 30 years, upgrades or migration to SMF will be needed (currently this is an expensive endeavor). The avionics industry can leverage the extensive commercial development and COTS hardware available for standard step index 9.3 micron mode field diameter single mode fiber used by the Telecom industry. Due to the short distances expected in avionics platforms, we do not expect significant nonlinear or dispersion effects. Thus installation of standard single mode fiber is preferred as opposed to using dispersion shifted fibers or smaller mode field diameters, bend-resistant designs which will increase the possibility of non-linear effects and reduce power handling capability. Specialty large core (as much as 35 μm) diameter SMF are also available such as crystal fiber but these are very fragile and difficult to handle and characterize besides their astronomically high cost of greater than \$100/meter. Developments in SMF were covered at the 2007 IEEE/AVFOP conference.

4.1.4 Critical Network Characteristics

Critical network characteristics to meet avionics systems, computing architecture and the underlying infrastructure needs, that enable support of future-proof networks in a flexible and scalable manner, include:

- supporting state-of-the-art bandwidth,
- a service rich environment
- low latency interconnection and switching

Additional essential network features for commercial aircraft platforms may include:

- Reduced network integration complexity: Systems integration is one of the most expensive and time consuming endeavor in developing a new aircraft. Implementation of a WDM LAN affects system integration critically in many ways. Higher level of integration results in higher level of complexity for safety analysis. For instance, highly integrated common data networks can be more complicated to certify than the separate network channels on the same platform.
- Improved network traffic efficiency: Inter-network domain traffic should be minimized and common technology elements among the different networks should be maximized.
- Fault tolerant network with graceful degradation: Network fault characteristics must be well understood for all aspects of fault hypothesis, failure mode complexity, fail safe, fail graceful, and fail silent (among others). Similarly, fault tolerant aspects of fault containment zone, fault detection, identification, isolation, reconfiguration, and fault degradation characteristic must be well understood.
- Providing high integrity network: Purely optical, unmanaged switch may not have integrity monitoring and policing features considered critical for safety systems. Currently no single thread device (not a self checking pair) can claim high integrity (e.g., $1\text{E-}9$ probability of undetected corrupted data for critical systems). This is different than reliability which is a dependability measure in terms of continuity of service e.g. time to failure.

Independent of high bandwidth, the network transport elements need to ensure temporal integrity (timing, delay), ordinal integrity (correct sequence of data), cardinal integrity (corruption of data value) and source integrity (authentication of the data source). Solutions providing more rigorous network security, management, and control of transported data are needed.

As such, the WDM LAN and its OBN infrastructure need to be flexible and scalable, to enable design and implementation of “future-proof” optical networks. While early implementations may not require large increases in capacity, it is desirable that future growth, in application requirements and number of applications supported can be accommodated without changing the cable plant that is initially put in place.

O-005: It is desirable to design an OBN that is scalable, enabling introduction of new network nodes, access ports and applications without having to recertify the optical physical infrastructure equipment and cables (e.g. during a technology refresh of the systems aboard an aircraft). Scalability encompasses:

- scaling the number of client nodes that can access ONEs at NAIs,
- scaling the number of backbone nodes (ONEs)
- scaling in data rate at NAIs
- scaling to support new applications and formats,
- scaling to meet key performance objectives for an OBN in a future-proof infrastructure.

Examples of scalability performance objectives are provided below and are further detailed in Appendices B and C.

In this section we provide highlights of two studies as two examples of the networking requirements aboard aircraft. The first example is a set of network performance requirements derived from a study conducted during a 2006-2007 DARPA project on Requirements for Optical Networks in Avionics (RONIA). In the second example, requirements are derived from Boeing analyses of messaging traffic to validate compliance with operational requirements that led to requirements for the JSF X-32 Demonstration Aircraft; results were used to project Airborne Antisubmarine Warfare (**ASW**) and Intelligence, Surveillance and Reconnaissance (**ISR**) platforms (i.e. ASW/ISR platforms) as summarized in a 2007 Boeing white paper.

4.1.4.1 RONIA Example: State of the art bandwidth

The following table provides representative examples of requirements derived from the DARPA funded Requirements for Optical Networks in Avionics (RONIA) program (under contract HR0011-06-C-0017) highlighting the diverse bandwidth, connectivity – number of links and nodes, redundancy and latency requirements that can be expected in tactical and widebody military aircraft platforms. Participants in the RONIA project included Telcordia Technologies (prime), Boeing, Lockheed Martin, NAVAIR and AFRL. More details about the RONIA study are provided in Appendix B (please refer to Section B.1 of this document).

Table 4 is a summary of the requirements derived from representative tactical and widebody platforms. These requirements will, in part, drive the set of functions to be supported in the WDM OBN Optical Network Elements (ONEs) defined in more detail Section 5 in this document. Table 4 combines the bandwidth and latency information in Appendix B.1, from Table B.1 and Table B.2, along with making the information more generic for avionic platforms. For example, RONIA Category F from Table B.1 and RONIA Category V from Table B.2 have been combined into Category 1 in Table 4 while RONIA Category D and RONIA Category U are combined into Category 2.

TABLE 4 - REPRESENTATIVE AVIONICS PLATFORM REQUIREMENTS (RONIA SUMMARY)

Category	Channel Data Rate (Gbps)	Total Supported Channels	Aggregate Data Rate (Gbps)	Channel Redundancy	Connection Type	Maximum Connection/ Routing Latency
1	0.03	32	1	Dual	Circuit	1 μ s
2	0.10	16	1.6	Quad	Circuit	5 μ s
3	0.65	16	10.4	Dual	Circuit	1 μ s
4	0.65	16	10.4	Dual	Switched	1 ms
5	1.25	16	19.6	Dual	Circuit	1 μ s
6	1.25	32	39.2	Dual	Circuit	1 μ s
7	2.5	8	20	Single	Circuit	1 μ s
8	2.5	16	40	Dual	Circuit	1 ms
9	2.5	64	160	Dual	Switched	5 μ s
10	10	32	320	Single	Circuit	10 ms

Additional modifications to the data represented in Table 4 include adjusting the channel data rate to agree with standard Telecom rates where possible such as the case for Appendices B & C which extends RONIA Category A and aligns more closely with the data rate for OC-192/STM-64. The total number of supported channels has been mapped to the nearest power of 2 for convenience. These two values then provide the aggregate data rate of the category for the purpose of determining the capacity of the required network. In the study results, channel redundancy refers to the minimum number of separate paths available. In the most basic example, dual redundancy would require two separate data links.

The connection type falls into two categories: circuit and switched. A circuit connection type includes physical connections, essentially an un-switched circuit. This type would cover streaming data and hard deterministic setups where a channel is guaranteed a certain amount of bandwidth. This would apply to a typical time division multiplexed (TDM) setup. A packet connection type refers to the case where the data is placed into packets and each packet is routed through the network on a packet-to-packet basis.

The latency time is one of two types depending on the connection type. For a circuit connection type, the time refers to the connection latency or setup time. This is the time required to establish a channel. Note that this latency is not incurred for every data bit but just during the initialization of the channel. For a packet connection type, the time refers to the routing latency. This is the time it takes to route a packet. For example in a routing device, how much time is required to read the packet header, transfer the packet to the correct output, and retransmit the packet.

This information was used to generate a set of network performance objectives for a baseline WDM LAN backbone network, as described in the tables in Appendix B in Section B.1, which include the overall number of links, nodes, and bandwidth supported based on the particular applications studied in RONIA.

RONIA Summary: While the data in Table 4 gives a perspective on the number of links or channels supported, the bandwidth expectations, and redundancy and latency requirements, it does not provide an estimate of the number of systems for each of the categories described. Another approach was used in the RONIA project to estimate the key overall aircraft network requirements and that data is provided in Tables B.1 and B.2 in Appendix B. In addition to bandwidth and node count requirements, the RONIA project included a preliminary analysis of the diverse latency and redundancy requirements represented by the systems included in the study. The result of the study can be found in a presentation approved for public distribution from the May 31, 2007 SAE WDM LAN Requirements working group meeting ("Motivation for WDM-based Optical networks in Avionics Applications"). Key network performance objectives for a backbone optical layer network that can provide a future-proof infrastructure include:

- Number of nodes supported: ~ 400 (assuming some nodes use aggregation)
- Data Rate: 1 Gb/s or greater per node (i.e. per data source or sink – either dedicated or aggregate)
- Number of links supported: > 500 (total number of links across all the systems studied)
- Total backbone capacity supported: ~ 1.4 Tb/s
- Latency: support multiple requirements in the same WDM infrastructure:
 - Connection latency includes circuit set-up in circuit-switched applications (~10 ms) & routing/processing latency for packet-switched applications (several μ sec)
 - Transport latency: propagation delay, correlated to aircraft size is minimal on airplanes (1 μ s or less). We assume < 100 ns for tactical and < 1 μ s for widebody.
 - Need to account for additional latency associated with the insertion of an optical network to support avionics systems.
 - Also analyze tradeoffs – e.g. compare optical connection setup time vs packet switching queuing/processing

- Redundancy: support multiple protection and restoration types in the same WDM infrastructure – the redundancy requirements impact the processes for fault detection, identification and reconfiguration.
 - Channel redundancy refers to the minimum number of separate paths available. For example, dual redundancy would require two separate data layer links.
 - Tactical and widebody platform included a combination of non-redundant, dual redundant and quad redundant subsystems.
 - Many redundancy options can be supported within a common WDM infrastructure; can specify redundancy requirement per “SLA” (COS / QOS) to satisfy a reliability or availability objective of the avionics application
 - WDM-based networks enable a logical circuit view vs physical link view of redundancy supported on the embedded optical infrastructure
- Connection type: support multiple connection types (e.g. random, bursty, continuous, circuit-switched and packet switched).

4.1.4.2 Boeing White Paper Example (2007)

The network objectives provided in this example are driven by a specific set of applications that emerged from a Boeing analysis of critical network characteristics to meet avionics computing architecture needs from Tactical aircraft to Airborne Antisubmarine Warfare (**ASW**) and Intelligence, Surveillance and Reconnaissance (**ISR**) platforms. The characteristics include: (1) state-of-the-art bandwidth; (2) service rich environment; and (3) low latency switching. Network connection performance evaluations were made on the next generation network developed by Boeing for its JSF X-32 Demonstration Aircraft. Its tactical computing architecture network was extrapolated to present day ASW/ISR computing architecture needs.

ASW/ISR system processing and network distribution is increasing along with the need to support increased messaging traffic. The ASW/ISR example demonstrates the need for equivalent or better network performance. The end-to-end message latency is dependent on network bandwidth, connection arbitration, and circuit switching time. Network throughput demands are ever increasing as a result of the increased traffic messaging demands that meet operational needs of emerging, more capable and more highly parallel ASW/ISR systems.

A more detailed description of the analysis and results can be found in Appendix C of this document.

We highlight key conclusions derived from the white paper and its analysis vis-à-vis WDM LAN:

Optical transport and WDM LANs will provide a viable and far more scalable infrastructure to carry low latency, deterministic Ethernet/Fiber channel and high capacity (e.g. 10 Gb/s signals) described in the application. Fault tolerant, optical WDM transport of connectionless packet and analog/non-packet traffic between access nodes on the ONE-based transport backbone will use specific ONE functions (three of the functions are highlighted here).

- a. to optically switch small packet messages (without dropping them due to blocking by a large packet message). This ONE function will require optical switching at sub-micro second speed;
- b. to configure optical paths for fault tolerance and to configure circuits for analog/non-packet based traffic. This ONE function will require optical switching at 1 to 50 millisecond speed;
- c. to unicast, multicast, and broadcast traffic (these traffic types can occur optically within the defined ONE or electrically within client nodes that interface to ONE through NAI ports)
 - For unicast traffic, an ONE function that selects a single wavelength is needed.
 - For multicast traffic, an ONE function that provides selective optical gain or wavelength conversion elements is needed for use within optical bus or network interface modules that selectively distribute bands of wavelengths.
 - For broadcast traffic, an ONE function that provides optical gain for cascading and splitting is needed within optical bus or network interface modules that passively distribute all wavelengths.

4.1.5 Aircraft Systems Differentiators

As shown in Section 4.1.4, the requirements for network performance (from both examples provided, RONIA and the JSF X-32 Demonstration Aircraft white paper) must accommodate a variety of signal types, format, data rates, latency, connectivity and protection/redundancy differentiators among others, to support the diverse set of aircraft systems. As such each of the aircraft systems can be described from among the following set of characteristics:

- Packet switched or circuit switched data
- Bursty or deterministic, random or continuous
- Analog or digital
- Aggregated and non-aggregated applications
- Unicast, multicast, broadcast.
- Non-protected, dual, triple or quad redundant

4.1.6 Connection Latency & Determinism

Latency in its plainest description is the time it takes for a signal to get from the network access interface (NAI) at node A to the NAI at node B without leaving the optical backbone network (OBN). As with optical and most other relevant network structures, this resulting latency is influenced by a variety of intermediate network entities. Latencies present in the network can be discerned into the two distinct categories of transport latencies and setup latencies. Transport latency is the time it takes for the information to travel from the source to the destination through either a previously determined network path or for connectionless services a path determined by each ONE on a hop by hop basis. Elements applicable to an optical network that contribute to this delay include the medium(s) of propagation, signal amplification/repeater stages, electronic to optical (E/O) and optical to electrical (O/E) conversion stages (wavelength conversion as an example), and optical switch stages. An example is provided in the Figure 7. Let the start of a frame appear at the output of Node A at time, t_1 , and arrive at the input of Node B at time, t_2 . The transport latency is defined as $t_2 - t_1$ for this example. The overall latency is the sum of the OBE latencies (including latencies attributed to ONE and to OFI, as shown in Figure 7, i.e. Transport Latency = $\Sigma(\Delta t_a, \dots, \Delta t_e) + \Sigma(\Delta t_1, \dots, \Delta t_4)$).

Also note that the transport latency is not all of the latency an application will encounter. For example, the node itself may add latency through adding headers to the application data which are necessary for the network. This additional latency introduced by the node is referred to as Node Latency and includes any queuing, processing, buffering, store-and-forward functions that the node may perform.

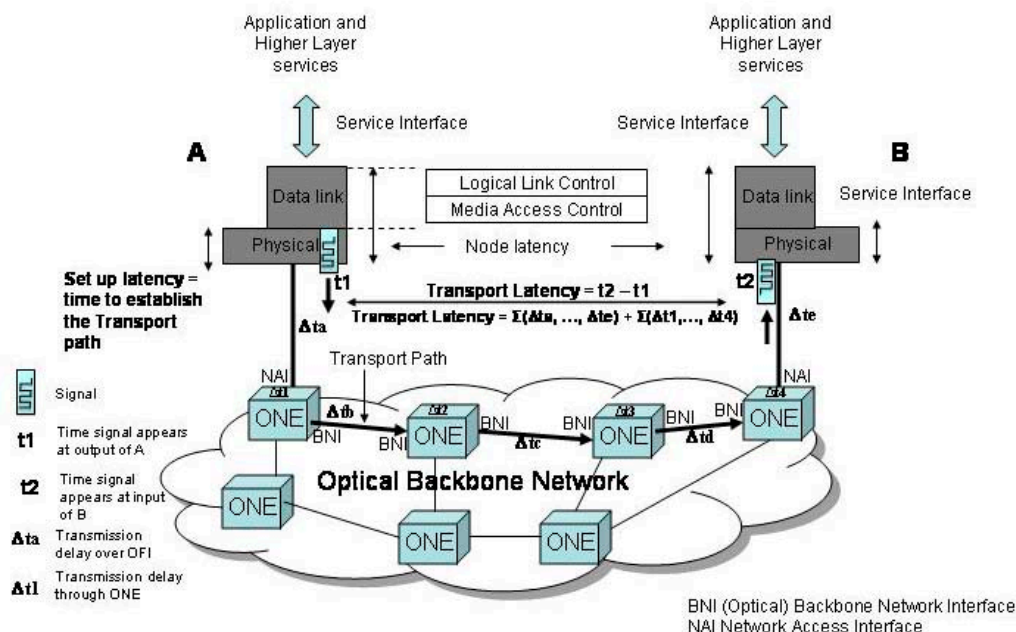


FIGURE 7 - OBN ONE INTERFACES AND ASSOCIATED OBN LATENCY CONTRIBUTORS.