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13. ABSTRACT Networks have been rapidly evolving over the last several decades and continue to do so today. This evolution has been driven by a need for increased performance, as characterized by increased data rates and larger bandwidth. This project focused on the development of a reconfigurable network architecture that connects existing Local Area Networks (LANs) to create an extended LAN. The network uses optical fiber and supports data transparency. This Fully Interconnected Optical Network Architecture (FIONA), uses Dense Wavelength Division Multiplexing (DWDM), wavelength conversion and out-of-band control to achieve all-optical routing within the network. The architecture uses all-optical wavelength conversion as both a mechanism to route data and to reconfigure the network in the event of a link failure. A portion of the network was constructed and a simple control algorithm was implemented. Proof of concept testing was completed, demonstrating all-optical routing of data and out-of-band control. The network has demonstrated some ability to handle mixed signal transmission, and its data transparent nature allows for the connection of heterogeneous LANs to form a single extended LAN. The reconfigurability of the network improves survivability and fault tolerance without necessarily adding redundant systems or links. Fiber optics allow for higher data rates and larger available bandwidth compared to existing copper networks. The mixed signal nature of the network eliminates the need for pre-transmission conversion of analog data and enables the interconnection of analog and digital devices. FIONA is an improvement over existing access network architectures, such as those used in shipboard and avionics applications. It provides greater connectivity between local area networks, resulting in increased network performance.				
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**DEVELOPMENT OF A FULLY INTERCONNECTED
OPTICAL NETWORK ARCHITECTURE (FIONA)**

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Abstract

Networks have been rapidly evolving over the last several decades and continue to do so today. This evolution has been driven by a need for increased performance, as characterized by increased data rates and larger bandwidth. This project focused on the development of a reconfigurable network architecture that connects existing Local Area Networks (LANs) to create an extended LAN. The network uses optical fiber and supports data transparency. This Fully Interconnected Optical Network Architecture (FIONA), uses Dense Wavelength Division Multiplexing (DWDM), wavelength conversion and out-of-band control to achieve all-optical routing within the network. The architecture uses all-optical wavelength conversion as both a mechanism to route data and to reconfigure the network in the event of a link failure. A portion of the network was constructed and a simple control algorithm was implemented. Proof of concept testing was completed, demonstrating all-optical routing of data and out-of-band control. The network has demonstrated some ability to handle mixed signal transmission, and its data transparent nature allows for the connection of heterogeneous LANs to form a single extended LAN. The reconfigurability of the network improves survivability and fault tolerance without necessarily adding redundant systems or links. Fiber optics allow for higher data rates and larger available bandwidth compared to existing copper networks. The mixed signal nature of the network eliminates the need for pre-transmission conversion of analog data and enables the interconnection of analog and digital devices. FIONA is an improvement over existing access network architectures, such as those used in shipboard and avionics applications. It provides greater connectivity between local area networks, resulting in increased network performance.

Keywords: Fiber Optics, Wavelength Division Multiplexing, Optical Network Architecture, Wavelength Conversion, Mixed Signal, Out of Band Control

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Introduction

When addressing the topic of the ever-changing battlefield, Lieutenant General Harry Raduege, the Director of the Defense Information Systems Agency, said that “U.S. military forces today are creating and executing plans using capabilities that were not available as recently as Operation Desert Storm. This is due to net-centric warfare and the information transfer and sharing that is made available by the Internet. Today, the nation's armed forces, armed with superior technology, gain power from information, access, and speed.”¹ Net-centric warfare (NCW) is defined as the military’s approach to combat in the information age and is highly dependent on the interoperability of communications equipment, data, and software to enable networking of people, sensors, and manned and unmanned platforms.² The purpose of this project was to design a unique fiber optic network architecture that will interconnect heterogeneous local area networks to improve communications and data flow.

Networks have been rapidly evolving over the last several decades and continue to do so today. The evolution has been driven by a need for increased performance, typically characterized by the need for increased data rates and larger bandwidth. One of the more recent developments in the communications field has been the use of fiber optic links within networks. The development of fiber optic networks allows for both higher data rates and increased transmission bandwidth. Fiber optic networks were originally used for telephone communications by GTE in Los Angeles and AT&T in Chicago. Further development of optical sources and photodetectors allowed fiber optic networks to operate at 1300 nm wavelengths where they exhibit lower power loss and no signal dispersion.³ This allowed fiber optics to be used for data transmission, specifically as the backbone for telecommunications including long haul broadband data networks. However, fiber has been less common in local area networks,

due to the prohibitive cost of optical components and lack of demand for the high bandwidth possible with fiber. Traditional wire and copper transmission mediums such as twisted pair or coaxial cable have been used to construct most LANs, and wireless LANs are probably the most common home based LAN. The dropping cost of optical components and recent advances in optical technology have made fiber local area networks possible. A fiber LAN not only allows networks to meet the increasing demands for bandwidth, but also allows for future growth within the network.

In addition to the increased bandwidth of fiber, there are numerous other advantages over traditional transmission media. Due to the optical nature of the transmission, fiber is relatively immune to electromagnetic interference (EMI). This is quite important in military applications, where the electromagnetic spectrum is used by communications, radar and electronic warfare (EW) emitters. The immunity of optical fiber to EMI makes it less susceptible to EW attacks and eliminates the many risks and problems posed by electromagnetic interference.⁴ Optical fiber also demonstrates very low loss when compared to copper, allowing for longer runs of fiber without the need for a repeater or regenerator. For shipboard and avionic applications, this is important because of the high loss interfaces that exist at bulkheads and transmission/reception points. Fiber optics also allows for the simultaneous transmission of mixed signals, meaning that both analog and digital signals can be transmitted simultaneously through the same fiber, eliminating the need for a pre-transmission analog to digital conversion. Mixed signal transmission allows both analog and digital networks to reside on the same extended LAN. For example, analog sensor data could be transmitted over the same fiber as a digital fire control network without having to perform any data conversion prior to transmission. Fiber demonstrates data transparency, meaning that fiber transmissions are not dependent on the

format of the digital data being transmitted. This allows fiber interconnects in networks to be protocol independent, allowing them to connect heterogeneous LANs without having to convert to a particular data format prior to transmission.

Background

The high bandwidth of fiber optic cabling enables new technologies, such as wavelength division multiplexing (WDM). WDM fiber networks carry multiple streams of data in the same fiber by placing each stream of data on a different carrier wavelength. These carrier wavelengths are then combined or “multiplexed” onto a single fiber to carry the information. The aggregate data is transmitted over the fiber until it reaches the destination where each of the carrier wavelengths is demultiplexed so that each signal can be received. WDM is an optical form of frequency division multiplexing (FDM). Frequency division multiplexing is used by telephone companies to carry multiple voice channels over a single telephone wire. Each voice channel is transmitted on a different frequency over the circuit and is then shifted back to its original baseband frequency at the receiver. WDM functions in a similar way, using distinct wavelengths over a single fiber instead of using different frequencies on a single wire. Since these data streams are essentially independent of one another, WDM allows for the simultaneous propagation of both analog and digital signals within the same fiber. Wavelength division multiplexing was made possible by the invention of the optical multiplexer (MUX). The MUX takes multiple optical inputs on different wavelengths and combines them into one output stream. The MUX also functions in reverse; taking a single input stream and breaking it out into multiple outputs, demultiplexing each on a different wavelength. By enabling a network to carry multiple data streams simultaneously, wavelength division multiplexing allows a network to take full

advantage of the bandwidth offered by the fiber without having to invest in expensive transmitters and receivers.

Adam Fisher implemented a WDM network at the Naval Academy as his Trident Scholar project in 2003.⁵ The network he built used an eight node perfect shuffle topology which is an eight node network that has a maximum of three hops between any source and destination. These nodes represent data sources and/or sinks on the network. As can be seen in Figure 1, the network was implemented using four distinct wavelengths

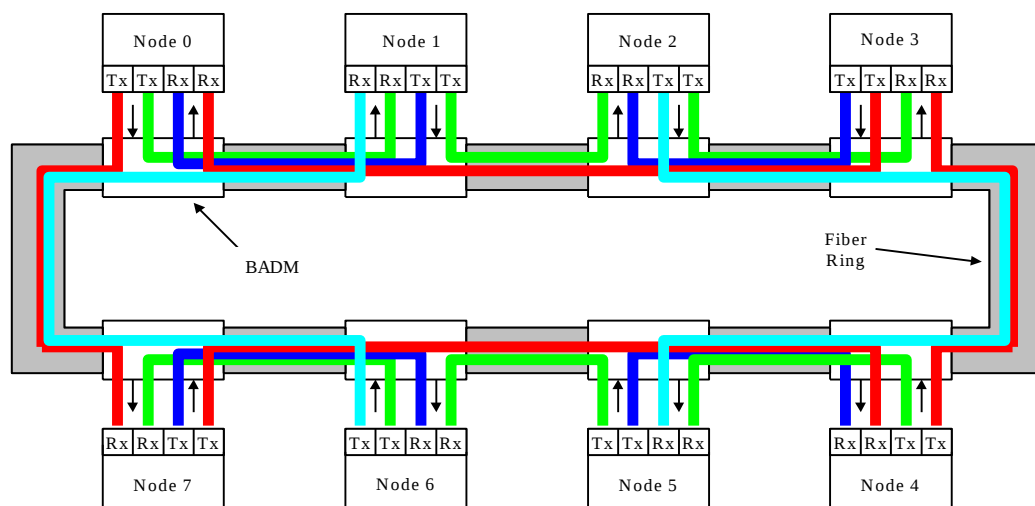


Figure 1: Eight Node Perfect Shuffle using WDM

on a single fiber ring. Note that each color represents a different wavelength that is used to transmit data through the network. There can be as few as two and as many as four different wavelengths in the single fiber ring at any time. The interface with each node uses a custom made Bidirectional Add/Drop Multiplexer (BADM) to add and drop signals from the network. The bidirectional nature of the BADM allows for some degree of reconfigurability within the

network because it offers multiple paths for each source/destination pair. Transmitters and receivers are labeled as Tx and Rx, respectively. Using this network, Fisher successfully demonstrated bidirectional data flow and mixed signal transmission. While Fisher's network successfully demonstrated wavelength division multiplexing, it lacked any form of control to regulate the flow of data across the network.

The task of implementing control was undertaken in 2004 by Joshua Wort as his Trident Scholar project.⁶ Wort's goal was to implement a packet switching algorithm within the network that had been designed by Fisher. Packet switching is the form of routing used by the internet. It functions by attaching headers to packets of data and using those headers to route the data through the network. This process, called encapsulation, is a form of in-band control because the control is embedded within the data and they are transmitted together on a single wavelength. Figure 2 shows the seven layer Open System Interconnect (OSI) model, a reference model developed by the International Standard Organization (ISO), which uses data encapsulation. The OSI reference model has seven separate layers that describe the different functions that are carried out in the communications process. These seven layers form what is known as the stack. The data begins at the top of the stack at the application layer where the first header is added. It then "proceeds" down the stack and a header is added at each successive layer. The

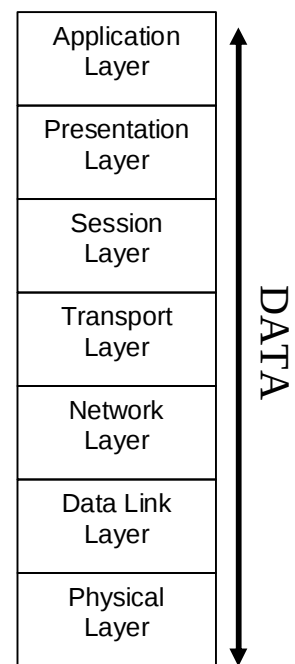


Figure 2: 7 Layer OSI Network Model

control of the data is local to each header and is processed in a peer to peer manner as the data moves through the network. At each node, whether it is an intermediate node or the final destination, the data travels back up a portion of the stack and the header for that layer is stripped

off and processed. A routing decision is then made, based on the address information contained in the header. Once the data reaches its final destination, it makes its way back to the application layer where it is presented to the end user. This routing method works well for the Internet, because the data is segmented into small packets and each packet is routed separately to the end destination. Therefore, a dedicated transmission path is not required for source/destination pairs. The OSI model also allows the Internet to use a “store and forward” routing method which means that packets are buffered at intermediate nodes along the transmission path.

Wort chose to use in-band control because his project focused on a single LAN where the control was only used to direct traffic from one homogeneous node to another. Out-of-band control utilizes a control signal that stays completely separate from the data signal throughout the entire transmission. As can be seen in Figure 3, the data remains

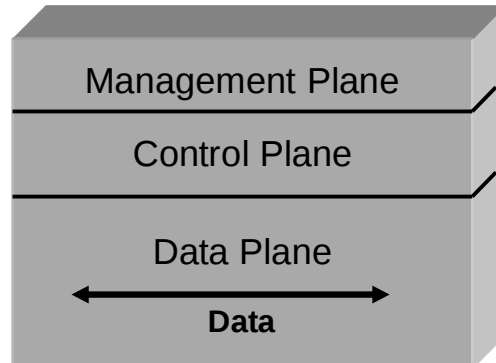


Figure 3: Out-of-Band Network Model

exclusively within the data plane, and the control signal stays within the control plane. Optically, the easiest way to implement out-of-band control is by using a separate wavelength channel for the control. Since the control signal is on a separate wavelength, it does not need to interact with the data. In many other mixed signal networks, analog data is converted to digital packets before being transmitted across the network. In this type of network, mixed signal

transmission is possible with in-band control because once the data is converted, the control can be easily added in the form of a header. However, with out-of-band control the analog data can be transmitted without being converted to digital packets because the control does not need to be added to the data. Since the control does not interface with the data, the network is then not dependent upon the format of the data. Hence, mixed signal transmission is possible when using out-of-band control.

Another characteristic of the packet switched network developed by Wort is that it required an optical to electrical to optical (OEO) conversion to take place at each node before any routing decisions could be made. This OEO conversion resulted in decreased network performance because the additional time required to perform these conversions increased the latency of the connection. One way to increase network performance was to create an all-optical network. In 2005 Clifford Jessop used an all-optical wavelength converter to help solve this problem.⁷ The schematic for this wavelength converter can be seen in Figure 4. Data is input on λ_1 , in this case 1548.1 nm, and is passed through an erbium doped optical amplifier (EDFA). The EDFA allows for independent adjustment of the input data power level. The signal is then multiplexed with continuous wave (CW) light on a second wavelength, λ_2 , which is generated by a tunable laser. The output wavelength is selected using the tunable laser and corresponds to λ_2 . Both signals are then passed through a semi-conductor optical amplifier (SOA). The wavelength converter uses the gain saturation characteristics of the SOA to transpose the data from λ_1 onto λ_2 . The output is then passed through an attenuator and the signal on λ_2 is extracted using a demultiplexer. One side effect of this process is that the data output on λ_2 is

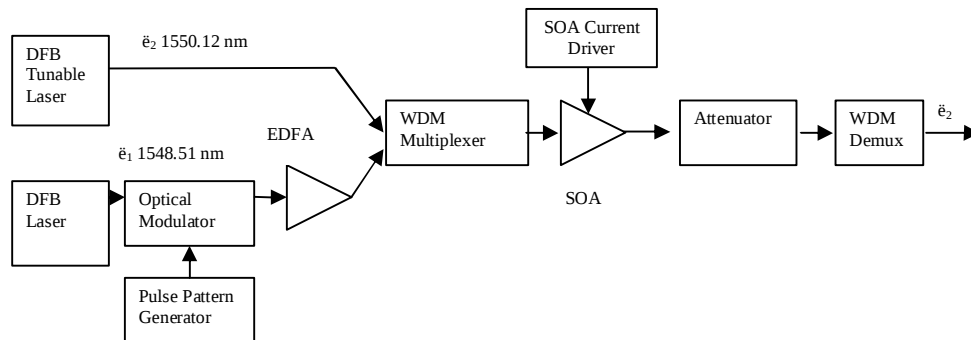


Figure 4: Cross-Gain Wavelength Converter

inverted from the data that was input on λ_1 . However, this can be easily corrected for digital data by using an inverter at the receiver. By combining the out-of-band control with the wavelength converter designed by Jessop, it is possible to have an all-optical routing solution for the WDM network and eliminate time consuming OEO conversions.

While Fisher's perfect shuffle network successfully demonstrated mixed signal transmission and bidirectional data flow, it was not designed to be used as a backbone to connect heterogeneous LANs. The requirements for the network in this project were originally derived from a problem statement that was issued at the 2005 Institute of Electrical and Electronics Engineers Avionics, Fiber Optics and Photonics (IEEE AVFOP) conference. According to this statement, "The program, *WDM Local Area Network SUPERNODE*, is aimed at development of an optical supernode technology capable of upgrading and/or replacing all previous avionics architecture network interface nodes.⁸" The first part of the problem statement specified that the network needs to be an all-optical network composed of multiple WDM supernodes and that these supernodes are required to upgrade or replace all existing avionics interface nodes. Therefore, they must be compatible with different types of networks and must interface with

existing legacy systems. Legacy systems are currently deployed systems that must continue to be supported when upgrading to a new network. Ideally, the network will also support mixed signal transmissions to allow for both analog and digital LANs in addition to supporting multiple digital data formats. Each supernode must be completely data transparent and protocol independent to allow for the numerous types of LANs that will be connected across the network. Finally, the network must be able to sustain battle damage and therefore needs to be reconfigurable in the event of a link failure. No existing network was found that satisfies all of these requirements; therefore, one needed to be developed.

Project Summary

Four major goals were set forth at the beginning of the project. The first was to define a network architecture that met the requirements of the AVFOP problem statement. This architecture should be well defined so that the backbone can be constructed and tested using current technology. The second goal was to design and program a control algorithm that will allow for autonomous control of the network. The algorithm should allow for reconfigurability within the network and should be testable on the constructed network model. The third goal of the project was to design and implement a control interface. The interface must allow the control algorithm to control the network and allow for the routing of data based on the information contained in the control signal. The interface includes the transmission medium for the control signal and any connections between the physical network and the computer that runs the control algorithm. The fourth and final goal of the project was a successful proof of concept demonstration of the network. This demonstration must involve the successful routing of data through the network using the control algorithm to make routing decisions. All four of these

goals were satisfied, and the end result was a successful proof-of-concept demonstration of a functional backbone network.

Network Architecture

Figure 5 shows a logical representation of the access network that was originally proposed at the inception of this project. This access network was designed to interface

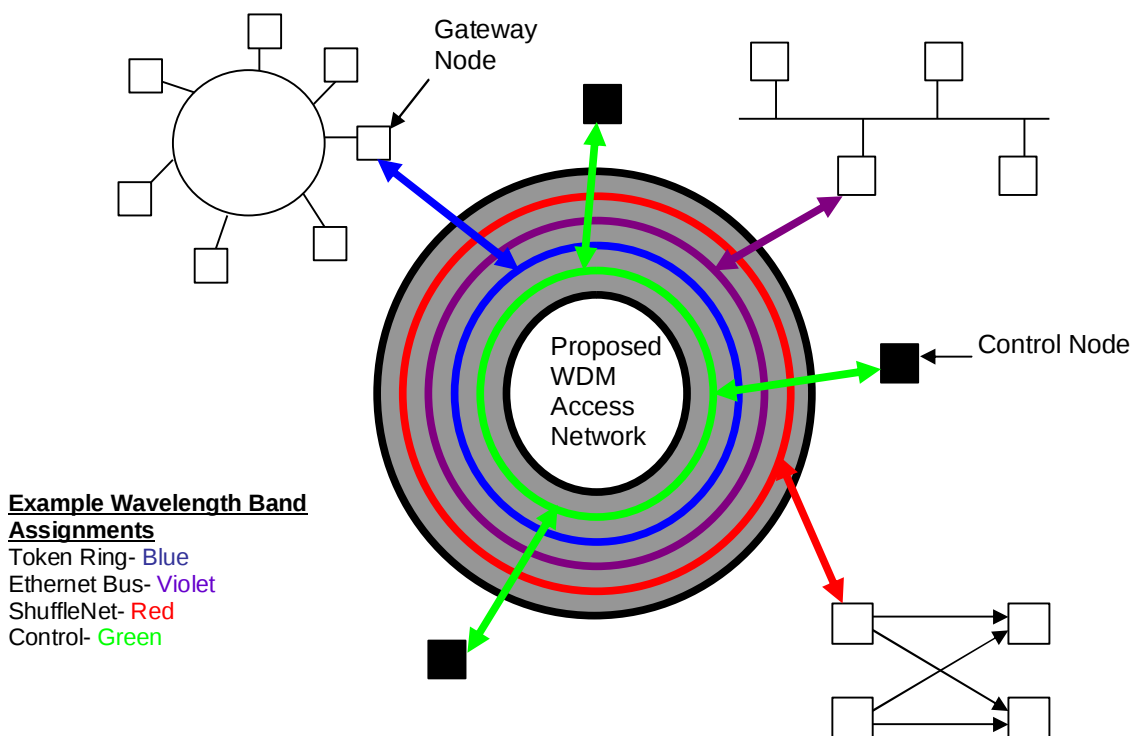


Figure 5: Logical Representation of Proposed Access Network

with existing LANs to create a single extended LAN. In this example, each single LAN could transmit across the access network on a given wavelength while the control nodes transmit across the access network on a separate (green) wavelength. Since the control signal uses a wavelength channel different than the data signal, this implements out-of-band control, as discussed earlier. However, much of this network architecture was not clearly defined, as can be seen in the

physical representation of the proposed network in Figure 6. This figure shows that the interface between the control nodes and external

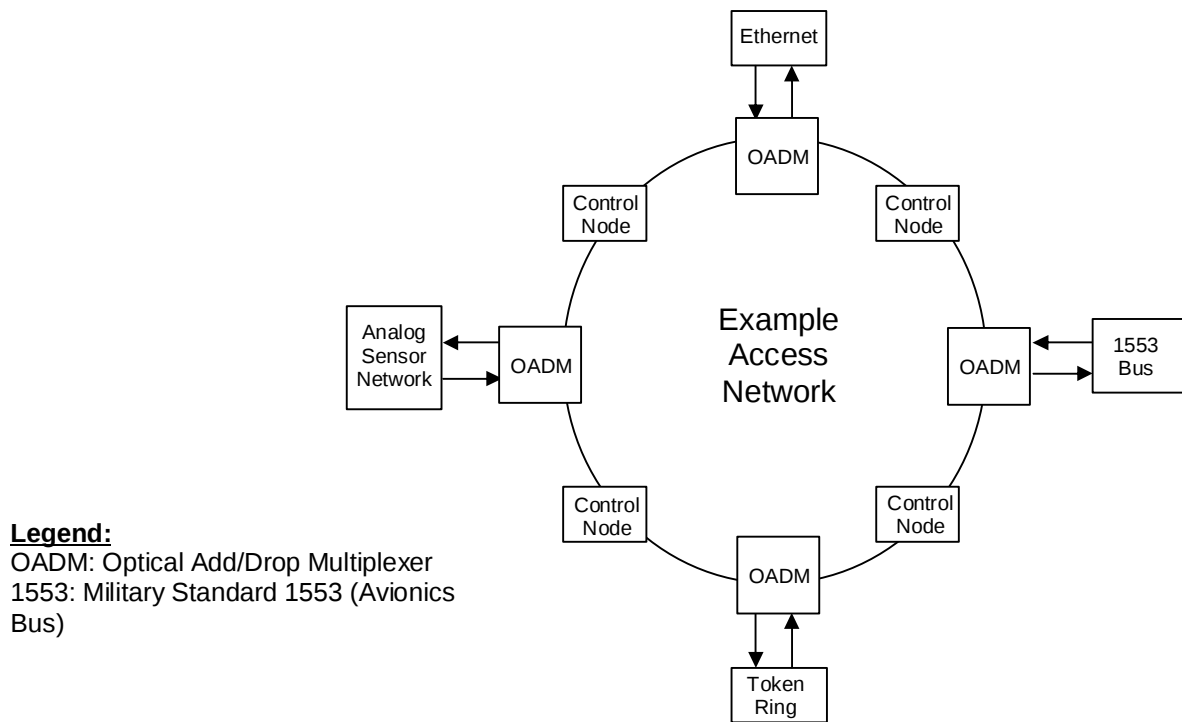


Figure 6: Physical Layout of Proposed Access Network

LANs was not defined beyond placing a control node between each LAN. Based on the original proposal, it was possible to build a control node capable of passing data and performing wavelength conversion. However, without further definition a full network was not physically realizable, and therefore, a proof-of-concept demonstration would not have been feasible.

Additional requirements and specifications were necessary to better define the network architecture. The Fiber Optics and Photonics Division at Naval Air Systems Command in Patuxent River, Maryland (NAVAIR) provided further clarification as to the particular specifications that the aviation community would desire in an advanced avionics network. Along with the specifications, NAVAIR provided a notional network as seen in Figure 7. The size of

the network was set at 128 nodes subdivided into 4 groups or subnets of 32 nodes. The network could be divided further as long as it met the minimum requirement of four groups. The performance requirements specified by

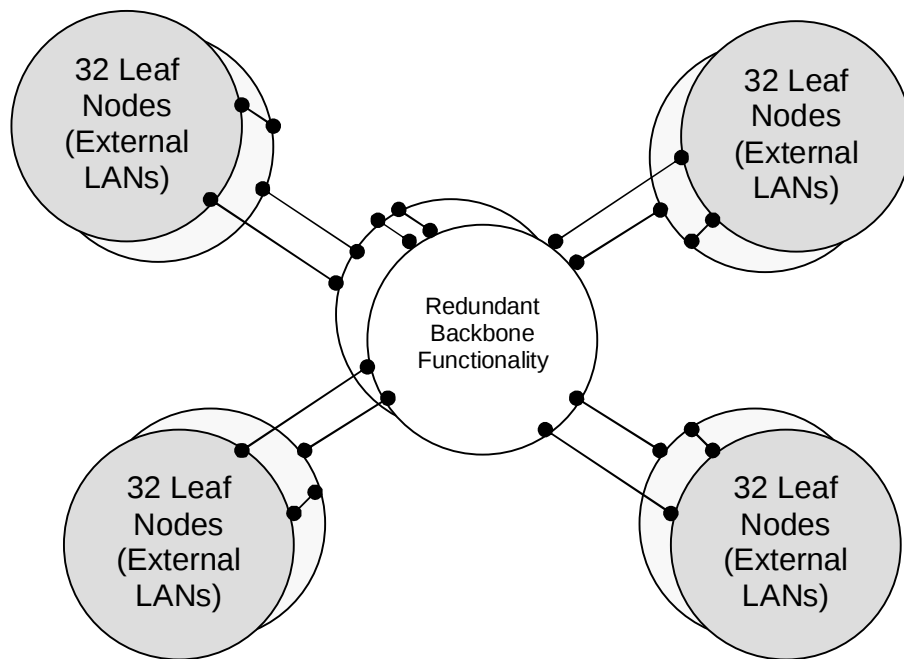


Figure 7: Network Layout Provided by NAVAIR

NAVAIR included the ability to send 8 simultaneous inter-subnet messages and 32 simultaneous intra-subnet messages. Inter-subnet messages are defined as messages that transit the access (backbone) network from a source LAN to a destination LAN and intra-subnet messages are defined as messages that remain local to a particular LAN. Another specification required reconfigurability in the case of a link failure.

Using the requirements derived from the AVFOP problem statement and the specifications recommended by NAVAIR, a notional network architecture was developed. We refer to the resulting network as a Fully Interconnected Optical Network Architecture (FIONA), and as shown in Figure 8, it contains a backbone with 16 access nodes. Approximately eight leaf

nodes can be attached to each access node, resulting in 128 total leaf nodes in the overall network. Although FIONA was designed to meet the

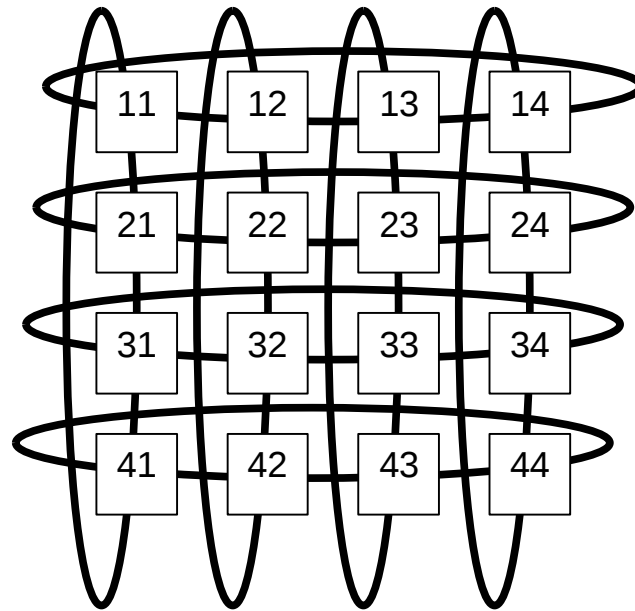


Figure 8: Fully Interconnected Optical Network Architecture

requirements of an avionics access network, it is completely scalable and can be expanded or reduced depending on the network requirements. FIONA could be used in other network backbone applications, such as aboard a ship or submarine. However, the avionics operational environment imposes some of the toughest constraints on the network physical layer. Hence, if FIONA meets avionics requirements, it likely can be adapted to other platforms and applications.

Though FIONA looks different than the originally proposed access network as seen in Figure 5, it implements the same backbone functionality. FIONA connects up to sixteen heterogeneous LANs via a transparent and protocol independent backbone network. The physical topology in each row/column is achieved by modifying the original eight node perfect shuffle network that was built by Adam Fisher. By creating node pairs, the network shrinks from eight nodes to four nodes, labeled A-D, as seen in Figure 9. In comparing Figure 9 to Figure 1,

note that four of the connections can be eliminated when the nodes are paired. Pairing consists of combining the BADMs at each of the two nodes shown in the black boxes.

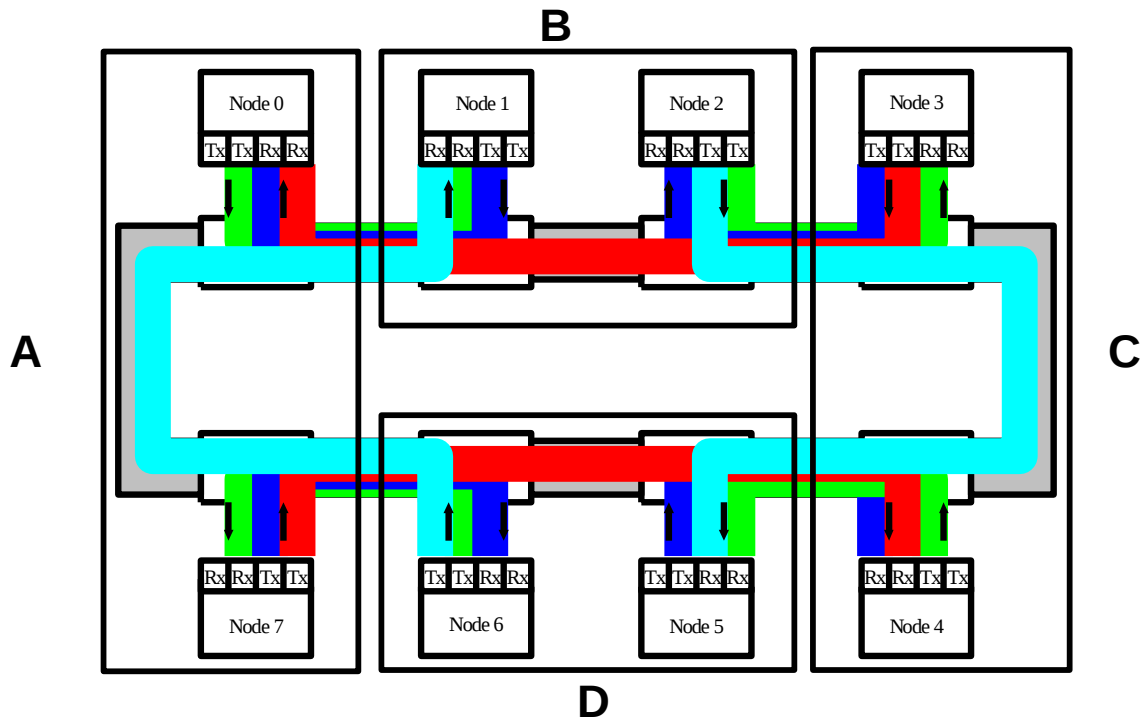


Figure 9: Eight Node Perfect Shuffle with Paired BADMs

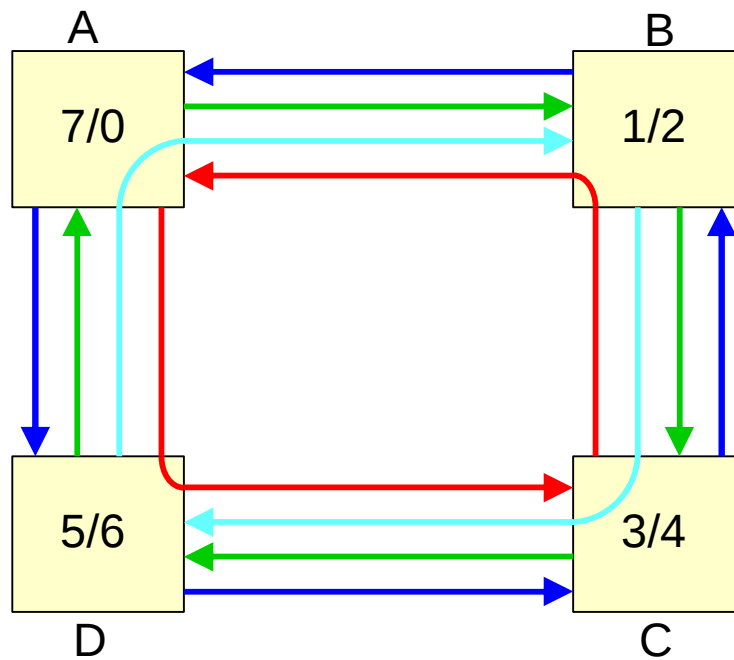


Figure 10: Fully Interconnected Four Node Crossbar

This pairing of nodes results in a logical network topology that implements a fully interconnected crossbar, pictured in Figure 10. In a fully interconnected crossbar, all nodes are directly connected to every other node within the crossbar. Each of these nodes consists of two BADMs and has three incoming wavelengths and three outgoing wavelengths. The nodes are connected on a single fiber ring. A crossbar allows for reconfigurability in the case of a break or link failure. As seen in Figure 11, if the

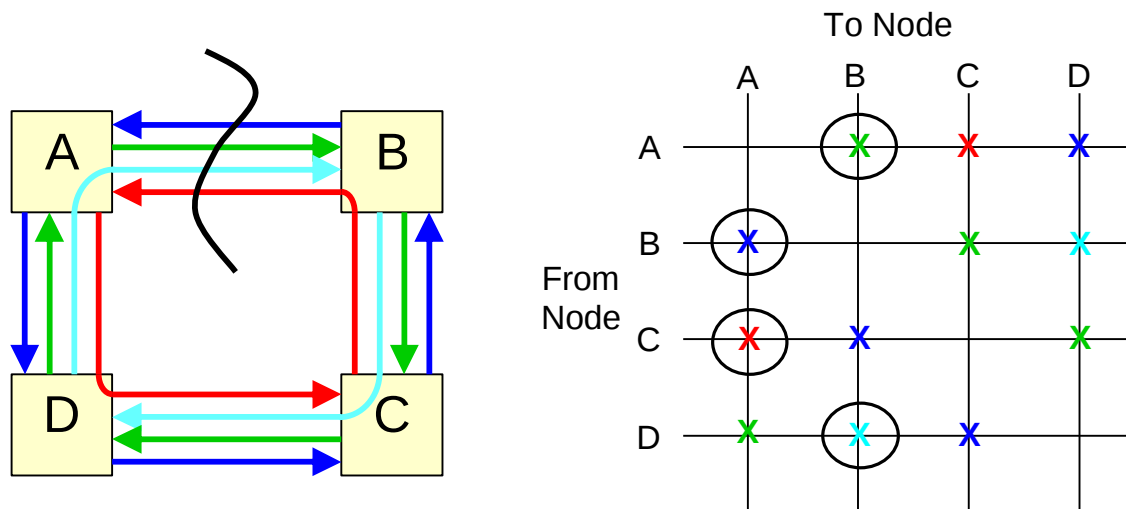


Figure 11: Crossbar with a Break Between Nodes A and B

connection between nodes A and B fails, the circled paths (previously available for transmissions) are no longer valid. However, even without the direct connections, several alternate paths exist between each pair of nodes. For example, communications between A and B could alternately use the red wavelength from A to C and the blue wavelength from C to B. Although this route requires two hops instead of one, nodes A and B are still able to communicate. However, if two failures were to occur within the crossbar, then isolation of a

single node would occur. Reconfigurability within the crossbar is referred to as local reconfigurability.

To implement the 16 node backbone network shown in Figure 8, each row and each column is interconnected using a crossbar, as just described. When connected as a 16 node mesh network, the resulting network requires, at most, two hops between any two backbone nodes. This is shown in Figure 12 where it would take one hop (on the red wavelength) to go from backbone node 11 to backbone node 13 and a second hop (on the blue wavelength) to go from backbone node 13 to backbone node 43. In this situation, node 13 acts as an intermediate backbone routing node. In FIONA, the transition from any column to any row (for example, from the red wavelength to the blue wavelength) is

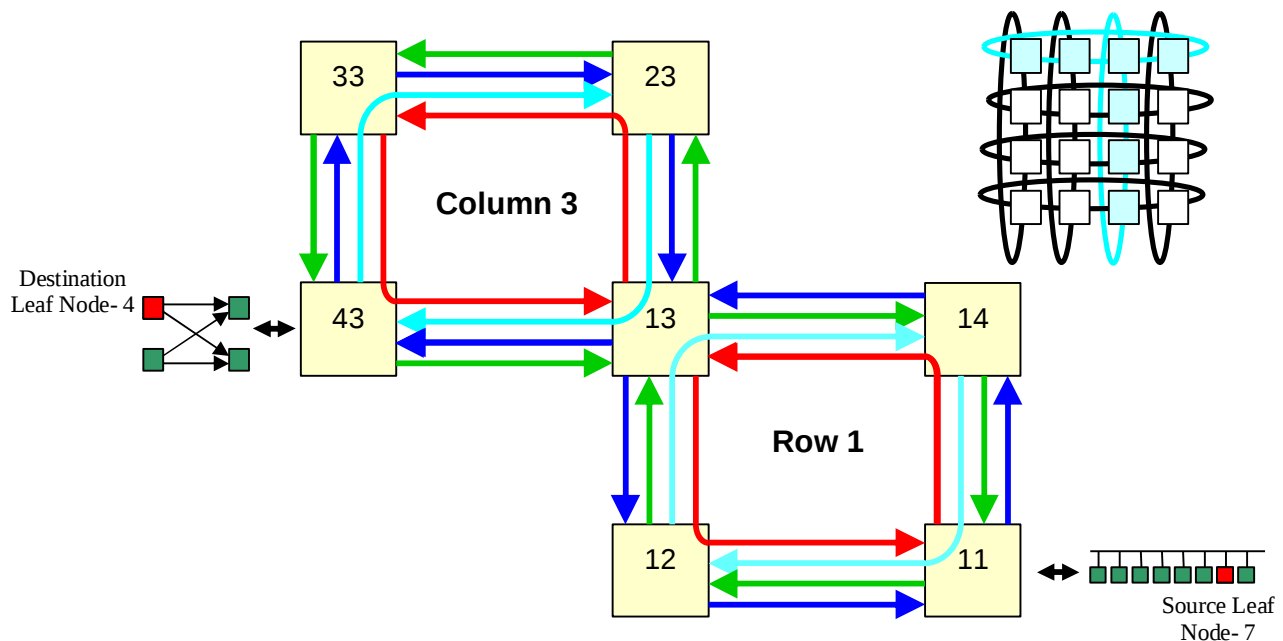


Figure 12: Intersection of Row 1 and Column 3 at Node 13

accomplished through wavelength conversion at an intermediate backbone routing node. In Figure 12, backbone node 13 is not the final destination of the signal. After being routed to

backbone node 13, the signal is then directed to a destination leaf node, such as leaf node 4, which is part of an external LAN attached to backbone node 43. An external LAN (consisting of some number of leaf nodes) is attached to each access node, as illustrated for backbone nodes 11 and 43 in Figure 12. Each signal originates from and is received by one of these leaf nodes.

Due to the interconnected nature of the entire backbone network, it exhibits a degree of global reconfigurability, meaning that the entire backbone can be reconfigured in response to the failure of a row or column. For example, if node 11 and 43 were communicating, node 13 could be used as an intermediate backbone node to route the signal from row 1 to column 3. However, if node 13 were to fail, node 41 could be used as an intermediate backbone node instead of node 13. This alternate path still takes two hops and avoids node 13. There are also numerous other paths that involve more than two hops between the source and destination; therefore, the network can sustain multiple link failures and still function properly.

Since each row and column is a fully interconnected crossbar, each node acts as an intermediate routing node between two crossbars. This is true for every one of the 16 nodes within the network. Therefore, each node is made up of 4 BADMs, two for the crossbar in a column and two for the crossbar in a row. As illustrated in Figure 12, FIONA uses two sets of wavelengths, one set for the vertical crossbars (columns) and one set for the horizontal crossbars (rows). Since each of the crossbars is on a separate fiber, the rows and columns can use the same wavelengths, and therefore, only four wavelengths are actually necessary for the entire network. This allows for a common part to be used throughout the network and reduces the number of specialized parts required to construct the network.

Based on the wavelengths used in Figure 12, Figure 13 shows a detailed schematic of node 11. Since node 11 is the intermediate node between column 1 and row 1, it contains a

wavelength converter that can be used to route data between row 1 and column 1 or to reconfigure connections within row 1 or column 1. The BADMs

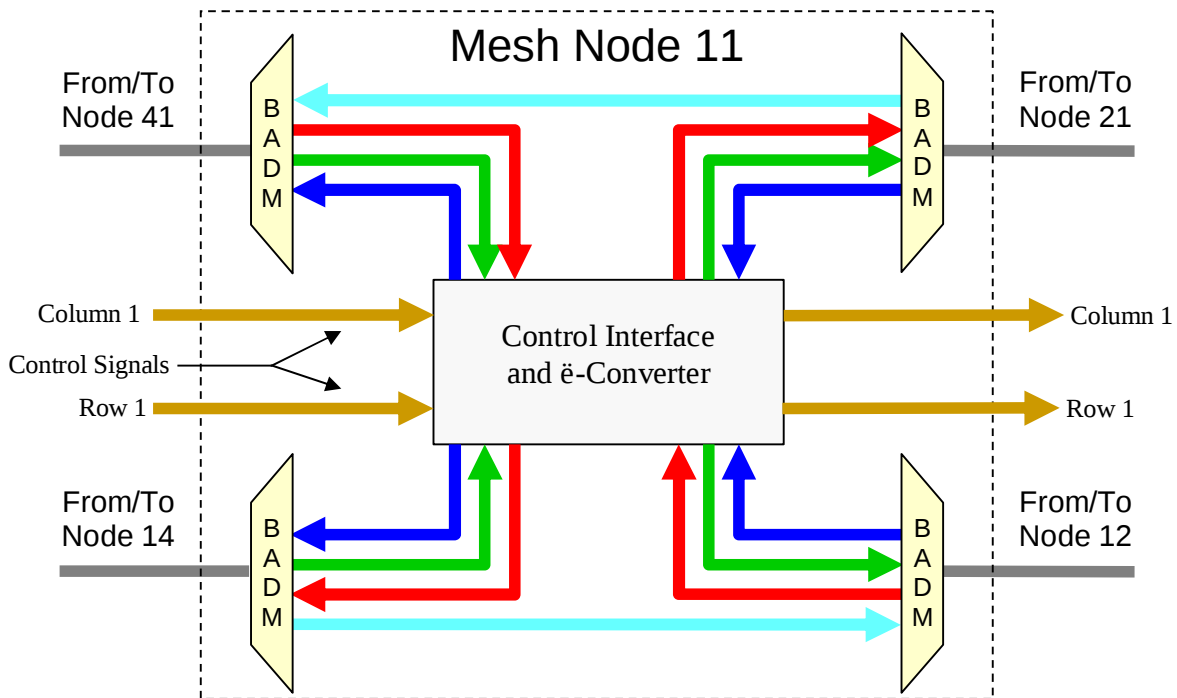


Figure 13: Schematic of Node 11

add/drop wavelengths to/from the fiber ring associated with row 1 and column 1. The control signal (shown in gold) is converted from an optical signal to an electrical signal by a media converter at each node. The control signal is then processed by a PC and a routing decision is made based on the information contained in the signal. The implementation of the wavelength (e) converter/PC interface is described in Figures 14 and 15. Figure 14 shows the control interface for each node. The optical control signal is converted to an electrical signal by a media converter. The electrical signal is then transmitted, using Gigabit Ethernet, to the PC and the signal is processed by the control algorithm. The algorithm controls the wavelength converter by sending electrical signals over the General Purpose Information Bus (GPIB) to specify the

wavelength and intensity of the DFB tunable laser (see also Figure 4). By changing the wavelength of the laser, the GPIB interface specifies the final output wavelength, λ_2 , of the

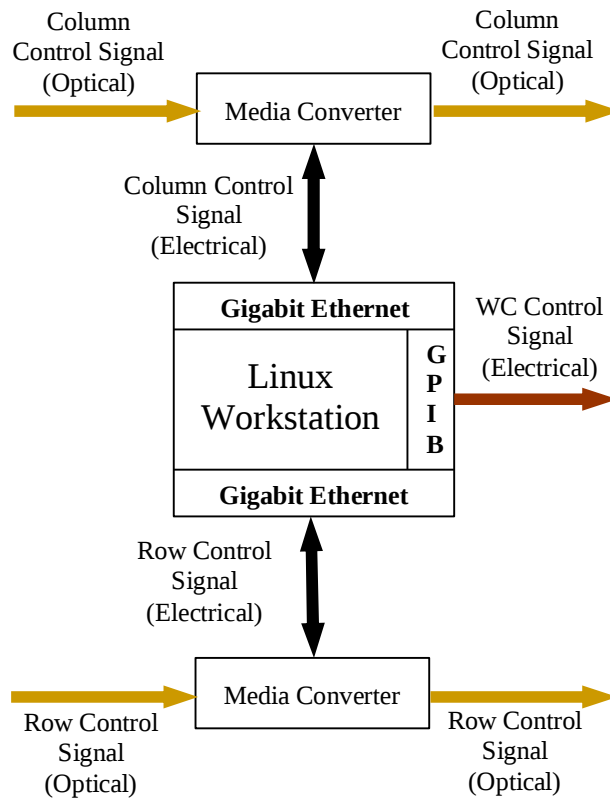


Figure 14: Control Interface at Each Node

wavelength conversion. The GPIB is also used to specify the input data wavelength, λ_1 , for the conversion as well. This is accomplished by using a 6 x 2 switch as shown in Figure 15. A 2 x 6 switch is also used to define the filter for λ_2 at the output of the wavelength converter. By combining the PC interface, shown in Figure 14, and the wavelength converter interface, shown in Figure 15, the control algorithm is able to route the data through the network using wavelength conversion. The path between the access node and leaf nodes has not yet been defined and was beyond the scope of this project.

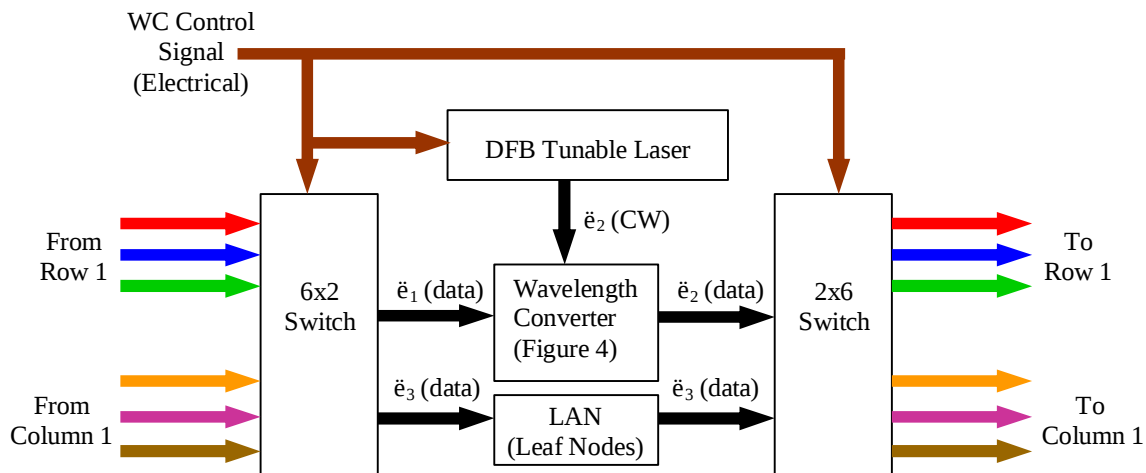


Figure 15: Wavelength Converter Control Interface at Node 11

Network Implementation

The first step in the project was the construction of a basic four node crossbar, as pictured in Figure 16. The additional pair of multiplexers between each pair of nodes was used to combine the control wavelengths with the data wavelengths onto a single fiber. The multiplexers

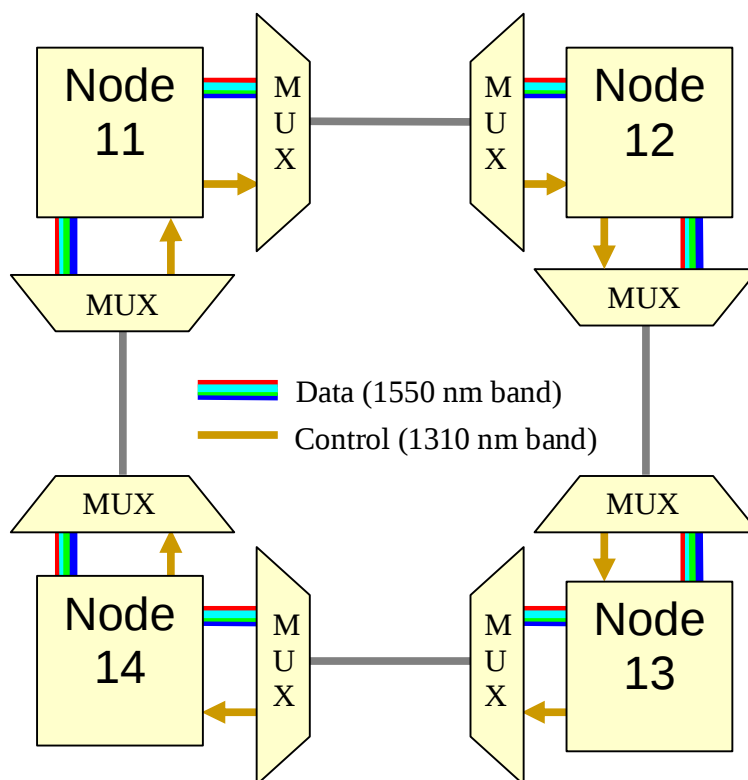


Figure 16: Four Node Crossbar with Intermediate MUX's

also separate the control signal from the data signal once it reaches a node. These are broadband multiplexers that combine wavelengths over a wider range of frequencies. This is necessary because there are multiple data and control signals that cover a band of wavelengths. The control signal is transmitted on the 1310 nm waveband whereas the data is transmitted on the 1550 nm waveband, implementing out-of-band control.

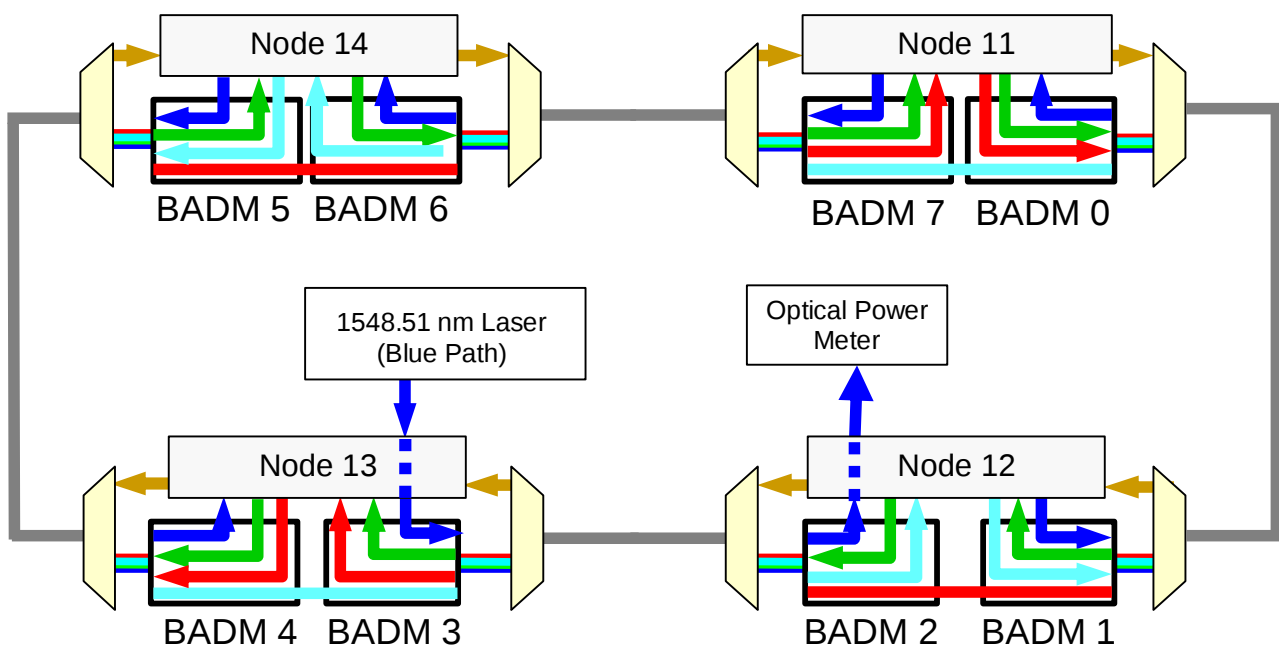


Figure 17: Test Setup for Crossbar Loss Measurements

Figure 17 illustrates a test set-up that was used to measure the loss for each path of the crossbar. A signal was generated using a laser that transmitted the wavelength for each path. The transmitted signal was received by a power meter at its destination and the loss was determined. Figure 17 shows the test setup for the blue path going from node 13 to node 12. Table 1 shows the loss measurements for every point to point connection in the network. There is some variation between each of the paths due to the differing values for connector loss. Fiber connections are very sensitive, and losses at the connections can be caused by a large number of

factors, including dirt, misalignment, over tightening and under tightening. Therefore, the loss at each connector is dependent on all of these variables, leading to variation in loss values measured at each connector. The average loss is around 3 dB per hop, because there is approximately a 1.5 dB loss through each BADM and each hop contains 2 BADMs. This is a relatively low amount of loss and allows for the tolerance of other losses in the link. A link power budget defines the amount of loss that a signal can sustain before error free reception is no longer possible, accounting for margins due to aging and degradation. As losses increase within

Path	Color	Wavelength (nm)	Measured Power (dBm)	Loss (dB)
11-12	GREEN	1550.92	9.09	1.53
11-13	RED	1550.12	5.05	4.89
11-14	BLUE	1548.51	6.65	3.02
12-11	BLUE	1548.51	7.06	2.61
12-13	GREEN	1550.92	5.73	4.89
12-14	CYAN	1549.32	6.96	3.41
13-11	RED	1550.12	2.89	7.05
13-12	BLUE	1548.51	3.79	5.88
13-14	GREEN	1550.92	8.11	2.51
14-11	GREEN	1550.92	8.57	2.05
14-12	CYAN	1549.32	5.38	4.99
14-13	BLUE	1548.51	6.62	3.05

Table 1: Loss Measurements for a Four Node Crossbar

a link, the errors in the transmitted data also increase. The link budget is set to insure that the bit error rate (BER) is sufficiently low. Bit error rate is defined as the number of bits in error divided by the total number of bits transmitted. Typical required bit error rates are 10^{-9} or 10^{-12} depending on the application. The link budget is important for avionics because connections can come loose during flight due to vibrations, causing increased losses in the link. If the link

budget is sufficiently large, additional losses may be incurred without impacting link performance.

In addition to measuring the loss for each path, the received signal was also viewed on the Optical Spectrum Analyzer (OSA). The input and output spectrum for the path shown in Figure 17 can be seen in Figure 18. The transmitted and received signals are both centered around 1548.51 nm. The signal is narrowband, occupying less than 0.2 nm of bandwidth. The resolution of the OSA was set to approximately 0.2 nm. The power of each signal is measured in dBm which is a logarithmic scale. Zero dBm is equal to one mW of power. The transmitted signal is 6 dB higher in power than the received signal due to the losses in the path, corresponding to an output power that is 25% of the input power.

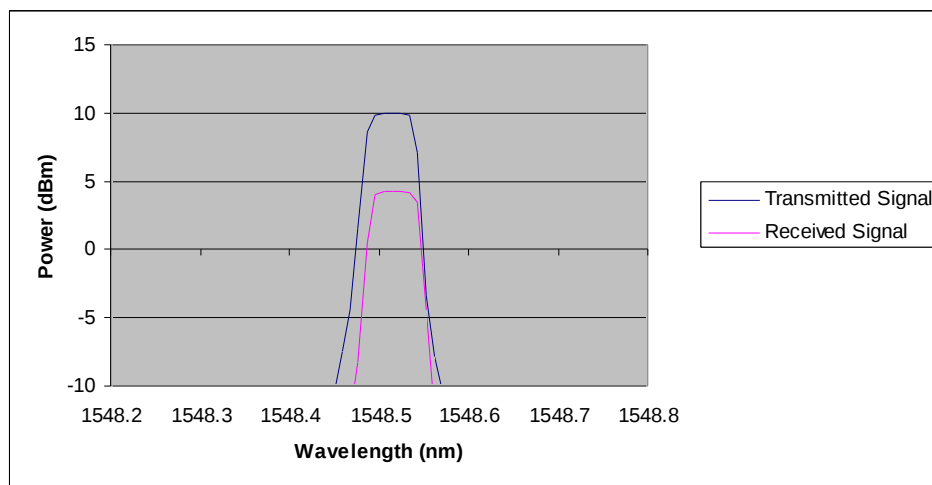


Figure 18: OSA Rendering of Point to Point Transmission

A wavelength converter is used to route data between rows and columns as well as for reconfigurability. Tests were run to verify the functionality of the converter within the network. Figure 19 shows a node with a wavelength converter inserted between the two BADMs that make up the node. For testing purposes the wavelength converter was inserted into Node 14

between BADMs 5 and 6. This not only allowed for the testing of the wavelength converter, but it also allowed for testing and evaluation of network

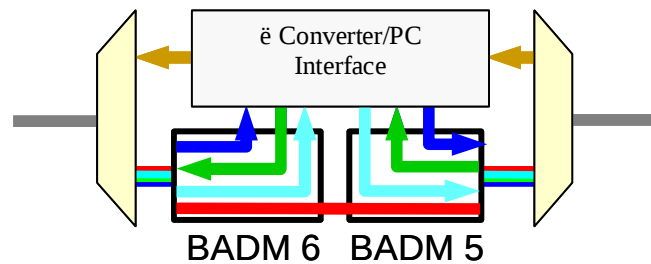


Figure 19: Node 14 with Wavelength Converter

reconfigurability. Figure 20 shows a link failure between nodes 11 and 12. However, as shown in Figure 11, even with the failure it is still possible to communicate from node 12 to node 11. This is accomplished by using the cyan wavelength to transmit from node 12 to node 14, and then converting to the green wavelength to transmit from node 14 to node

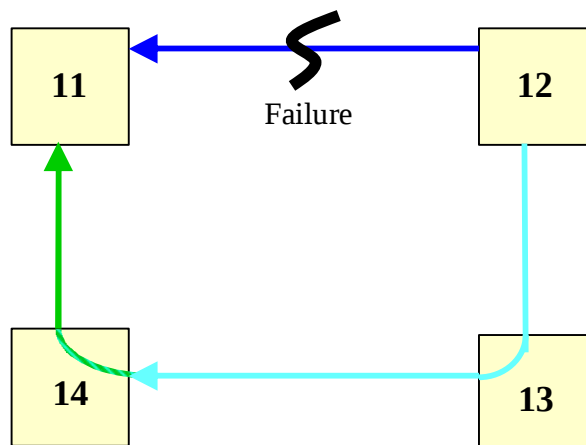


Figure 20: Alternate Path Using Wavelength Conversion

11. Figure 21 shows the transmitted and received signals as viewed on the OSA. The transmitted signal is centered around 1549.32 nm, the cyan wavelength (shown in cyan in Figure

21), and the received signal is centered around 1550.92 nm, the green wavelength (shown in blue in Figure 21). The converted signal was successfully transmitted through the network and was received on the correct output fiber, thereby demonstrating successful routing based on wavelength conversion.

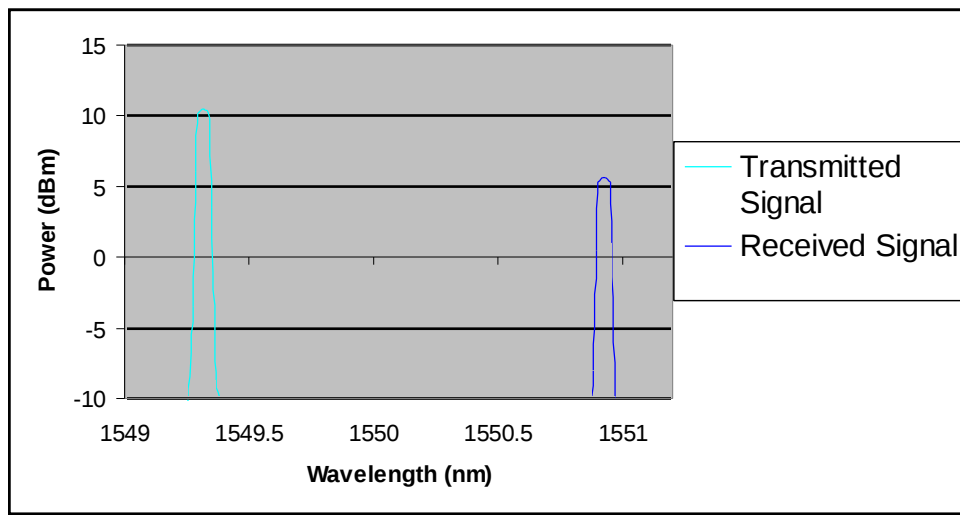


Figure 21: OSA Rendering of Transmission Using Wavelength Conversion

Control Algorithm Design

After successful development and implementation of the network architecture, a control algorithm was needed to control the wavelength conversion and routing process. Since there was no existing algorithm that could be used for this type of architecture, it was necessary to design a new control algorithm for FIONA. To support mixed signal capability, a design decision was made to use a circuit switched transmission protocol within FIONA. A circuit switched network means that each transmission has its own dedicated path for the duration of the transmission. An example of a circuit switched network is the landline telephone system. When a user places a call, they have their own dedicated circuit for the duration of the phone call. If the circuit is broken, the transmission is also broken and the call is terminated. However, the call cannot

normally be interrupted by other phone calls, because it is dedicated to the user's transmission until the call is ended by hanging up the phone. Call waiting would be an exception to this example because the transmission can be interrupted by another call. Once the phone is hung up, the circuit is disestablished and is now available to other users. The same is true for the data streams within FIONA. Each stream has a dedicated circuit or path until the transmission is complete. This dedicated path allows for the transmission of continuous analog data over the network. This is important because FIONA was designed to operate in a mixed signal environment and if FIONA were a packet switched or slotted network, it would not be able to transmit analog data without a pre-transmission analog to digital conversion.

In addition to being a circuit switched network, FIONA is also a connection-oriented network. A connection-oriented network uses a handshaking protocol between the source and the destination to establish a connection over which data can be transmitted. In a circuit switched network, this is equivalent to creating the circuit, a dedicated path between the source/destination (SD) pair. Due to the reconfigurable nature of FIONA, there are a large number of possible paths between any given SD pair. However, the initial implementation of the control algorithm only addresses the two most efficient paths between an SD pair, the two-hop paths. As shown in Figure 8, in the absence of failures between two nodes on a different row or column, there are always two possible two-hop paths between any two nodes within the network. Future work could increase the depth of the search algorithm to include 3 and 4 hop paths. Paths longer than 3 or 4 hops monopolize too much of the network for a single transmission; therefore, it is better for a source to simply wait and attempt the transmission when a shorter path becomes available. In wide area networks, data is buffered within the network at intermediate routers or within the connections themselves. Because FIONA's intended purpose was to interconnect

local area networks buffering of data within the network was not practical and therefore was not considered. Therefore, in the case of blocking within the backbone network, the control algorithm was designed to buffer data at the source. This means that if a path is not available between a given SD pair, then the data will be stored at the source, and the source will simply wait for a path to become available. The algorithm prevents multiple transmissions from being able to vie for the same wavelength in the same way a bus topology only allows one user at a time. This ensures that each transmission will have its own dedicated path and that data will not be lost during the transmission due to collisions. Some of these algorithm characteristics were dictated by the original network requirements, and others were determined by decisions made during the design process. After determining the characteristics of the control algorithm, it was necessary to design a protocol that satisfied the above requirements.

Control Algorithm Implementation

The control algorithm is a distributed software program run on Linux workstations at each of the backbone nodes. The algorithm is responsible for setting up and controlling all transmissions across the backbone network. In order to do this, some prior knowledge about the network is assumed to exist at each backbone node. This knowledge includes the overall network topology, the number of nodes within the network, the location of particular leaf nodes, and the address of the all nodes in each node's row and column. FIONA acts as a backbone network, serving to interconnect heterogeneous local area networks. As a backbone network, FIONA provides the path between source/destination leaf node pairs. Given that each backbone node knows the topology and the location of the attached leaf nodes, requests for transmission always originate from a source leaf node within one of the LANs connected by FIONA, such as the highlighted leaf node attached to backbone node 11 in Figure 12. Figure 22 shows a block

diagram description of how the control algorithm would operate for the transmission between nodes 11 and 43, as shown in Figure 12. After the request for a transmission is received by the backbone node, the control algorithm begins to process the request.

Determining the Path

The algorithm begins by determining the possible paths between the source backbone node and the destination backbone node. This is done by using the QueryPath() function, which returns the indices of the two intermediate nodes between the SD pair. Continuing with the example shown in Figure 12, the algorithm would

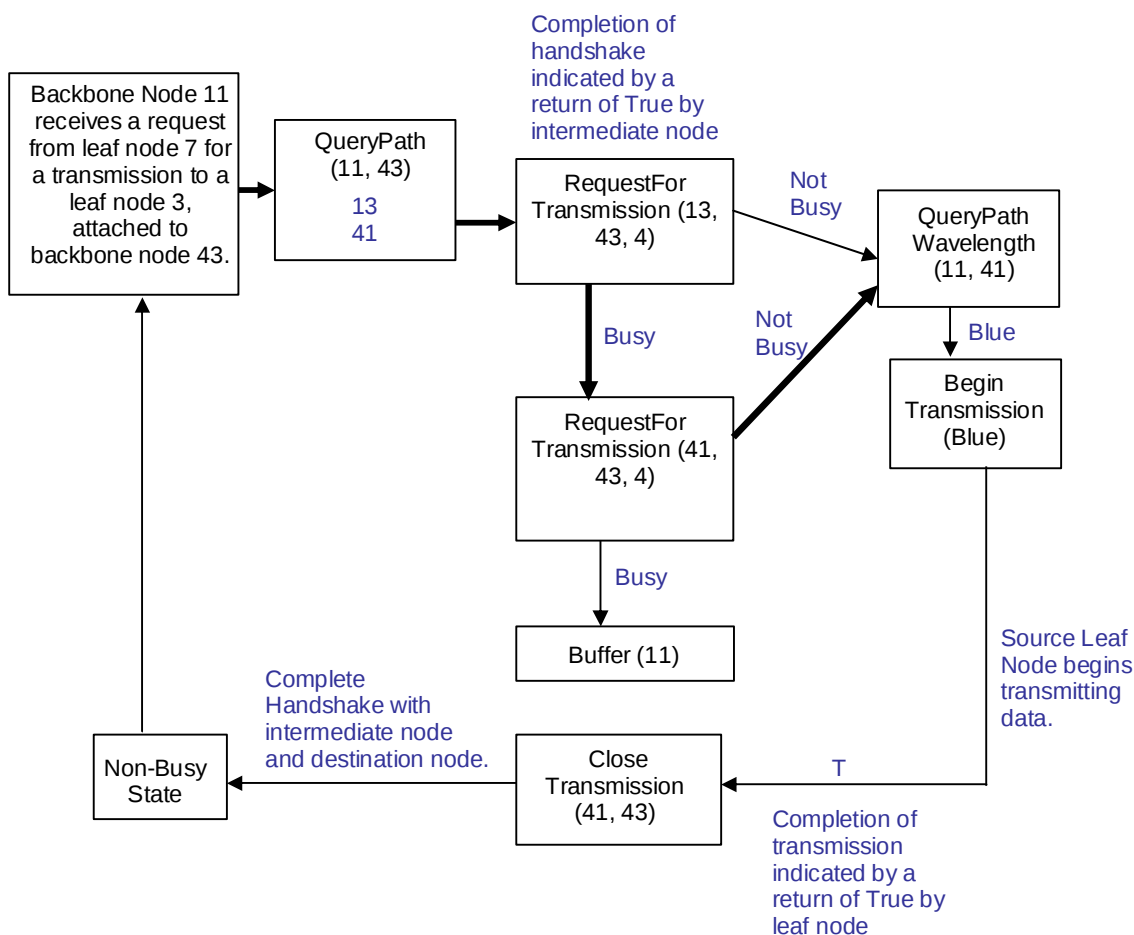


Figure 22: Control Algorithm Block Diagram

determine the available paths between nodes 11 and 43. In this case, because it involves a row/column transition, the only two paths that are considered by the current version of the algorithm are the two shortest (two-hop) paths between the SD pair. These two paths are 11-13-43 and 11-41-43. Therefore, the QueryPath() function would return the values of '13' and '41' (shown in blue in Figure 22) since these are the intermediate nodes for the two possible paths between nodes 11 and 43. Once the algorithm has determined the possible paths between the SD pair, it begins a handshake process to establish the connection between the nodes involved in the transmission.

Establishing the Path- Failed Three-Party Handshake

The control algorithm uses two different handshakes to establish a connection between an SD pair. The first handshake, shown in Figure 23, is a three party handshake

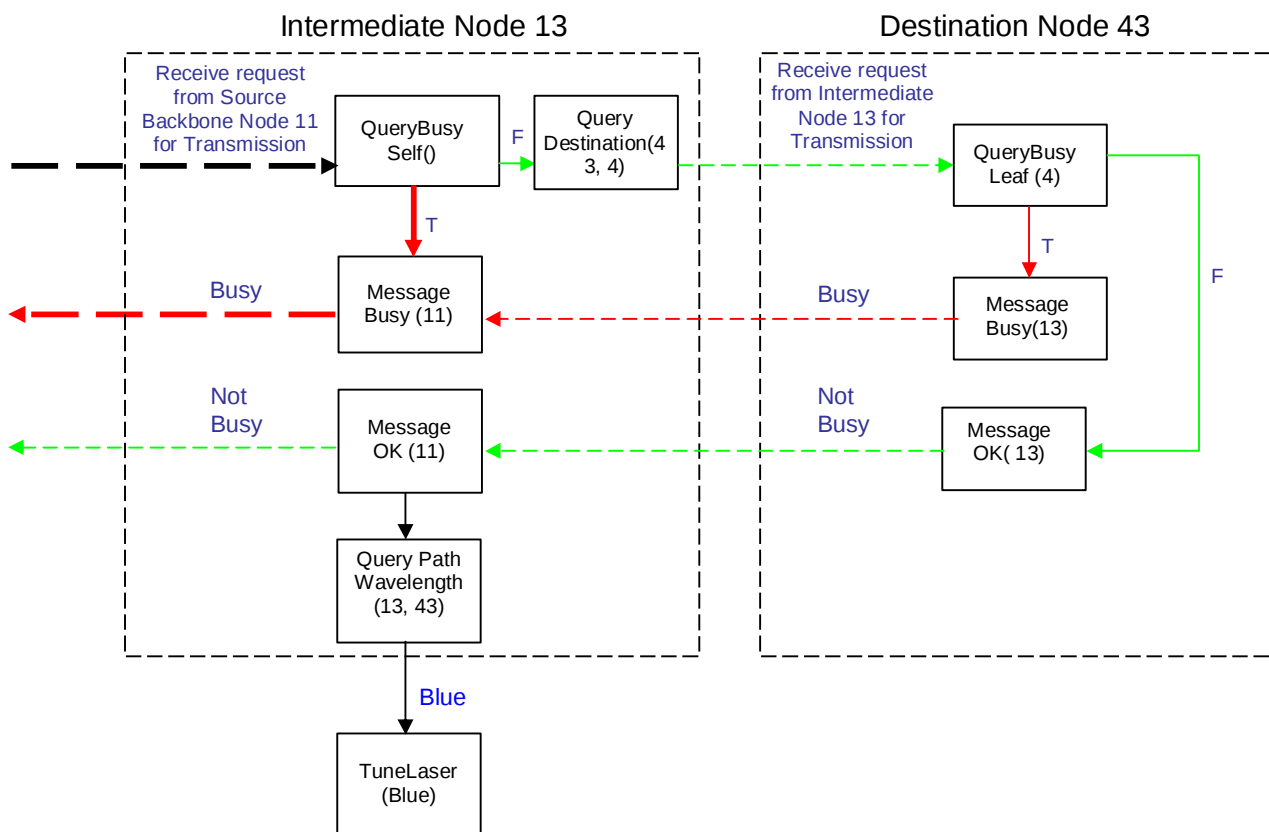


Figure 23: Failed Three-Party Opening Handshake - Nodes 11, 13, and 43

that occurs when a row/column transition is required, such as the transmission between backbone nodes 11 and 43. The second handshake is a two-party handshake discussed later. For the first example, a failed three-party handshake is described. The handshake begins when the source backbone node (node 11) sends a handshake request, using the `RequestForTransmission()` function (shown in Figure 22), to the intermediate backbone node (node 13). This request prompts the intermediate node to check its status using the `QueryBusySelf()` function, shown in Figure 23. This function determines if the wavelength converter at node 13 (the intermediate backbone node) is already being used to route data from another source. If the wavelength converter is in use, the intermediate backbone node (node 13) cannot yet route data to the destination backbone node (node 43). If the wavelength converter is busy at node 13, the `QueryBusySelf()` function will return a value of 'true.' This causes the intermediate backbone node (node 13) to send a 'busy' message to the source backbone node (node 11) indicating that the wavelength converter is unavailable. This indicates that the path is currently unavailable, and the handshake is terminated. The bold arrows in Figure 23 show this sequence of events. When the source backbone node (node 11) receives the 'busy' signal it then initiates a handshake with the second available path through intermediate backbone node 41.

Establishing the Path- Successful Three-Party Handshake

In this example, a successful three-party handshake is shown for the alternate path of nodes 11, 41 and 43. Figure 24 shows the row/column wavelengths for the alternate path connection, using intermediate backbone node 41. As shown in Figure 22, the source backbone node initiates a handshake using the same `RequestForTransmission()` function that was used to initiate the first handshake. Since intermediate backbone node 13 is busy, this request is sent to backbone node 41, the second possible intermediate backbone node. Figure 25 shows a

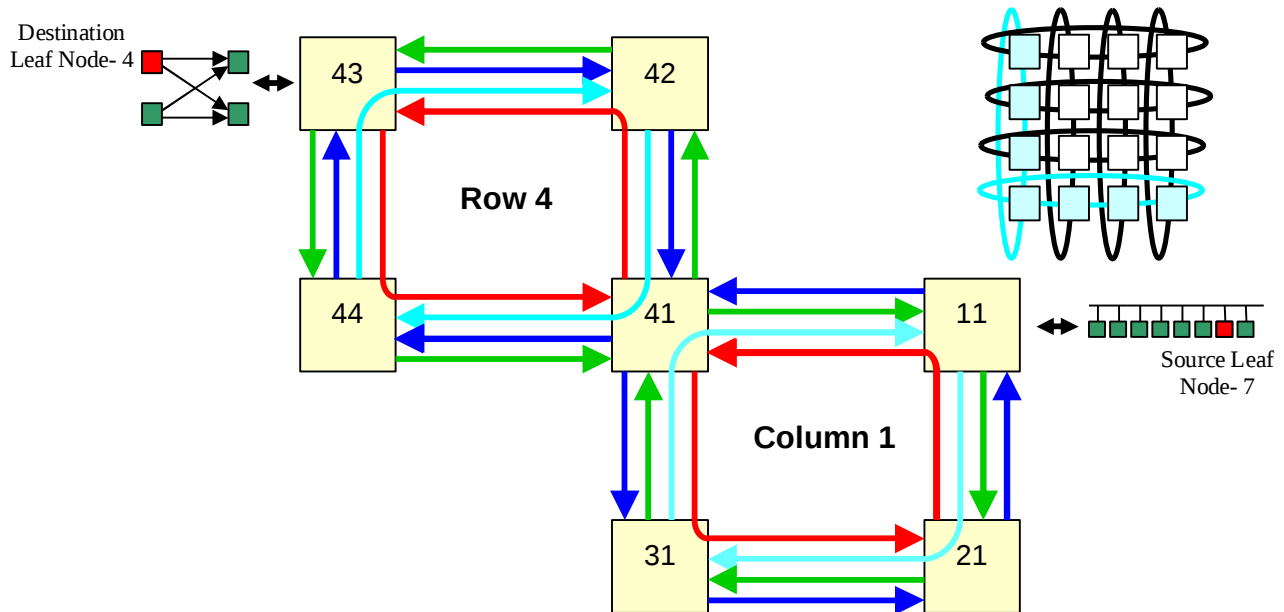


Figure 24: Intersection of Row 4 and Column 1 at Node 41

successful three-party handshake, initiated by the second `RequestForTransmission()` call, between nodes 11, 41 and 43. Again, the handshake begins with backbone node 11's request causing the intermediate backbone node (node 41) to query its own state. However, this time the wavelength converter is not busy and the function returns a value of 'false.' Therefore, the wavelength converter at backbone node 41 is available to route the data to the destination backbone node (node 43). The next step in the handshake is to ensure that the third party, the destination leaf node, is available to receive the data. To this end, the intermediate backbone node sends a query to the destination backbone node (node 43) using the `QueryDestination()` function (see Figure 25). This function sends a message to the destination backbone node, requesting the status of the destination leaf node. When the request is received by the destination backbone node, it immediately queries the destination leaf node (node 4) to ensure that it is available to receive the data. If the destination leaf node is busy, the function returns a value of 'true,' and a 'busy' message is forwarded from the destination backbone node to the source

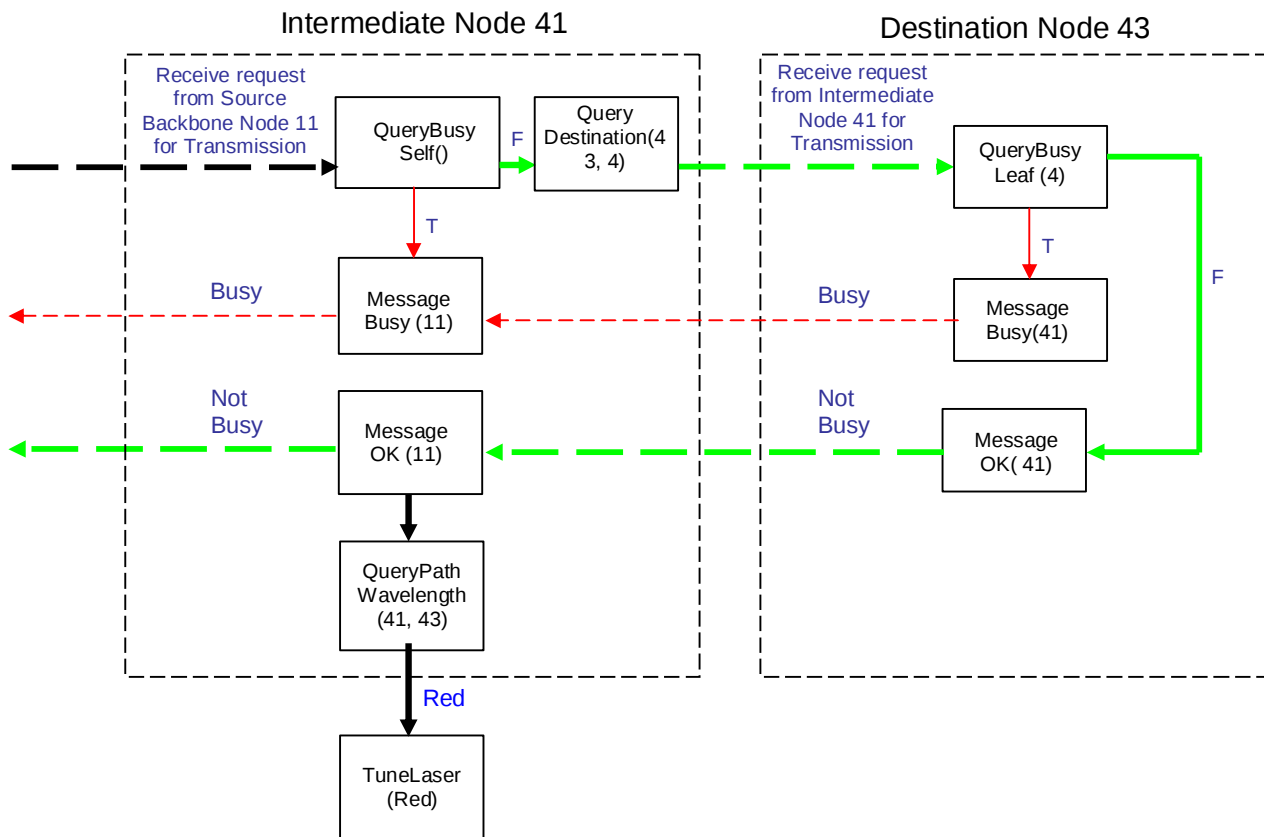


Figure 25: Successful Three-Party Opening Handshake -Nodes 11, 41, and 43.

backbone node, thus terminating the handshake. However, if the destination leaf node is not busy, then a value of 'false' is returned and a message of 'not busy' is sent by the `MessageOK()` function, shown in Figure 25, to the intermediate backbone node (node 41). This message is then forwarded on to the source backbone node (node 11) using the exact same `MessageOK()` function. With the reception of a 'not busy' message (generated by the `MessageOK()` function) from the intermediate backbone node (node 41) the handshake is now complete between nodes 11, 41, and 43 and a circuit has been established.

Source Buffering

It is also possible that the wavelength converters at nodes 13 and 41 were both being used to route data between two other SD pairs. If this occurs, then there are no available circuits between node 11 and node 43. Therefore, as discussed earlier, the data is buffered at the source until a circuit becomes available. When the source leaf node receives the message to buffer its data, it becomes the source leaf node's responsibility to request another transmission. When one of the intermediate backbone nodes completes its current transmission it will return to a 'non-busy' state. At this point, if the source leaf node repeats its original request, a sequence similar to the one shown in Figure 24 occurs, resulting in a successful handshake and an established circuit.

Creating the Path

While the 'not busy' message was being forwarded to the source backbone node (figure 24), the intermediate node was also determining what wavelength will route the data to the destination backbone node. This is done using the `QueryPathWavelength()` function, as shown in Figure 24. The function returns 'red' as the wavelength between nodes 41 and 43. The intermediate node then uses this information to instruct the tunable laser to tune to the red wavelength using the `TuneLaser()` function. Now that the laser has been tuned, any data passing through the wavelength converter at node 41 will be routed on the red wavelength to node 43 until the laser receives a command to tune to another wavelength. This circuit defines the path that the data will take for the duration of the transmission. As shown in Figure 22, the algorithm now queries the wavelength necessary to route the data from the source backbone node (node 11) to the intermediate backbone node (node 41) using the `QueryPathWavelength()` function. The function returns a value of 'Blue', indicating that the wavelength used to route the data from

node 11 to node 41 is the blue wavelength. Once the path has been established and the wavelength converters have been appropriately tuned, the path is finalized and ready for transmission.

Begin Transmission

Once the path has been created, the source backbone node (node 11) then uses the function `BeginTransmission()` to send a message to the source leaf node indicating that a path has been created and that the source leaf node should begin transmitting on the indicated wavelength, in this case the blue wavelength. Since the wavelength of the data determines its destination, by having the source leaf node transmit the data on the blue wavelength the control algorithm succeeds in routing the data from the source backbone node (node 11) to the intermediate backbone node (node 41). Once the data reaches the intermediate backbone node on the blue wavelength, the data is immediately converted to the red wavelength. Again, the wavelength of the data determines its destination and the red wavelength routes the data to the destination backbone node (node 43). Throughout this entire process, the data remains optical and no outside signal or device manipulates the data as it is being transmitted across FIONA. When the source leaf node has completed its transmission, it returns a 'true' to the source backbone node to indicate that it is done transmitting. The source backbone node must now close the circuit using the `CloseTransmission()` function as shown in Figure 22.

Disestablishing the Circuit

The circuit is closed by a closing handshake, shown in Figure 26. The `CloseTransmission()` function sends a message to the intermediate backbone node indicating that the transmission is complete. This causes the intermediate backbone node to call the function `CloseDestination()`, which sends a message to the destination backbone node that the

transmission has been completed. The backbone node then calls the function `CloseSelf()`. This function returns the destination leaf node and the destination backbone node to a non-busy state and they are both available for a new transmission request. The destination backbone node then sends an acknowledgement (Ack) back to the intermediate backbone node (node 41) indicating that both the destination backbone node and the destination leaf node received the message. Upon receiving the Ack from the destination backbone node, the intermediate backbone node,

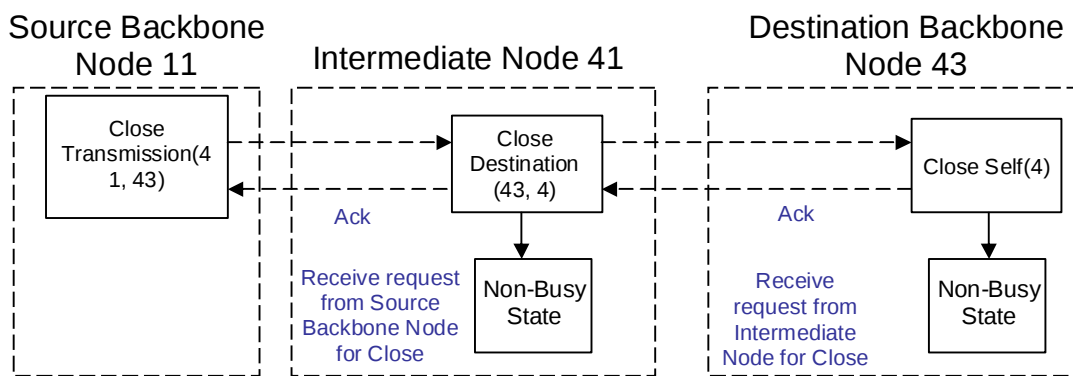


Figure 26: Closing Handshake- Nodes 11, 41, and 43

itself, transitions to a non-busy state and sends its own Ack to the source backbone node. When the source backbone node receives the Ack from the intermediate backbone node, the source backbone node transitions to a non-busy state and the circuit is closed. At this point the transmission has been completed and the source backbone node (node 11) awaits another transmission request from one of its leaf nodes.

In the case of a transmission that does not involve a row/column transition, a three-party handshake is not necessary. Instead, a two-party handshake is used to establish the circuit. Figure 27 shows a general block diagram of the two-party handshake. The algorithm is similar to the three party handshake except there is no intermediate node or wavelength converter

involved. Therefore when the source backbone node queries the destination node, it is simply checking to see if the destination leaf node is ready to receive the transmission. If the destination leaf node is busy then the transmission is buffered until the leaf node completes the current transmission. If the

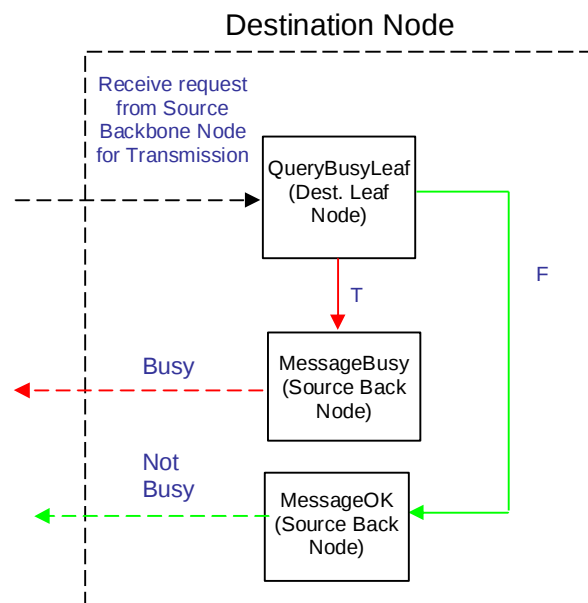


Figure 27: Two-Party Handshake General Block Diagram

destination leaf node is available, a circuit is established and the transmission is carried out in the same manner that was detailed above. Appendix B includes general block diagrams for all parts of the control algorithm (general algorithm, opening handshakes and closing handshakes) as well as definitions for all the functions used in the algorithm.

Control Interface

The control algorithm interface with the physical network consists of three devices. The control signal was transmitted using Gigabit Ethernet Media Converters which convert an electrical Ethernet signal into an optical Ethernet signal. The tunable laser was controlled via the General Purpose Information Bus (GPIB), which allowed for remote control of the laser.

Finally, the semiconductor optical amplifier (SOA) was driven using a serial port interface to provide a constant drive current.

The first interface involved the transmission and reception of the actual control signal. The control data was transmitted and received at each node by a media converter. The media converter received the optical signal and converted it to an electrical signal that could be processed by the workstation. Figure 28 shows the control path between

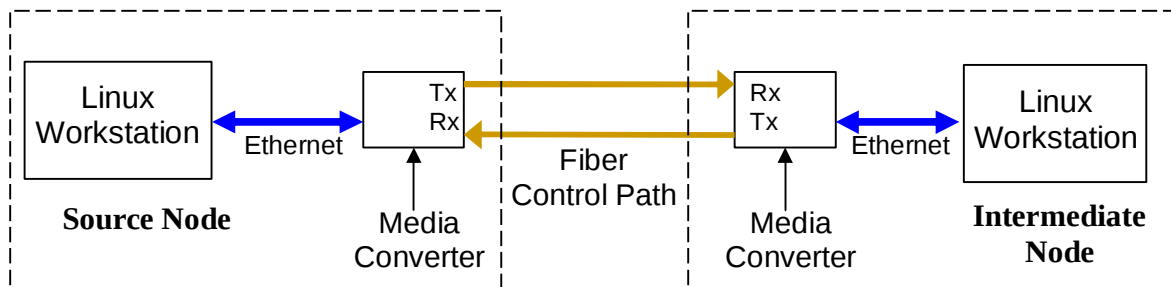


Figure 28: Laboratory Implementation of the Control Path

two nodes as implemented in the laboratory. The control path was a full duplex connection, meaning that communications occur in both directions simultaneously. The Ethernet connection between the media converter and the workstation was an electrical signal that was transmitted using Gigabit Ethernet protocol.

The second interface was between the tunable laser and the workstation. The tunable laser determines the output wavelength of the wavelength converter and therefore determines the destination of the data. The workstation interface with the tunable laser uses a General Purpose Information Bus (GPIB), IEEE Standard 488. The GPIB commands recognized by the laser allowed the computer to change the wavelength and intensity of the tunable laser by interfacing with the GPIB drivers installed on the workstation.

The third and final interface was the current driver for the semiconductor optical amplifier (SOA) in the wavelength converter. The SOA needs a constant drive current of 350 mA to get maximum performance out of the wavelength converter. This is controlled and monitored by the workstation using the serial port and a program called VDRIVE. For the laboratory measurements the program was run on a laptop and maintained a constant drive current of 350 mA. This interface would change if FIONA were to be implemented outside of a laboratory setting. After successfully interfacing the physical network with the control algorithm, the network was capable of supporting a proof-of-concept test.

Proof of Concept Testing

The most complicated transmission that could take place in FIONA would be a transmission that involved a row/column transition, a three party handshake, and a wavelength conversion. This type of transmission can be seen in figure 29, which shows

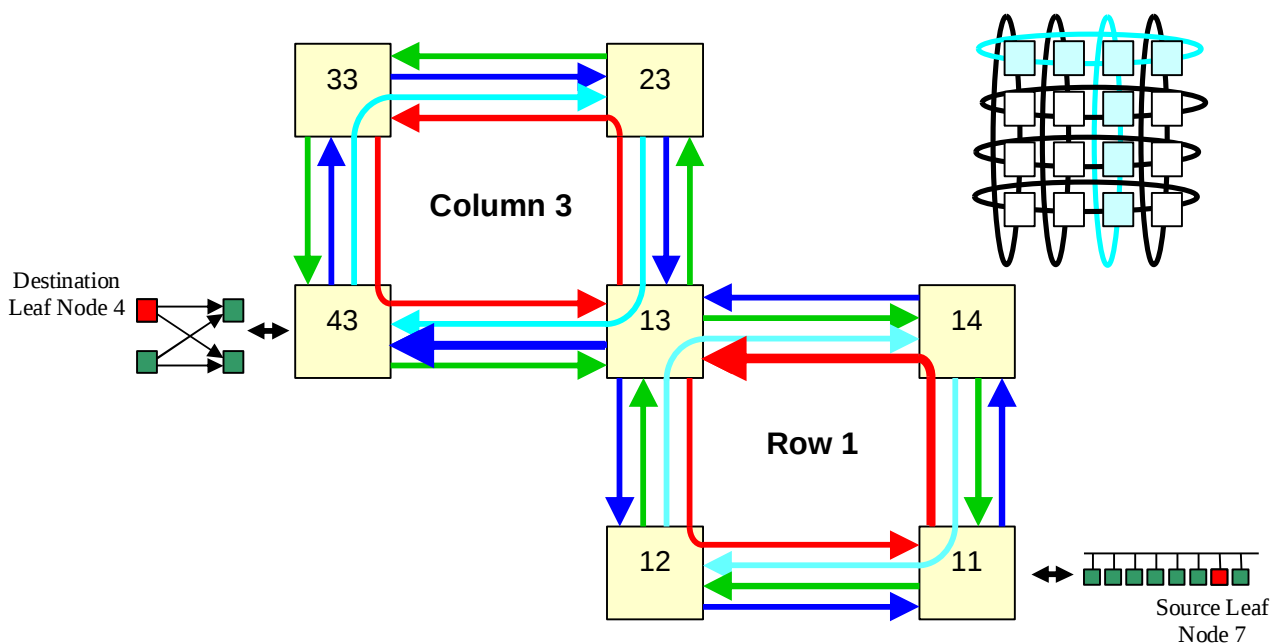


Figure 29: Proof of Concept Transmission Path

the transmission that was used to discuss the control algorithm. This transmission originated from a leaf node attached to backbone node 11, was converted from the red wavelength to the blue wavelength at backbone node 13, and was received by a leaf node attached to backbone node 43. Figure 30 shows the test setup used to simulate this transmission. Both analog and digital signals were transmitted using this test setup to ensure FIONA's ability to function in a mixed signal environment.

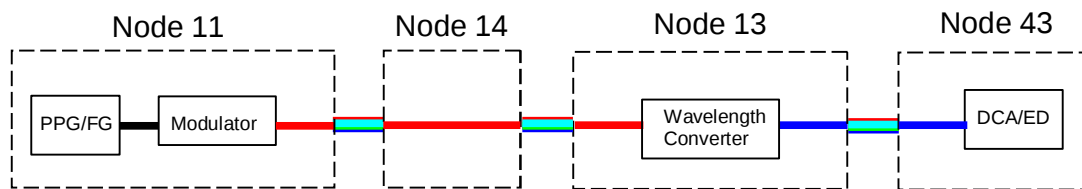


Figure 30: Proof of Concept Transmission Test Setup

To test the system's digital functionality, a pulse pattern generator (PPG) was used to generate a 2.5 Gb/s digital signal. This signal was then received by an error detector, used to detect incorrectly received data (errors), or a Digital Communications Analyzer (DCA), to view the waveform versus time. Two values used to measure a network's digital performance are bit error rate (BER) and extinction ratio. BER, as shown in equation 1, is defined as the number of bits in error divided by the total number

$$\text{BER} = \frac{\text{Bits in Error}}{\text{Total Bits Transmitted}} \quad (1)$$

of bits transmitted. The measured bit error rate for the proof of concept transmission was approximately 10^{-13} , although it is believed that the value would approach zero if the test were run for a longer period of time. Extinction ratio, as shown in equation 2, is defined as the ratio of

the average power in a digital '1' divided by the average power in a digital '0'. The measured extinction ratio for the proof of concept was 4.27 dB. This means that

$$\text{Extinction Ratio} = \frac{\text{Avg Power of a 1}}{\text{Avg Power of a 0}} \quad (2)$$

the power of a '1' was 2.67 times greater than the power of a digital '0'. This can be seen in the eye diagram shown in Figure 31. An eye diagram is a collection of digital '1' and

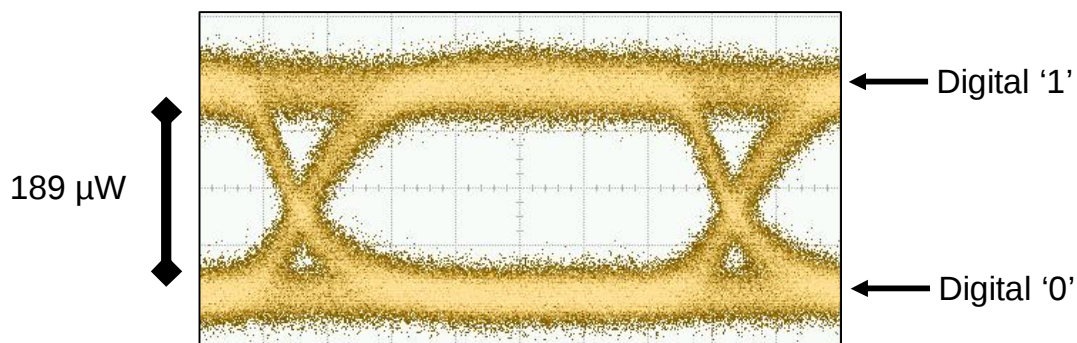


Figure 31: Eye Diagram of Proof of Concept Test @ 2.5 Gb/s

'0' values sampled over time and plotted on the same axis. The result is a collection of all the possible '1' and '0' values, including noise and distortion. The top bar is the collection of digital '1' values and the bottom bar is the collection of digital '0' values. The white space between these two bars is called the eye. The size of the eye represents the difference in power between a digital '1' and a digital '0'. A large difference between a '1' and a '0' makes it easier for the receiver to distinguish between a '1' and a '0' leading to a lower number of transmission errors within the network.

To test the analog functionality of FIONA, a function generator (FG) was used to generate a 15 MHz sine wave. This signal was then modulated onto the optical light wave and transmitted across the proof of concept test setup, shown in figure 30. Due to the gain

characteristics of the semiconductor optical amplifier (SOA) used in the wavelength converter, the signal was not accurately converted. However, a distorted signal was received, demonstrating FIONA's ability to handle analog transmissions if an analog wavelength converter were used.

Future Work

Currently, there is only enough hardware in the laboratory to support one row and one column of the architecture. As a result, FIONA has only gone through proof of concept testing and there are some areas of future research and testing that could be done with a full 16 node backbone network. These tests would further prove FIONA's capabilities and would allow for additional data to be collected on FIONA's performance. The control algorithm that was designed for FIONA only allows for two hop paths to be used for transmissions. Future versions of the algorithm could include three and four hop paths to reduce the probability of blocking within the network. In addition, priority queuing could be added to the algorithm to provide determinism within the network leading to an increased quality of service. The use of semi-custom hardware for network construction would also improve network performance. The algorithm could be run on field programmable gate arrays (FPGA's) instead of Linux workstations, thereby reducing the overhead required to run the control algorithm and possibly reducing network latency. The use of custom optical components with higher data rates, faster tuning speeds, and faster switching speeds would result in increased optical performance and higher overall throughput across the network backbone. Finally, the interface between the leaf nodes and the backbone nodes needs to be further defined and tested before FIONA can be deployed in a real world application.

Conclusion

The result of this Trident Scholar project was an extended local area network that had the capability to interconnect heterogeneous LANs and function in a mixed signal environment. FIONA's fiber optic physical layer offers many advantages over existing physical layer technologies. These advantages include an immense bandwidth, a relative immunity to electromagnetic interference, and signal transparency. FIONA efficiently uses the bandwidth offered by fiber optics, without the need for expensive high bandwidth transmitters and receivers by implementing wavelength division multiplexing. This lowers the overall cost of the network while allowing for data rates exceeding 10 gigabits per second, per wavelength. FIONA's ability to support mixed signal transmissions eliminates the need for pre-transmission analog to digital conversion, reducing network latency and increasing network performance. The use of the fully interconnected crossbar topology as the building block for FIONA results in a high degree of reconfigurability within the network. FIONA is not only reconfigurable within each crossbar but it can also reconfigure in the event of an entire crossbar failure. This level of reconfigurability increases the network's fault tolerance and its ability to isolate faults once they occur, leading directly to improved reliability and survivability of the network. FIONA is an improvement over existing access network architectures, such as those used in shipboard and avionics applications. It provides greater connectivity with higher bandwidth between local area networks, resulting in increased network performance.

Endnotes

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Appendix A: Glossary of Terms

ADM: Add/Drop Multiplexer, an optical device that adds or drops signals from the optical network. This device is used in wavelength division multiplexing to combine multiple signals into a single data stream and to drop signals from the stream.

BADM: Bidirectional Add/Drop Multiplexer, an ADM that allows data to pass in both directions.

BER: Bit Error Rate, a ratio of the total number of bits received in error to the total number of bits transmitted. For modern telecommunications and data networks, a BER of 10^{-9} or 10^{-12} is usually required.

CW: Continuous Wave, laser light that is not modulated by data.

dB: decibel, a logarithmic scale representing the ratio between two quantities that is often used to compare two known power quantities.

dBm: a ratio of the current power compared to a milliwatt.

DWDM: Dense Wavelength Division Multiplexing, WDM with the frequencies (or wavelengths) located closer together in the spectrum.

Electronic Warfare: The manipulation of the electromagnetic spectrum to conduct warfare against enemy aircraft and troops.

Extinction Ratio: A ratio of the power contained in a digital '1' divided by the power contained in a digital '0'.

FDM: Frequency Division Multiplexing, the transmission of multiple data streams using different frequency bands to carry each stream of data.

GPIB: General Purpose Information Bus, a standard specified by the IEEE (IEEE 488) for control of laboratory devices.

LAN: Local Area Network, a small sized computer network that often does not exceed the size of a room or small building.

Media Converter: A device used to convert between electrical Ethernet signals and optical signals.

mW: milliwatt, one thousandth of a Watt. This is the unit typically used to measure optical power.

OEO conversion: Optical-Electrical-Optical conversion, the process by which information is taken from an optical format to an electrical format for data routing and back into an optical signal for retransmission onto the network.

OSI Network Model: Open Systems Interconnect Model. A seven layer model, defined by the international standards organization, used to model most in-band network protocols.

Rx: Receiver.

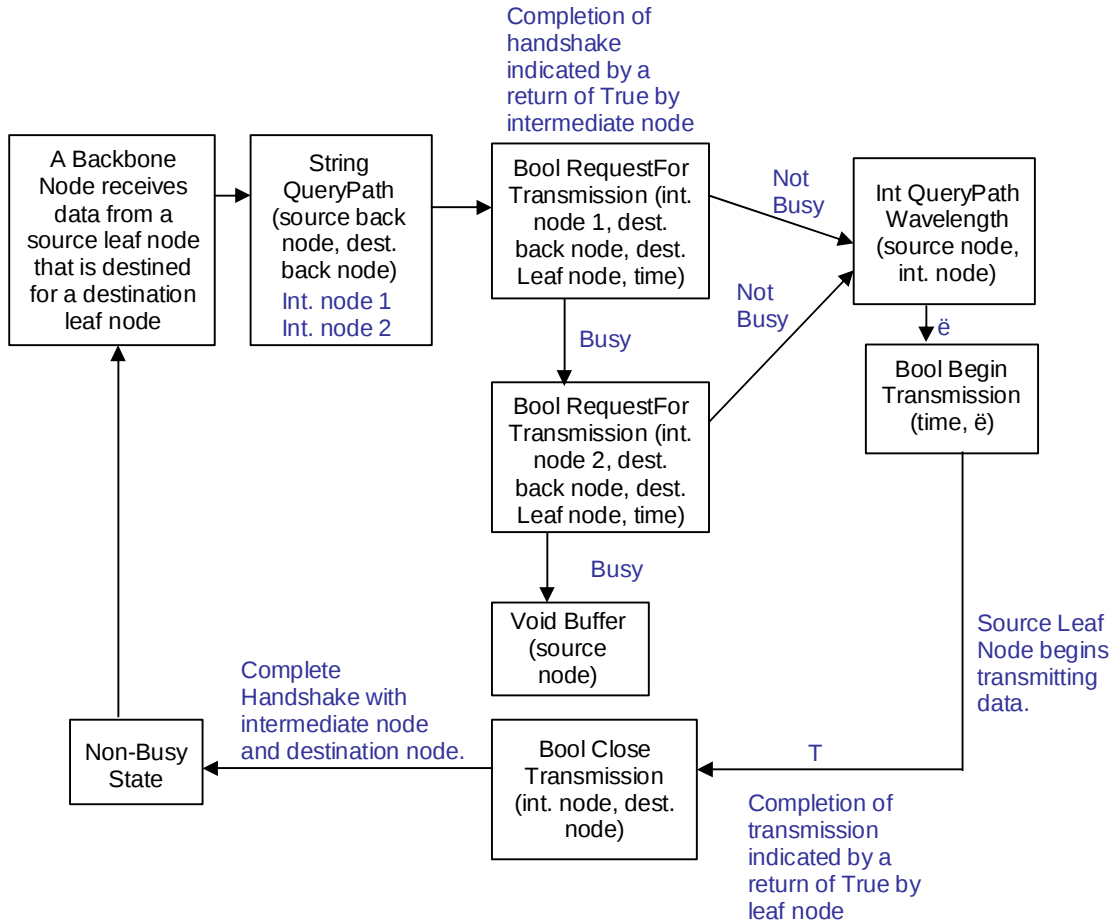
SD Pair: Source Destination Pair.

Tx: Transmitter.

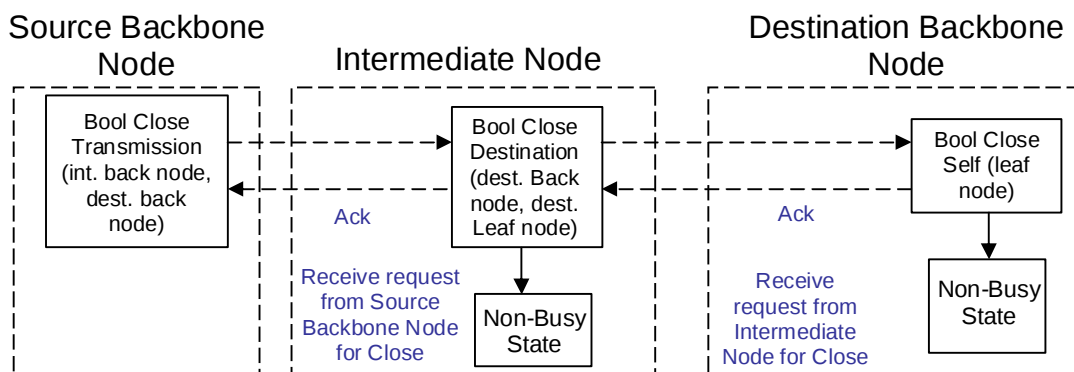
Wavelength Converter: A device used to transpose data from one wavelength to another.

WDM: Wavelength Division Multiplexing, a form of FDM where multiple streams of data are transmitted on a single fiber with each stream of data occupying a distinct wavelength.

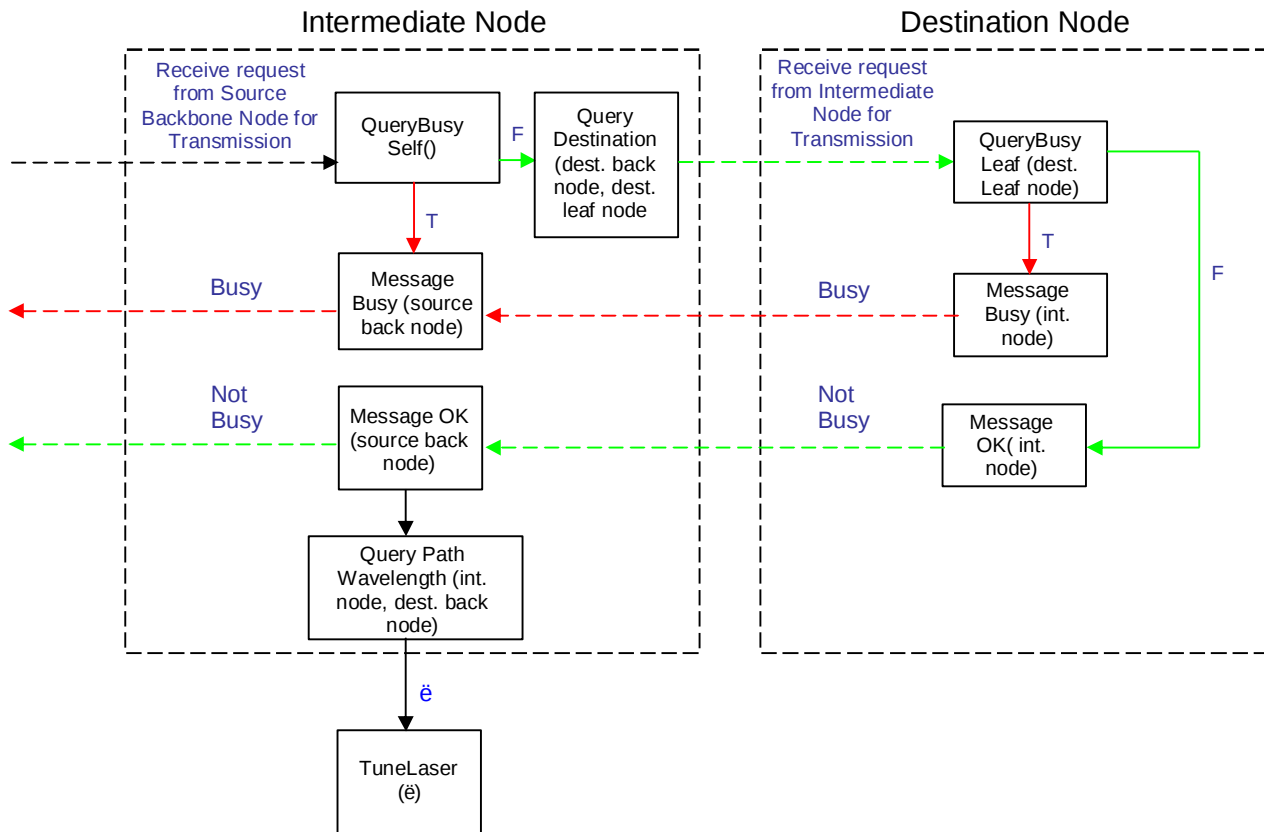
Appendix B: Generic Control Algorithm Block Diagrams



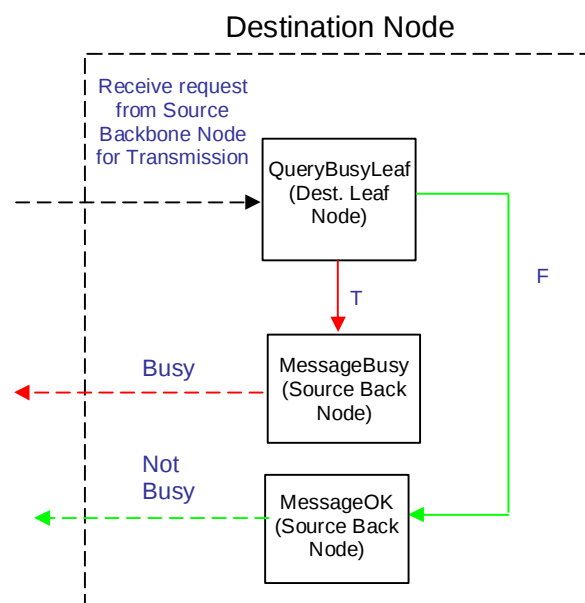
Generic Block Diagram of Control Algorithm



General Block Diagram of Closing Handshake



General Block Diagram of a Three-Party Opening Handshake



General Block Diagram of a Two-Party Handshake