ENTERPRISE VIRTUAL PRIVATE NETWORK (VPN) WITH DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM) DESIGN

by

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Abstract

ENTERPRISE VIRTUAL PRIVATE NETWORK (VPN) WITH DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM) DESIGN

by

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An innovative computer simulation and modeling tool for metropolitan area optical data communication networks is presented. These models address the unique requirements of Virtual Private Networks for enterprise data centers, which may comprise a mixture of protocols including ESCON, FICON, Fibre Channel, Sysplex protocols (ETR, CLO, ISC); and other links interconnected over dark fiber using Dense Wavelength Division Multiplexing (DWDM). Our models have the capability of designing a network with minimal inputs; to compute optical link budgets; suggest alternative configurations; and also optimize the design based on user-defined performance metrics. The models make use of Time Division Multiplexing (TDM) wherever possible for lower data rate traffics. Simulation results for several configurations are presented and they have been validated by means of experiments conducted on the IBM enterprise network testbed in Poughkeepsie, N.Y.

ACKNOWLEDGMENTS

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Many thanks to my parents Victor and Teodora and my family for having me taught the way to persevere. This work is especially dedicated to the memory of my father who left this world for the great initiation while this work was being pursued.

I am very grateful to my wife Hilaria, my children Harrison and William for standing by me; this work is dedicated to them.

"So Mote It Be!" "Que Así Sea!"

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CHAPTER 1

INTRODUCTION

While some fiber optic applications, such as trans-oceanic or submarine systems, have been the subject of extensive simulation and performance modeling, the simulation of metropolitan area optical fiber links has only become accepted practice over the past five years or so [43], [86]. This is partly because many commercial networks were manually designed using conservative engineering rules which insured acceptable operation in a well-defined set of circumstances. Also, as a practical matter in order to guarantee network performance and test the network prior to installation, the entire link (*optical transmitter, receiver and fiber*) was supplied by a single manufacturer. Thus, while undersea networks could clearly justify simulation tools as a way to reduce design effort, lower risk, and contain costs when using state-of-the-art components, the requirement for modeling other networks was not as clear. This has changed with the introduction of more complex technologies, such as wavelength division multiplexing (WDM), in metropolitan area networks (MANs), and with the increased interest in providing high reliability data communication networks for disaster recovery and other applications. Simulation tools can be used not only to optimize performance, but also to reduce capital expenditures and design networks to meet future upgrade requirements without the need for major reconfiguration or new construction.

Because of huge demand for bandwidth to support new data processing applications, WDM has found applications in storage area networks (SANs) over extended distances (tens to hundreds of km). Some of these SANs can encapsulate data in a SONET [2] frame structure using the recently standardized Generic Frame Procedure (GFP). Another option is the direct transport of storage data over Ethernet protocols, as advocated by the Ethernet last-mile consortium and other standard bodies. A third option, which has been widely deployed prior to the introduction of GFP and metro Ethernet, is the use of enterprise virtual private networks (VPNs) with either dark fiber or wavelength-based services. These networks employ a wide range of protocols, reflecting the heterogeneous environment in typical Fortune 500 data centers, including a mixture of ESCON, FICON, Fibre Channel, and vendor-proprietary protocols such as a Parallel Sysplex [1], [9], [85]. Not all of these protocols can be readily encapsulated in SONET or Ethernet networks, and many have protocol specific requirements for recovery and performance that are not addressed using GFP. These requirements will continue to be addressed through wavelength-based dark fiber services for the foreseeable future.

In this thesis, we concentrate on the need for vendor-independent WDM network design and modeling tools in this environment by developing computer models for physical layer design of enterprise VPNs. These models were validated against real WDM topologies constructed on the TeraPlex Testbed at IBM Corporation, and comparisons were made between different network equipment designs used on the same topology with the same mixture of traffic. For example, optical link budgets are an important restriction in the MAN, where it is desirable to avoid the use of expensive optical amplifiers for distances on the order of 50-100 km. Longer distances can be achieved by using recently developed dispersion-compensating fiber, such as large effective area (LEAF) fibers [1]; however, it is expensive to install new fiber in this environment, so there is an interest in modeling the ability of legacy single-mode fibers to support the required distances. Our model facilitates the design of such networks without compromising the bit error rate of the network.

ORGANIZATION OF THE DISSERTATION

After the introduction, in chapter 1, chapter 2 discusses background on optical networking. Chapter 3 describes topologies, protocols, the DWDM technology; the chapter wraps up by describing some common data center applications which is the main focus of this study. Chapter 4 presents the tasks that entail the design and modeling of DWDM networks; a comprehensive work includes the network modeling approach, depiction of the hubbed-ring and logical-mesh-topology solutions, description of the link budget flow chart; fiber optic link requirements and Bit Error

Rates (BER); the chapter concludes by presenting the optical link budget models. Chapter 5 presents experimental results for several cases and discusses the importance and future directions for this research; at last, MATLAB codes for our models are included in the appendix.

CHAPTER 2

BACKGROUND ON OPTICAL NETWORKING

In the following sections we present background on optical fiber communications such as optical fiber advantages, optical fiber modes, optical networking and DWDM network considerations, etc.

OPTICAL FIBER COMMUNICATIONS

An optical fiber is a piece of glass or plastic in which communications signals are transmitted from one location to another in the form of light. These signals are digital pulses or continuously modulated analog streams of light representing information. These can be voice, music, data, video information or any other type of information. These same types of information can be sent on metallic copper wires or through the air on microwave frequencies, but fiber optics offer many benefits not available in any conventional metallic conductors or microwaves. A picture which represents a fiber optic component is shown in Figure 2.1

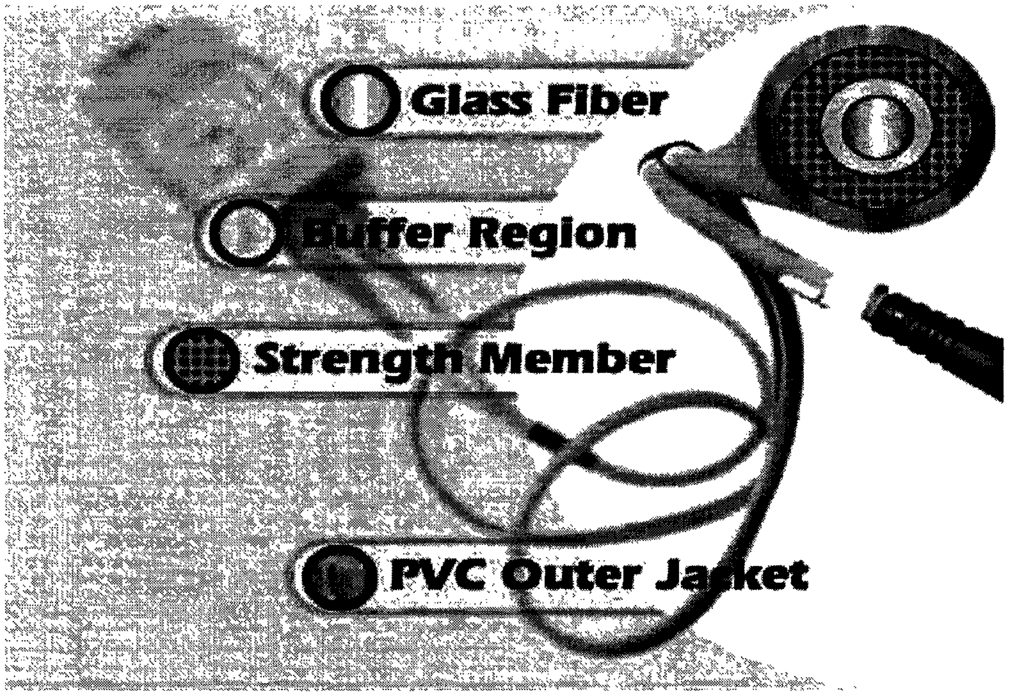


Figure 2.1 Optical fiber components

OPTICAL FIBER ADVANTAGES

The main advantage of optical fiber is that, it can transport more information longer distances in less time that any other communication medium. When comparing the data transmission performance with conventional cabling, the true benefits of fiber optics become apparent. Optical fiber is not susceptible to electromagnetic interference (EMI), thus fiber offers a much cleaner signal than metallic copper wires. Plus, signals in fiber do not degrade, as quickly as in copper wires; therefore uninterrupted cable lengths are possible. Fiber is totally immune to virtually all kinds of interference, including lightning. It does not conduct electricity; then it is ideal for volatile environments where spark from a conventional broken copper line could result in explosive consequences. If a fiber cable is broken, there is no risk of electrical shock. It can therefore come in direct contact with high voltage electrical equipment and power lines. As the basic fiber is made of glass, it will not corrode and is unaffected by most chemicals. It can be buried directly in most kinds of soils or exposed to most corrosive atmospheres in chemical plants without significant concern. A fiber optic cable, even one that contains many fibers, is usually much smaller and lighter in weight than a wire or coaxial cable with similar information carrying capacity. It is easier to handle and install, and uses less duct space [7].

OPTICAL FIBER CONSTRUCTION

Optic Fiber is comprised of a light-carrying core surrounded by a cladding that traps the light in the core by the principle of *total internal reflection.* By making the fiber's core of material with higher refractive index, we can cause light in the core to be totally reflected at the boundary of the cladding for all the light that strikes at greater than the critical angle. The critical angle is determined by the difference in the composition of the materials using the core and cladding. The core and cladding are usually fused silica glass covered by a plastic coating, called the buffer that protects the glass fiber from physical damage and moisture. Surrounding the buffer region is the strength member usually made of braided Kevlar; this region provides the mechanical strength for the cable, so that the fiber is not overly stressed. The final outer coating is a PVC jacket that protects the enclosed fiber from every day wear and tear, as shown in Figure 2.1.

OPTICAL FIBER MODES

Optical fiber comes in two types: *single-mode* and *multi-mode*.

Single Mode Fibers:

Single mode fibers are used to transmit one signal per fiber. They have small cores (9µm *in diameter*) and transmit infrared laser light ($\lambda = 1300nm$). Single-mode fiber carries light according to one propagation mode and along one trajectory; it can handle a lot of data with low loss of signal.

Multi Mode Fibers:

Multi-mode fibers are used to transmit many signals per fiber. They have larger cores (*62.5*µm *in diameter*) and transmit infrared light ($\lambda = 850nm$ *to 1300nm*) from light-emitting diodes (LED). LANs use multimode fibers. Multimode fibers maybe of the *step-index* or *graded-index* design as seen in Figure 2.2.

Step Index:

S*tep-index* fiber consists of a core of low loss glass surrounded y a cladding of even lower refractive index glass. The difference in refractive index between the two types of glass causes light to continually bounce between the core/cladding interfaces along the entire length of the fiber. Since each mode or angle of light travels a path, a pulse of light is dispersed while traveling through the fiber, limiting the bandwidth of step-index fiber.

Graded Index:

In graded-index fiber, only one type of glass is used, but it is treated so that the index of refraction gradually decreases as the distance from the core increases. The result of this construction is that light continuously bends toward the center of the fiber much like a continuous lens. Since light travels faster in the lower index of refraction glass, the light will travel faster as it approaches the outside of the core. Likewise, the light traveling closest to the core center will travel the slowest. A properly constructed index profile will compensate for the different path lengths of each mode, increasing the bandwidth capacity of the fiber by as much as 100 times over that of step-index fiber [7].

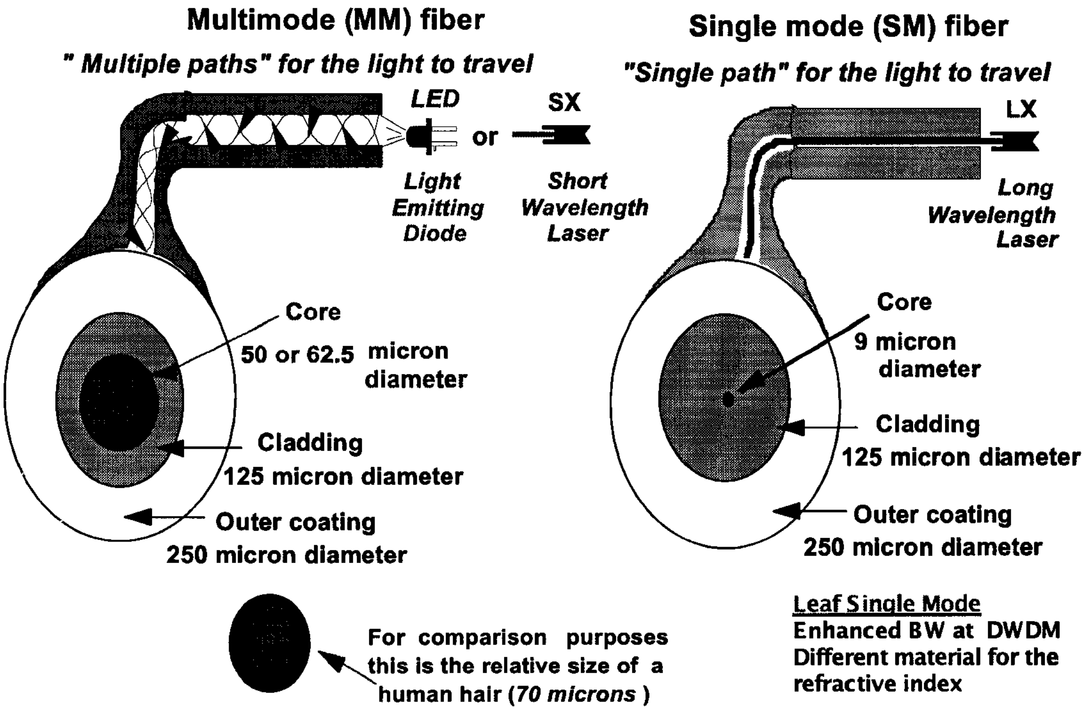


Figure 2.2 Single Mode and Multimode fiber

OPTICAL NETWORKING

One of the major issues of today's networking is the exponential demand for more bandwidth. Prior to the introduction of optical networks, the reduced availability of fibers became a big problem for the network providers. With the development of optical networks and the use of Dense Wavelength Division Multiplexing (DWDM) technology we have achieved a great up to date solution in network evolution. The SONET/SDH network architecture is best suited for voice traffic rather than today's high-speed data traffic. The upgrading of the system to handle this type of traffic is very expensive and hence the need for the development of an intelligent all-optical network.

Optical networks are high-capacity telecommunication and data communication networks based on optical technologies and components that provide routing, grooming, and restoration at the wavelength level as well as wavelength-based services. We can classify networks into three generations depending on the physical-level technology employed.

First Generation Networks:

In first-generation networks, see Figure 2.3, the links were copper-based or microwave technologies e.g. Ethernet, satellites, etc.

Second Generation Networks:

In second-generation networks, the copper or microwave links were linked with optical fibers see Figure 2.3. In these networks the switching of data has still being performed in the electronic domain while the transmission of data has been done in the optical domain.

Third Generation Networks:

In third-generation networks, Wavelength Division Multiplexing technology has been employed see Figure 2.3. In these networks the switching and transmission of data is performed in the optical domain. This technique provides bandwidth availability that no other previous technology has provided to us. Furthermore, the use of non-overlapping channels allows each channel to operate at peak speeds [5].

Name	Family	Designed for	MUX/SW Schemes at Inception	Principal Media at Inception	Capacity	Typical Payload	Protocol Inter-working
T1/E1	First	Voice, Non-BOD Static	TDM E/E/E	Copper: (Early 1960s)	Mbps	Fixed Length	No
SONET/SDH	Second	Voice, Non-BOD Static	TDM O/E/O	Copper, Fiber (Mid - 1980s)	Gbps	Fixed Length	Some what PPP, IP, ATM
OTN	Third	Voice, Video Data, Tailored QoS, BOD, Dynamic	WDM O/O/O	Fiber (Late - 1990s to Early 2000s)	Tbps	Fixed or variable lengths	Yes: PPP, IP, ATM, MPLS

Figure 2.3 Three Generations of Digital Transport (carrier) Networks

WHY IS DWDM USED?

The exponential growth in telecommunications and data communications have led many enterprise businesses' current fiber installation to reach their maximum capacity originally planned; even though most cables included many spares fibers when installed, this growth has made use many of them and new capacity is needed. To expand the capacity we can use three approaches:

1. I*nstall more cables*,
2. I*ncrease system bit-rate or multiplex more signals,* or
3. Use W*avelength Division Multiplexing.*

More fiber optic cable installation will be a preferred method in many cases, especially in metropolitan areas, since fiber has become incredibly inexpensive and installation methods more efficient. But if conduit space is not available or major construction is necessary, this may not be the most cost effective.

System bit-rate increase may not prove to be cost effective either. Many systems are already running at SONET **OC-48** rates (***2.5Gbps***) and upgrading to **OC-192** (***10Gbps***) is expensive, it requires changing out all the electronics in a network, and adds four times the capacity, more than maybe necessary.

The third alternative, Wavelength Division Multiplexing (WDM), has proven to be more cost effective in many instances. It allows current fibers to share transmission of different channels at different wavelengths (*colors*) of light. Systems that already use fiber optic amplifier as repeaters also do not require upgrading for most WDM systems.

Multiplexing wavelength is a way to take advantage of the high bandwidth of fiber optic cables without requiring extremely high modulation rates at the transceiver. With an available bandwidth of about 25 THz, a single fiber could carry all the telephone traffic in the United States on the busiest day of the year. This technology represents an estimated $1.6 Billion market with over 50% annual growth. Wavelength multiplexing systems may be classified according to their wavelength spacing and number of channels as follows [3]:

Coarse Wavelength Division Multiplexing (CWDM):

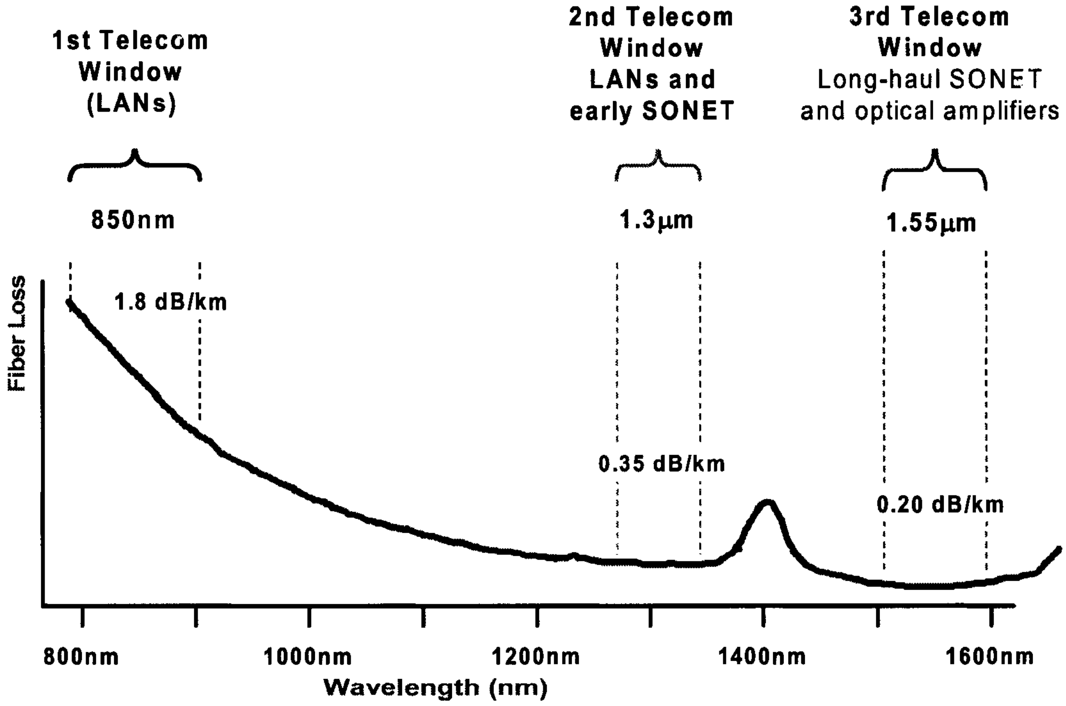
Coarse WDM systems typically make use of 2 – 3 wavelengths widely spaced. Applications of this technology in data communications are limited, although recently coarse WDM systems with 4 to 8 channels have been used in small networks.

Wide Spectrum Wavelength Division Multiplexing (WWDM):

Wide-Spectrum WDM systems can support up to 16 channels, using wavelengths that are spaced relatively far apart. These systems are meant to serve as low-cost alternative to DWDM for applications that do not require large number of channels on a single fiber path; and are being considered as an option for the emerging 10 Gbps Ethernet standard [4].

Dense Wavelength Division Multiplexing (DWDM):

Dense WDM systems employ wavelengths spaced much closer together, typically following multiples of the International Telecommunications Union (ITU) industry standards grid [5], with wavelengths near 1550nm and minimum wavelength spacing of 0.8nm (100GHz) see Figure 2.4 below for fiber operating wavelengths.



Reference: Nortel Networks Tutorials

Figure 2.4 Fiber Optic Operating Wavelengths

This may be further subdivided as follows:

First Generation DWDM:

First-generation DWDM systems typically employed up to 8 full-duplex channels multiplexed into a single-duplex channel.

Second Generation DWDM:

Second-generation DWDM systems employ up to 16 channels.

Third-generation DWDM:

Third-generation DWDM systems employ up to 32 channels; this is the largest system currently in commercial production of data communications applications.

Fourth Generation or Ultra Dense WDM:

Fourth-generation or Ultra-dense WDM is expected to employ 40 channels or more and may deviate from current ITU grid wavelengths; channel spacing as small as 0.4nm (50GHz) have been proposed [6]. These systems are not yet commercially available.

Normally one communication channel requires two optical fibers, one to transmit; and the other to receive data; a multiplexer provides the means to run many independent data or voice channels over a single pair of fibers. This device takes advantage of the fact that different wavelength of light will not interfere with each other when they are carried over the same optical fiber; this principle in known as wavelength division multiplexing (WDM). The concept is similar to frequency division multiplexing (FDM) used by FM radio, except that carrier "frequencies" are in the optical portion of the spectrum (*around 1550nm wavelength, or* $2x10^{14}\,Hz$). Thus by placing each data channel on different wavelength (*frequency*) of light, it is possible to send many channels of data over the same fiber; this principle is shown in Figure 2.5. More data channels can be carried if the wavelengths are spaced closer together; this is known as dense wavelength division multiplexing (DWDM). Following standards set by the ITU [5], the wavelength spacing for DWDM products is a minimum of 0.8nm, or about 100GHz. In practice, many products use a slightly broader spacing such as 1.6nm, or about 200GHz, to simplify the design and lower the overall product cost.

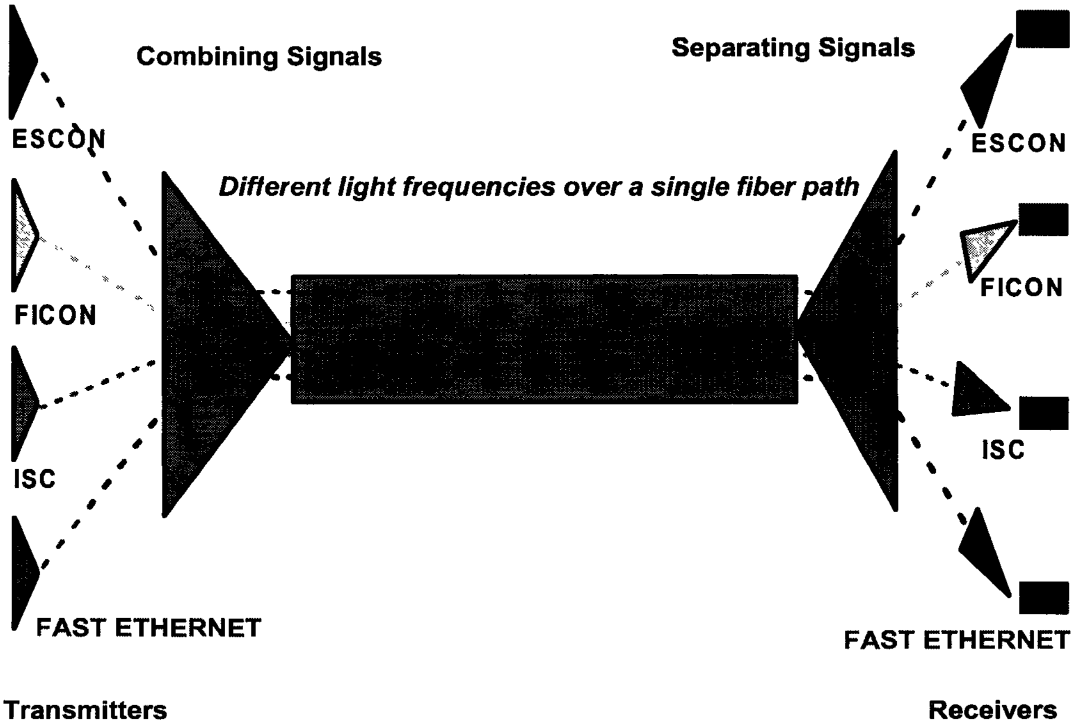


Figure 2.5 The principle of DWDM

Note that the process is in principle protocol independent; it provides a selection of fiber optic interfaces to attach any type of voice or data communication channel. Input data channels are converted from optical to electrical signals, routed to an appropriate output port, converted into optical DWDM signals, and then combined into a single channel. The wavelengths may be combined in different ways; for example, a diffraction grating or prism may be used – Demultiplexing reverses the process, Dielectric Add/Drop filters are also used in this process, this process is shown in Figure 2.6. Filters have some insertion and absorption loss associated with it; this can affect the link budget in large WDM network.

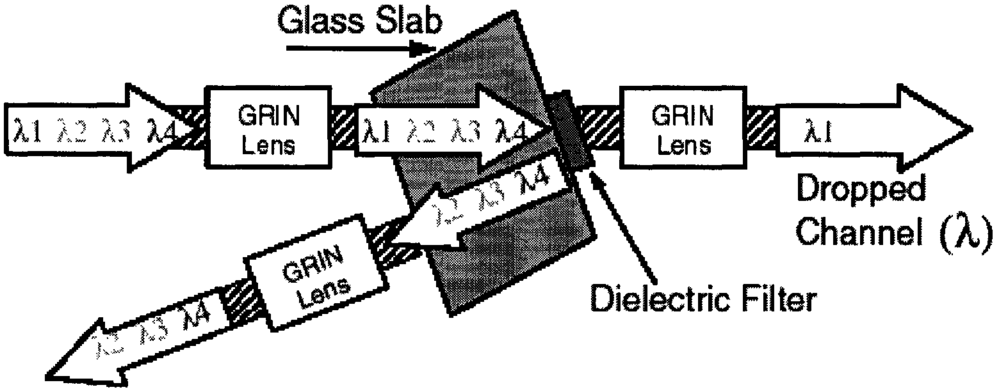


Figure 2.6 Dielectric Add/Drop filter

DWDM DESIGN CONSIDERATIONS

There are many important characteristics to consider when designing a DWDM system. One of the most obvious design points is the largest total number of channels (*largest total amount of data*) supported over a multiplexed fiber optic network. Typically, one wavelength is required to support a data stream; duplex data streams may require two different wavelengths in each direction or may use the same wavelength for bi-directional transmission. Additional channel capacity may be added to the network using a combination of WDM and other features, including TDM and wavelength reuse. Wavelength reuse refers to the product's ability to reuse the same wavelength channel for communication between multiple locations; this increases the number of channels in the network. A tradeoff is that systems with wavelength reuse cannot offer protection switching on the reused channels.

Time Division Multiplexing (TDM) is another way in which some WDM products increase the number of channels on the network. Multiple data streams share a common fiber path by dividing it into time slots, which are then interleaved onto a fiber as illustrated in Figure 2.7. TDM acts as a front-end for WDM by combining several low data rate channels into a higher data rate channels; because higher data rate channel only requires single wavelength of the WDM, this method provides increased number of low-speed channels. As an example, if the maximum data rate on a WDM channel is 1 Gbps, then it should be possible to accommodate by TDM up to 4 channels over this wavelength, each with a bit rate of 200 Mbps, and still have some margin for channel overhead and other features. The TDM function may be offered as part of a separate product, such as a data switch, that interoperates with the wavelength multiplexer; preferably, it would be integrated into the WDM design.

Some products only support TDM for selected telecommunications protocols such as SONET; indeed, the telecom protocols are designed to function in a TDM-only network, and can be concatenated at successively faster data rates. However, since WDM technology can be made protocol independent, it is desirable for WDM to also be bit-rate and protocol-independent, or at least be able to accommodate other than SONET-based protocols. This sometimes referred to as being “frequency agile.”

A way to measure the capacity of the multiplexer is by its maximum bandwidth, which is the product of the maximum number of channels and the maximum date rate per channel. This will give to the designer a pretty good estimate of available bandwidth that the system will support.

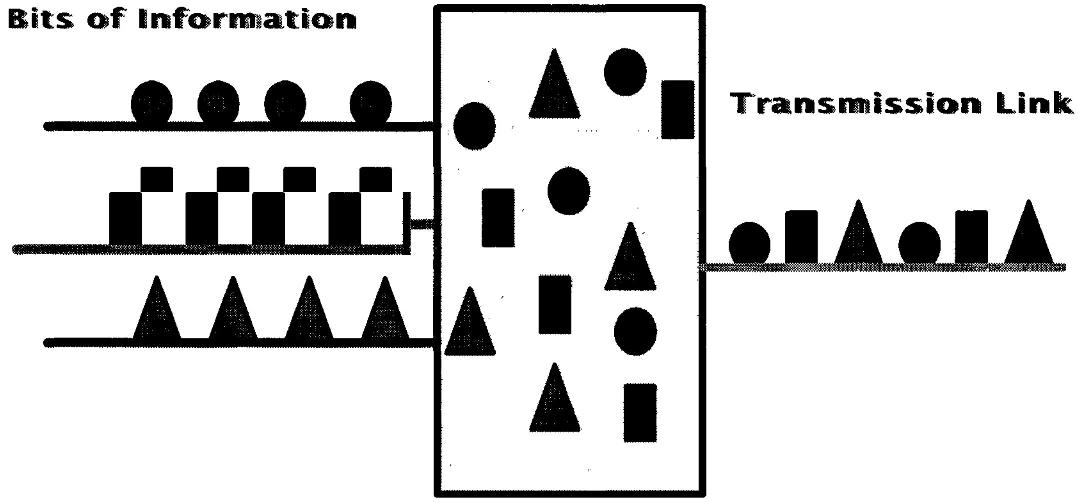


Figure 2.7 Time Division Multiplexing (TDM) Illustration

Another important design consideration in the design of WDM equipment is the number of multiplexing stages (*or cards*) required. It is desirable to have the smallest number of cards supporting a full range of datacom and telecom protocols. Generally speaking, a WDM device contains 2 optical interfaces, one for attachment of input or client signals (*which may be protocol specific*) and one for attachment of the WDM signals. Each client interface may require a unique adapter card; for example, some protocols require a physical layer that is based on an LED transmitter operating over 62.5 micron multimode fiber, others use short-wavelength lasers with 50 micron multimode fiber, and still others require long wavelength lasers with single-mode fiber. Likewise, each channel on the WDM interface uses a different wavelength laser transmitter tuned to an ITU grid wavelength, and therefore requires unique adapter card. Some designs place these 2 interfaces on a single card, which means that more cards are required to support the system; as an example, a product with 16 wavelength channels may require 16 cards to support ESCON, 16 more to support ATM, and in general to support N channels with M protocols would require N*M cards. Typically N = 16 to 32 channels and M = 10 to 15 protocols, so this translates into greater total cost for a large system, greater cost in tracking more part numbers and carrying more spare cards in inventory, and possibly lower reliability (*since the card with both features can be quite complex*). Protocols supported by WDM, is shown in Table 2-1

Table 2.1: Protocols Supported by WDM, Including Native Physical Layer Specification and Attachment Distances;
MM = Multi-Mode fiber, SM= Single-Mode fiber, TX = Transmitter, RX = Receiver,
LX = Long Wavelength Transmitter, SX = Short Wavelength Transmitter

Protocol Type	Physical Layer Specification (dB)	Native Attach Distance
ESCON/SBCON MM and Sysplex Timer MM	TX: -15 to -20.5 RX: -14 to -29	3 Km
ESCON/SBCON MM	TX: -3 to -8 RX: -3 to -28	20 km
FICON SM	TX: -3 to -8.5 RX: -3 to -22	10 km
ATM 155 MM	TX: -14 to -19 RX: -14 to -30	2 km
ATM 155 SM	TX: -8 to -15 RX: -8 to -32.5	10 km
FDDI MM	TX: -14 to -19 RX: -14 to -31.8	2 km
Gigabit Ethernet LX SM	TX: -14 to -20 RX: -17 to -31	5 km
Gigabit Ethernet SX MM (850 nm)	TX: -4 to -10 RX: -17 to -31	550 m
HiPerLinks for Parallel Sysplex & GDPS	TX: -3 to -11 RX: -3 to -20	10 km

DISTANCE AND REPEATERS

The total supported distance for a WDM system may depend on the number of channels in use; adding more channels require additional wavelength multiplexing stages and the optical fibers can reduce the available link budget. The available distance is also a function of the network topology; WDM filters may need to be configured differently, depending on whether they form an optical seam (*configuration that does not allow a set of wavelengths to propagate into the next stage of the network*) or optical bypass (*configuration that permits wavelengths to pass through into the rest of the network*). Thus, the total distance and available link loss budget in a point-to-point network may be different from the distance in a ring network. The available distance is typically independent of data rate up to around 2Gbps; as it is shown in the simulation results in chapter 5. At higher data rate; dispersion may limit the achievable distances. This should be kept in mind when installing a new WDM system planned to be upgraded to significantly higher data rates in the future. The maximum available distance and link loss may also be reduced if optional optical switches are included in the network for protection purposes. In some cases, it is possible to concatenate or cascade WDM networks together to achieve longer total distances [1].

LATENCY

DWDM devices also function as channel extenders, allowing many datacom protocols to reach previously impossible distances (50 -100 Km or more). Combined with optical amplifier technology, this has led some industry analysts to proclaim "the death of distance," meaning that connection distances should no longer pose a serious limitation in optical network design. However, in many real-world applications, it is not sufficient to simply extend a physical connection; performance of the attached datacom equipment must also be considered. Latency or propagation delay due to extended distances, remains a formidable problem of optical data communication. The effect of latency is often protocol specific or device specific. For example, using DWDM technology it is possible to extend and ESCON channel to well over 50 Km. However, many ESCON control units and DASD are synchronous, and exhibit timing problems at distances beyond 43 Km., other protocols, such as FICON, can be designed to perform much better at extended distances.

PROTECTION AND RESTORATION

Backup fiber protection or restoration refers to the multiplexer's ability to support a secondary fiber path for redundancy in case of a fiber break or equipment failure. The "1+1" SONET type protection switching is the most desirable one, this standard is used by the telecom industry, in which the data is transmitted along both the primary and backup paths simultaneously, and the data switches from primary to the backup path within 50ms. There is also a trunk switch, which simply switches from the primary path to the backup path if the primary path breaks – the switching time is typically within 100ms. New architectures have also been proposed, such as bi-directional wavelength path switching ring (BWPSR), which uses bi-directional wavelength protection and a wavelength-based protection trigger self-healing ring network [18].

NETWORK MANAGEMENT

Some DWDM devices offer minimal network management capabilities, limited to a bank of colored lamps on the front panel; others offer sophisticated IP management and are configured similar to a router or switch. Many types of network management software are available in datacom applications; these are often based on standard SNMP protocols supported by many applications such as HP Openview, CA Unicenter, and Tivoli Netview. Optical management of WDM may include various forms of monitoring the physical layer, including average optical power per channel and power spectral density, in order to proactively detect near end-of-life components to optimize performance in amplified WDM network.

COMMERCIAL DWDM SYSTEMS

Many commercial DWDM products in use today have been developed for the telecommunications and data communications market; there are also a number of testbed and service trials underway, and new products or technologies are being proposed at a rapid pace. Some examples include Optera 5200 from Nortel, the FSP 2000 from Adva, the ONS 15540 from Cisco [1], [20], the MultiWave WDM terminal from Ciena Corp., the WaveMux from Pirelli, which handles up to 10 OC-192 channels or 32 OC-48 channels. There are more companies involved in developing DWDMs, for more complete listing check the book by Shepard [20].

CHAPTER 3

TOPOLOGIES, PROTOCOLS, TECHNOLOGY AND DATA CENTER APPLICATIONS

In the following sections we present description of common topologies, most relevant protocols, and finally the technologies with their application in Data Centers.

TOPOLOGIES

Conventional SONET networks are designed for the WAN and are based on reconfigurable ring topologies, while most datacom networks function as switched networks in the LAN and point-to-point in the WAN or MAN. There has been a great deal of work done on optimizing nationwide WANs for performance and scalability, and interfacing them with LAN and MAN topologies; WDM plays a key role at all three network levels. The topologies we will describe are point-to-point, Ring, hubbed-ring, logical ring mesh, Parallel Sysplex and GDPS.

Point-to-Point:

This is the simplest of the other implementations. A point to point topology is a connection between two DWDM connections across a pair of single fibers as shown in Figure 3.1. This is implemented with two fiber channels, one of which is considered an East link, and the other a West link. Point-to-point topologies can be implemented with or without Optical Add/Drop Multiplexers (OADM). These networks are characterized by ultra-high channel speeds (10 to 40 Gbps), high signal integrity and reliability, and fast path restoration. In the MAN, amplifiers are often not needed.

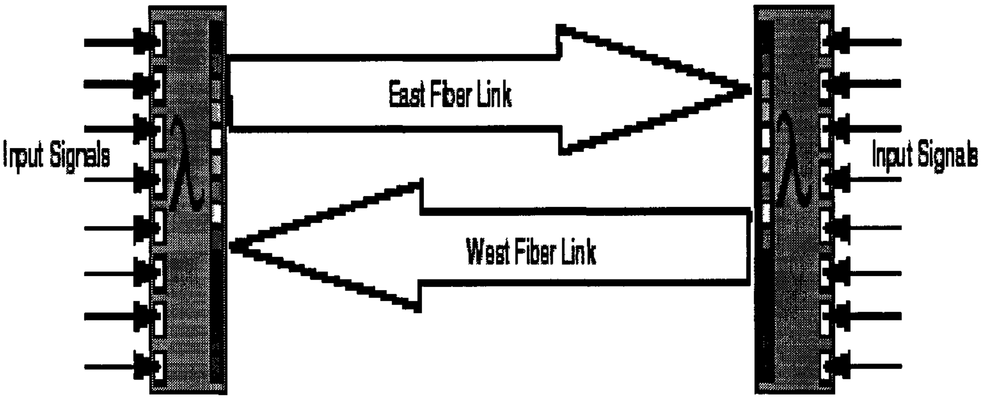


Figure 3.1 Point-to-point topology

Protection in point-to-point topologies can be provided in a couple of ways. In first generation DWDM, redundancy is at the system level. Parallel links connect redundant systems at either end. Switching in case of failure is the responsibility of the client equipment, while the DWDM systems just provide capacity. In second generation DWDM, redundancy is at the card level. Parallel links connect single systems at either end that contain transponders, multiplexers, and CPUs. In this case protection has migrated to the DWDM equipment, with switching capabilities under local control. One type of implementation, for example, uses a "1+1" protection scheme based on SONET Automatic Protection Switching (APS), see Figure 3.2.

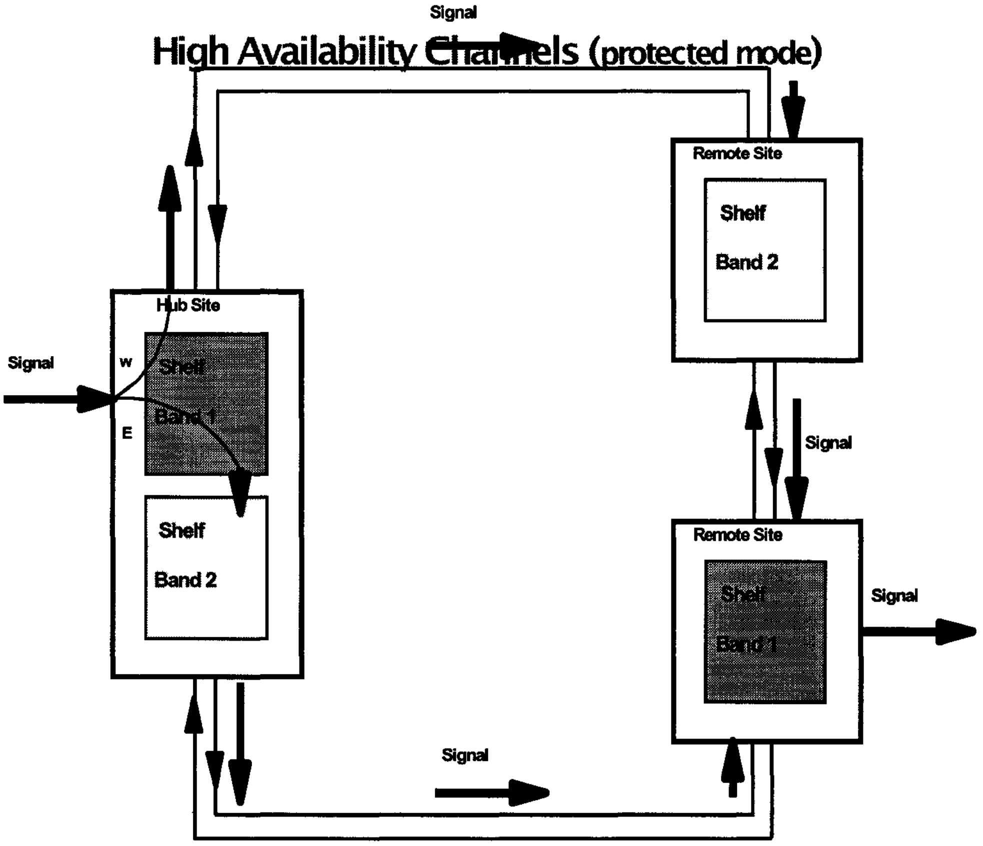


Figure 3.2 Point-to-point configuration with "1 + 1" protection

Ring:

This topology is typically implemented where many geographically dispersed locations need to be connected. This solution could be implemented with only one or more DWDM's or could comprise of many components including OADM devices and hubs. Channels can be dropped or added at one or more nodes on a ring. Rings have many common applications, including providing extended access to Storage Area Networks (SANs), where increasing capacity of existing fiber is desirable.

Hubbed-Ring:

A hubbed ring is composed of a hub node and two or more add/drop or satellite nodes. All channels on the ring originate and terminate on the hub node. At the add/drop node certain channels are terminated (dropped and added back) while the channels that are not being dropped (express channels) are passed through optically, without being electrically regenerated, this is shown in Figure 3.3.

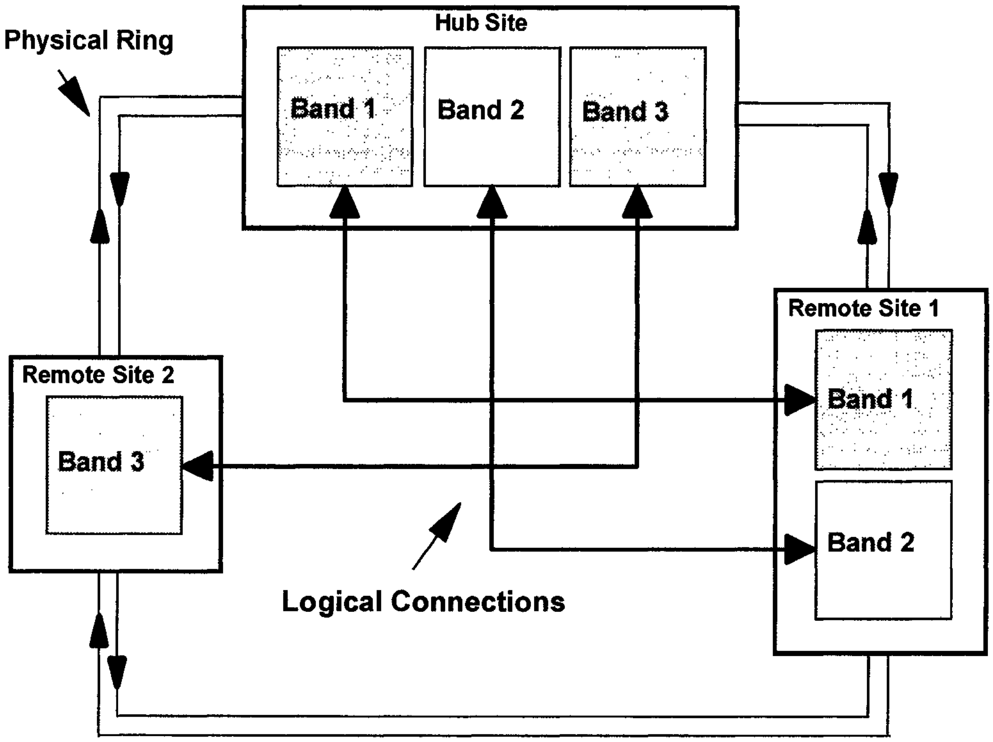


Figure 3.3 Hubbed-Ring topology

Logical Meshed Ring:

A meshed ring is a physical ring that has the logical characteristics of a mesh. While traffic travels on a physical ring, the logical connections between individual nodes are meshed [82]. Mesh architectures are the future of optical networks. As networks evolve, rings and point-to-point topologies will still have a place, but mesh will be the most robust topology. This development will be enabled by the introduction of optical cross-connects and switches that will in some cases replace and in other case supplement fixed DWDM devices. This type of topology is shown in Figure 3.4

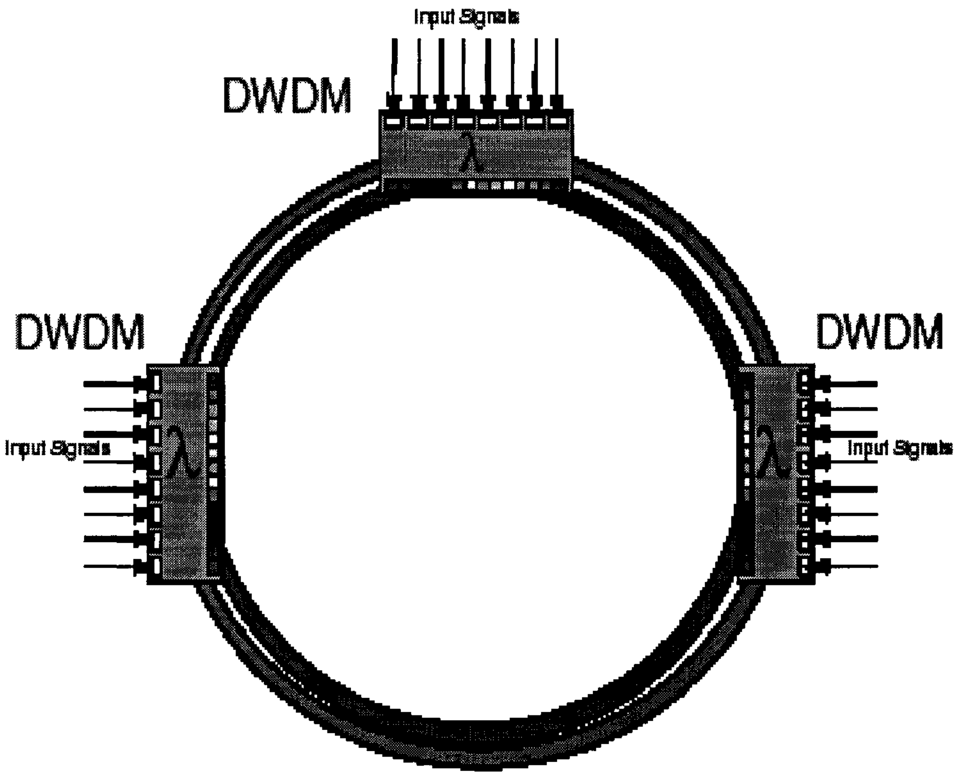


Figure 3.4 Logical mesh ring topology

DWDM mesh networks, consisting of interconnected all-optical nodes, will require the next generation of protection. Previous protection schemes relied upon redundancy at the system, card, or fiber level – redundancy will now migrate to the wavelength level. This implies that data channel might change wavelengths as it makes its way through the network, due either to routing or to a switch in wavelength because of a fault [15].

Consequently, mesh networks will require a high degree of intelligence to perform the functions of protection and bandwidth management switching. The benefits in flexibility and efficiency, however, are potentially great. Mesh networks will be highly dependent upon software management. A protocol based on Multiprotocol Label Switching (MPLS) is currently under development to support routed paths through an all-optical network [5].

East and West:

Dense Wavelength Division Multiplexers are often composed of shelves each of which operates in a specified wavelength band, which is determined by the wavelength band of the optical modules installed in the shelf; this principle is shown in Figure 3.5. Each shelf is divided into two parts, the West side and the East side. The two sides must have the same wavelength band.

A site can have many channels, each operating on a different wavelength within the shelf's wavelength band. Each West side channel has the same wavelength as the corresponding East side channel.

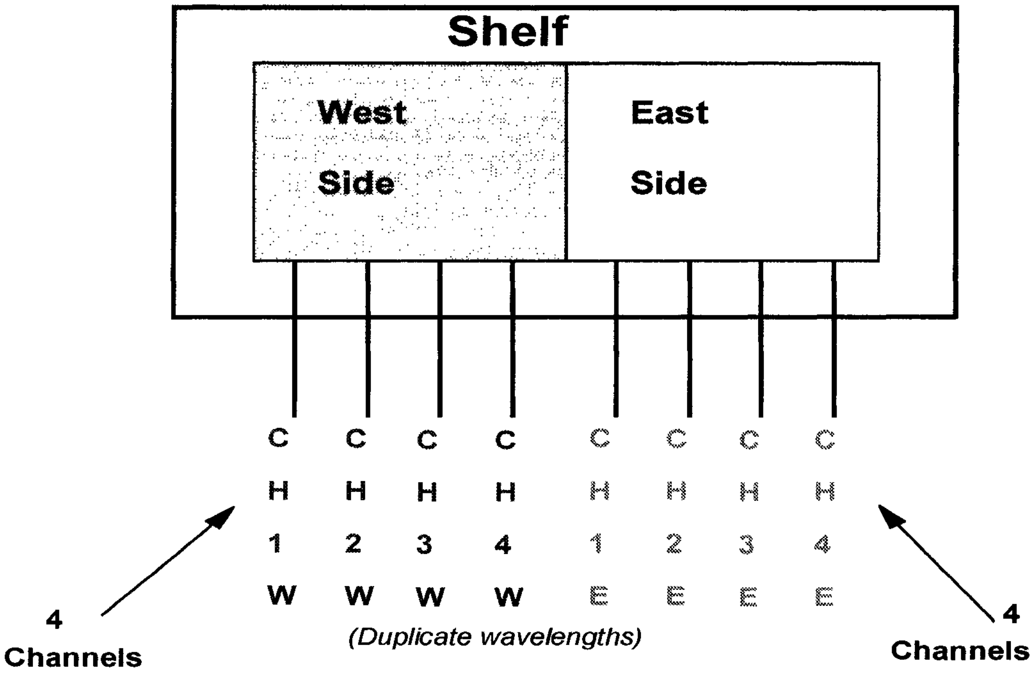


Figure 3.5 DWDM module with East and West

PROTOCOLS

In this section we will depict some of the commonly encountered protocols. We will very briefly explain Asynchronous Transfer Mode (ATM), Gigabit Ethernet, SONET, Fiber Channel, ESCON, FICON, ETR, CLO and ISC.

Asynchronous Transfer Mode (ATM):

ATM is a dedicated connection switching technology that organizes digital data into 53 – byte cell units and transmits them over a physical medium using digital signaling technology. Individually, a cell is processed asynchronously relative to other related cells and is queued before being multiplexed over the transmission path. Because ATM is designed to be easily implemented by hardware (rather than software), faster processing and switch speeds are possible. The pre specified bit rates are either 155.52 Mbps or 622.08 Mbps. Speeds on ATM networks can reach 10 Gbps.

Many service providers favor ATM because it can encapsulate different protocols and traffic types into a common format for transmission over a Synchronous Optical Network (SONET) infrastructure. Meanwhile the data networking world, which is by far mostly IP-oriented, favors packet over SONET (POS), which obviates the costly ATM intermediate layer. The scaling capacity of gigabit and multi-gigabit routers combined with advancements in IP, make it possible to foresee and IP-based network that is well suited for carrying primarily data traffic, and secondarily voice.

Nonetheless ATM remains strong in the metropolitan area. It can accommodate higher speed line interfaces and provide managed virtual circuit services while offering traffic management capabilities. Consequently, ATM edge devices are commonly used to terminate traffic, including VoIP, DSL, and Frame Relay.

Gigabit Ethernet:

The Ethernet protocol is the world's most popular LAN protocol. This standard has evolved from the original shared 10 Mbps technology, developed in the 1970's, to the recently completed Gigabit Ethernet standard, (the first Gigabit Ethernet standard (802.3z) was ratified by the IEEE 802.3 Committee in 1998). Gigabit Ethernet is the newest version of Ethernet and it supports data transfers rates of 1 Gbps.

Gigabit Ethernet is a proven technology for easy migration from and integration into traditional Ethernet. It is relatively inexpensive compared to other technologies that offer the same transmission rate, but does not provide quality of service (QoS) or fault tolerance on its own. Because the optical physical layer can support much longer distances than traditional Category 5 cable, Gigabit Ethernet over fiber (1000BASE-LX, for example) can be extended into the wide-area using DWDM.

The latest innovation is 10 Gigabit Ethernet, and is motivated by the need to interconnect Ethernet LANs operating at slower data rates. The 10 Gigabit Ethernet can be used to aggregate slower access links (in the backbone). With 1550nm serial lasers, distances of 40 to 80 Km are possible with 10 Gigabit Ethernet over standard SM fiber.

Ethernet has proven to be adaptable, reliable, and simple technology. Implementations are standard and interoperable, and cost is much less than SONET or ATM. The emerging potential of Ethernet is to serve as a scalable, end-to-end solution. Network management can also be improved by using Ethernet across the MAN and WAN.

SONET and SDH:

SONET and SDH are a set of related standards for synchronous data transmission over fiber optic networks. Synchronous Optical Network (SONET) is the United States version of the American National Standards Institute (ANSI) and Synchronous Digital Hierarchy (SDH) is the International Telecommunications Union (ITU) standard.

SONET and SDH specify interface parameters, rates, framing formats, multiplexing methods, and management for synchronous TDM over fiber. It takes *n* bit streams, multiplexes them, and optically modulates the signal, sending it out using a light emitting device over fiber with a bit rate equal to (incoming bit rate) x n. Thus traffic arriving at the SONET multiplexer from four places at 2.5 Gbps will go out as a single stream at 4 x 2.5 Gbps, or 10 Gbps.

As a transport technology, SONET is an “agnostic” protocol that can transport all traffic types, while providing interoperability, protection schemes, network management, and support for a TDM hierarchy. Upgrading a SONET is expensive, as line-rate specific network elements are required at each point of traffic ingress or egress. The use of DWDM increases the capacity of embedded fiber, while preserving SONET infra-structure; this is an alternative to expensive SONET upgrades. For example, SONET multiplexing equipment can be avoided by interfacing directly to DWDM equipment from ATM and packet switches. Migration from SONET to

DWDM may be the most important application in the near term. This migration begins by replacing backbones with DWDM, then move toward the edges of the network.

Fibre Channel:

Fiber Channel is a technology for transmitting data between computer devices at a data rate of up to 2 Gbps. It is especially suited for connecting computer servers to shared storage devices and for interconnecting storage controllers and drives. Fiber Channel is the predominant data link technology used in storage area networks (SANs). Since Fiber Channel is three times as fast, it has begun to replace the Small Computer System Interface (SCSI) as the transmission interface between servers and clustered storage devices. Fiber channel is more flexible; devices can be as far as 10 kilometers apart if optical fiber is used as the physical medium. Optical fiber is not required for shorter distances, however, because Fiber Channel also works using coaxial cable and ordinary telephone twisted pair. Standard for Fiber Channel are specified by the Fiber Channel Physical and Signaling standard, and the ANSI X3.230-1994, which is also ISO 14165-1. Fiber Channel can be implemented in a point-to-point, arbitrated loop, or mesh topology using a switch.

ESCON/SBCON:

ESCON/SBCON (Enterprise System Connection/Serial Byte Connection) channel is a bidirectional, point-to-point 1300nm fiber optic data link with maximum data rate of 200 Mbps minus overhead. The physical layer specifications can be found in [3]. ESCON supports a maximum unrepeated distance of 3 Km using 62.5 μm multimode fiber and LED transmitters with an 8-dB link budget, or a maximum unrepeated distance of 20 Km using single mode fiber and laser transmitters with a 14-dB link budget. The laser channels are also known as ESCON extended distance features (XDF). Physical connection is provided by an ESCON duplex connector as illustrated in Figure 3.6; the connector features a unique spring loaded retractable dust cover, which protects the ferrules when the connector is not in use and retracts on insertion into an ESCON receptacle. Initially, the ESCON duplex connector was offered in both multimode and single-mode versions, color coded with black and orange fiber jacket for multimode and gray connectors and yellow fiber jacket for single mode. Recently, the single-mode ESCON links have adopted the SC duplex connector as standardized by FC (see Figure 3.7). Using repeaters or switches, an ESCON link can be extended up to three times the normal distances; however, performance of the attached devices typically falls off quickly at longer distances due to the longer round trip latency of the link, making this approach suitable only for applications that can tolerate a lower effective throughput, such as remote backup of data for disaster recovery.

ESCON devices and CPUs may communicate directly through a channel-to-channel attachment, but more commonly attach to a central non-blocking dynamic cross-point switch. The resulting network topology is similar to a star wired ring, which provides both efficient bandwidth utilization and reduced cabling requirements. The switching function is provided by an ESCON director, a non-blocking circuit switch. Although ESCON uses 8 B/10 B encoded data, it is not a packet switching network; instead, the data frame header includes a request for connection that is established by the director for the duration of the data transfer. An ESCON data frame includes a header, a payload of up to 1028 bytes of data, and a trailer. The header consists of a 2-character start of frame delimiter, a 2-byte destination address, a 2-byte source address, and 1 byte of link control information. The trailer is a 2-byte cyclic redundancy check (CRC) for errors and a three-character end-of-frame delimiter [36].

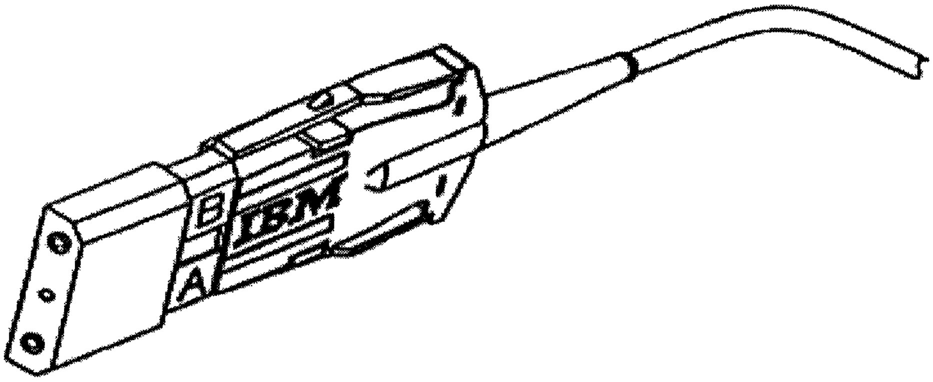


Figure 3.6 ESCON duplex fiber optic connector

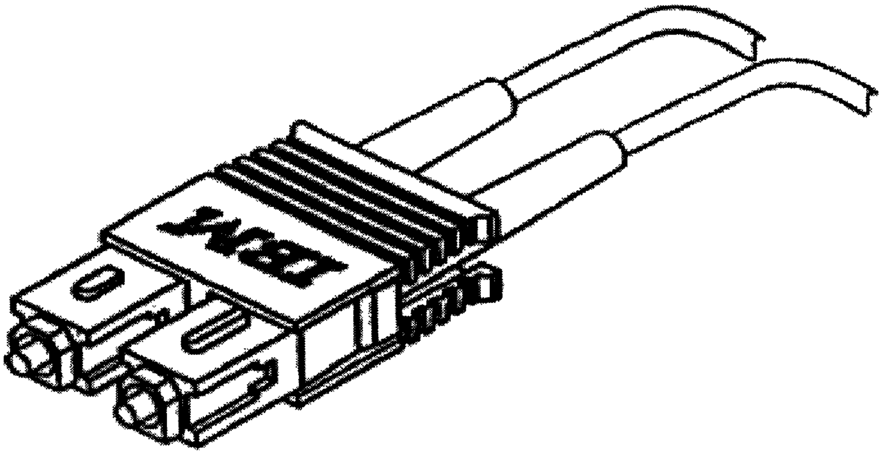


Figure 3.7 Single mode SC duplex fiber optic connector

FICON:

FICON (Fiber Channel Connection) was introduced in May 1998 on the IBM G5 servers. It is an implementation of Fiber Channel (FC) – it is a high speed I/O link with provisions to facilitate limited use of the ESCON physical cable plant. All FICON links use LW (1300nm) laser sources. The FICON physical layer supports data rates of 1.062 Gbps on single mode fiber up to 10 Km with a 7-dB link budget, compatible with FC physical layer specifications. In addition, FICON enables the use of both 50 μm and 62.5 μm multi-mode fiber with a mode conditioning patch cable, similar to the emerging gigabit Ethernet standard, at distances up to 550 m with a 5-dB link budget. A FICON adapter card is available for ESCON directors which enables up to 8 ESCON channels to be time division multiplexed on a FICON link, and FICON directors are expected to be available in the near future. One of the main advantages of FICON is the lack of performance degradation over distance that is seen with ESCON as seen in Figure 3.8. FICON can reach a distance of 100 km before experiencing any significant drop in data throughput.

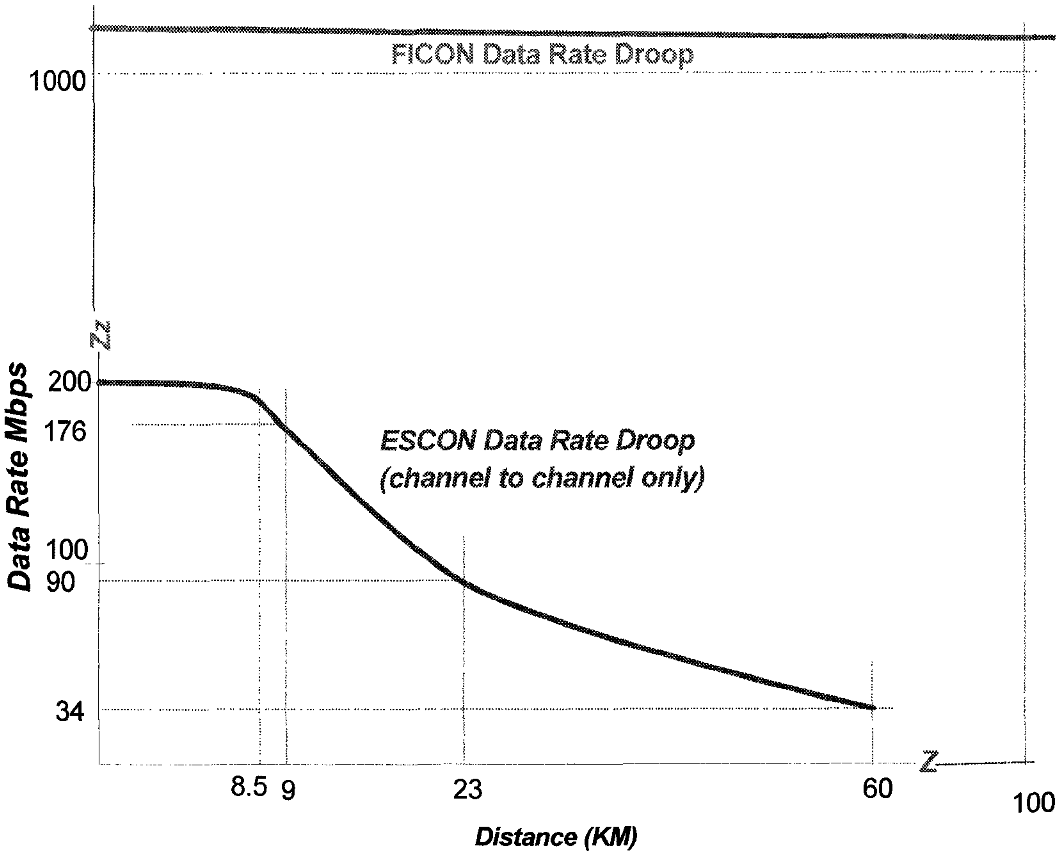


Figure 3.8 ESCON/FICON distance performance

Sysplex Timer – External Time Reference (ETR):

The External Time Reference (ETR) or Sysplex Timer is a mandatory requirement for any multi Central Processor Complex (CPC) Sysplex (base or parallel) environment. It is used to synchronize the time across all systems. The Sysplex Timer is one of the most critical components in a Sysplex because any system that loses access to the timer will load a non-restartable, disabled wait state [18].

The ETR is provided by the IBM 9037 Sysplex Timer. The model is available in both basic and expanded availability configurations. The base configuration is a single timer unit (which is a single point of failure); the expanded availability configuration is the recommended configuration for a production Sysplex environment.

There are 2 types of fiber links associated with the Sysplex Timer:

(i) Control Link Oscillator (CLO) links are connections between the two timer units in an expanded availability configuration. Two links are provided for redundancy.

(ii) External Time Reference (ETR) links are the connections between the CPC and the timer units. Each CPC should have at least one connection to each timer unit in an expanded availability configuration.

A typical 9037 expanded availability configuration is shown in Figure 3.9.

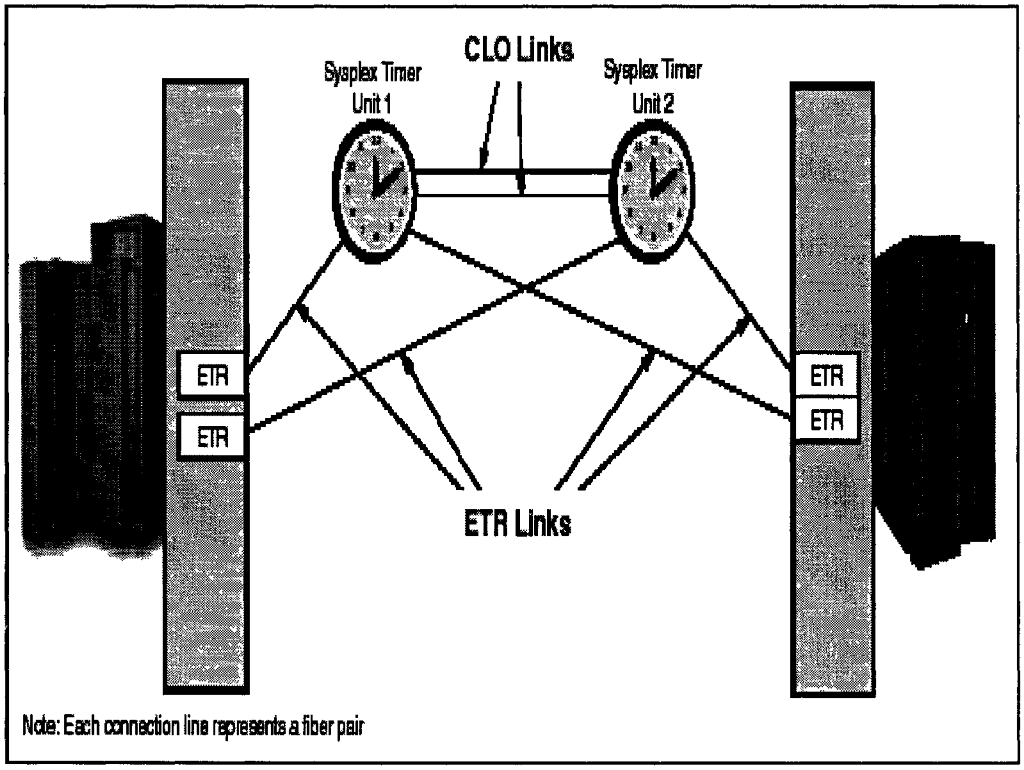


Figure 3.9 Sysplex Timer Expanded Availability configuration connections

The 9037 links use multimode fibers for both ETR and CLO links. The maximum distance (cable length) for both types of links is 3 km. Each of the fiber links shown in Figure 3.9 is a jumper cable with 2 fibers, one for data transmission in each direction.

The time of date (TOD) clocks in the two 9037s units are synchronized using the hardware on the CLO card and the CLO links between the 9037s. Both 9037 units are simultaneously transmitting the same time synchronization information to all attached CPCs via the ETR links. Critical information is exchanged between this two 9037s every 1.048576 seconds, so that if one of the 9037 units fails, the other will continue transmitting clock signals to the attached CPCs.

The Optera 5200 from Nortel and the FSP 2000 from Adva can be used to extend the 9037 Sysplex Timer connections up to 40 km. With this extension, the same availability recommendations that apply within a site should be applied across sites. One Sysplex Timer should be installed in each site and all CPCs should have one connection to each Sysplex Timer unit.

The previous Sysplex Timer configuration example with the processors and timer units in a separate sites and cross-site connections are extended via the use of the fiber extender network, this is shown in Figure 3.10.

Sysplex Timer links (CLO and ETR) are not supported as high availability channels with the use of Fiber Extenders. The reason for this is related to the critical timing requirements for signals on the ETR and CLO links. Hubbed-ring configurations are also not supported for Sysplex Timer links, because there is no guarantee that in this configuration the transmit and receive paths will have lengths within the 10 meter limit, as required for processor TOD clock synchronization [18].

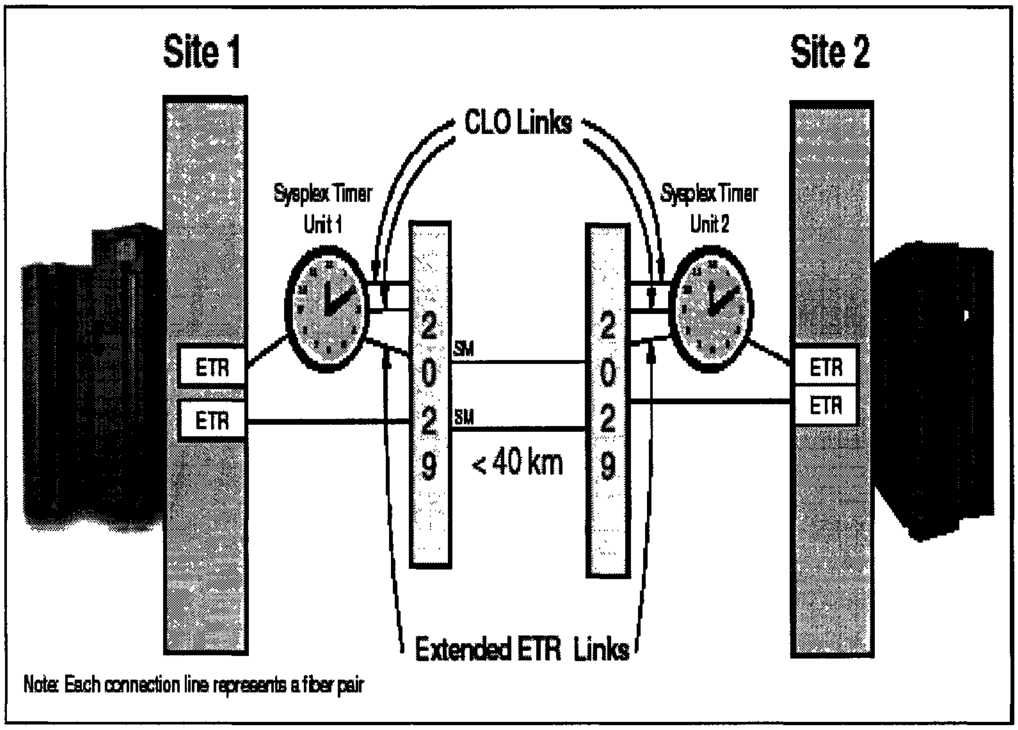
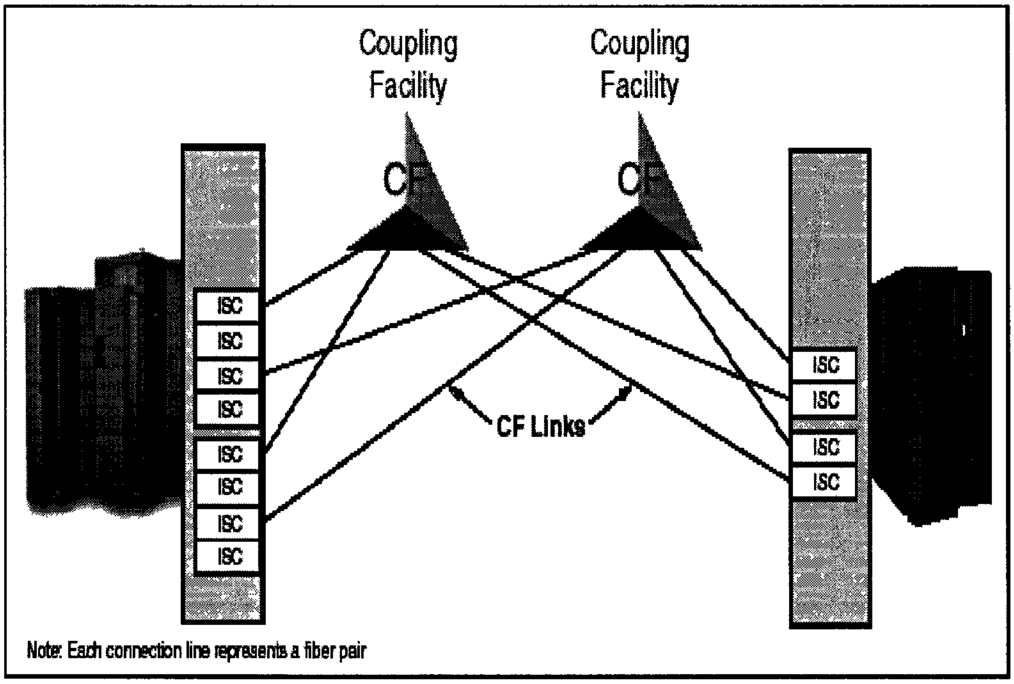


Figure 3.10 Cross-Site Sysplex Timer Expanded Availability Configuration

Coupling Facility (CF) Links:

Coupling Facility links are critical resources in a Parallel Sysplex environment. Connectivity between an operating system and a Coupling Facility is provided by coupling links known as InterSystem Coupling (ISC) links or High Performance Links (HiPerLinks). The recommendation for availability is to have a least two coupling facilities in a production Parallel Sysplex environment, each one having at least two CF links to each system. Parallel Sysplex of a simple configuration with two

CPCs, is shown in Figure 3.11, two coupling facilities and two links between each CPC and coupling facility. More links may be necessary for capacity and performance reasons. There are several different types of coupling links [18].



Note: Each connection line represents a fiber pair

Figure 3.11 Coupling Facility (CF) link connections

GENERATIONS OF DWDM TECHNOLOGY

Given the rapid growth of the WDM technology, it is not possible to comprehensively list all of the commercial products being introduced, or all of the research efforts currently underway to support future products. A sample of selected WDM companies and WAN backbone carriers is presented in [1]. Instead of attempting to give a detailed technical description of all the major commercial WDM product offerings, we will select one representative product to illustrate first-generation and third-generation devices (*fourth-generation ultra-dense WDM devices are not yet commercially available*). We are briefly going to explain first-generation devices; next third-generation WDM will be explained in some detail, since this system has being the base for our development – we are going to describe the main features, functionality, value, connectivity and solution of the fiber saver; based on Nortel OPtera 5200 MultiService Platform.

First Generation WDM:

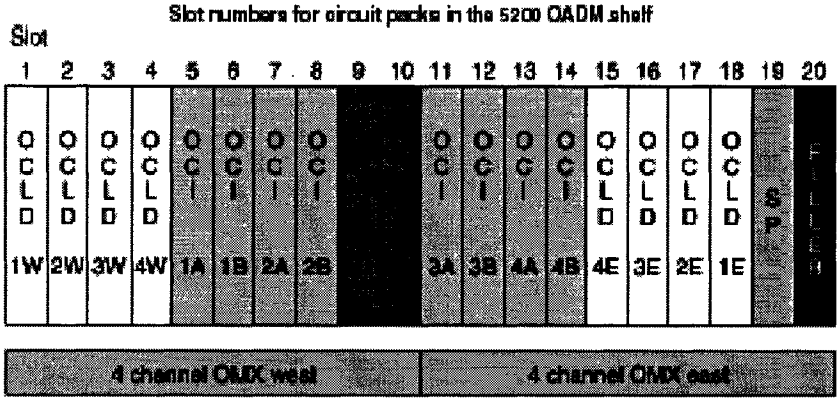
One example of a first-generation DWDM system is the IBM 9729 Optical WDM [1], [9], [10]; the first WDM product developed specially for data communication industry, it became available as special request product in 1993 and was released as commercial product in 1996. It allows up to 10 full-duplex links (*20 independent data streams*) over a single fiber, using different adapter cards, a mixture of ESCON, Fibre Channel, FDDI, and ATM links can be plugged into the device, which is protocol independent. The data is re-modulated using distributed feedback laser diodes with wavelengths spaced 1nm apart near 1550nm region, in C-band only. The optical signals are then combined using diffraction grating with embedded fiber pigtails, and coupled into a single-mode fiber; another unit at the far end of the link demultiplexes the signals.

Third Generation WDM:

In February 2000 IBM announced the third-generation DWDM solution, the Fiber Saver (FS), as a follow up to the first generation 9729 technology [11], [12]. This product is the result of a joint development relationship with Nortel Networks. The Fiber Saver is based on the same building blocks used in the Nortel OPtera Metro 5200 MultiService Platform.

The two products share a common set of hardware and software, although the Fiber Saver supports only pre-tested level of OPtera hardware and code. While the OPtera is provided as a standard telecom service provider package, the FS is repackaged by IBM with additional features, including turnkey installation with a pre-tested and configured PC, a class 1 laser eye safety cabinet for enterprise applications, integrated patch panels for native attachment of all data communication interfaces, and standard dual AC power supplies. The FS is a modular scalable approach to DWDM. Each FS model contains up to 2 shelves mounted in a 19-inch rack inside a standard-size data communication cabinet. The cabinet also contains standard dual redundant power supplies, an optical patch panel, and Ethernet hub for managing inter-shelf communications.

The shelf consists of a card cage that holds different types of adapters, a maintenance panel with power supply breakers and connections for monitoring and telemetry, some fiber slack management, a dual redundant cooling unit, and a tray containing the optical multiplexing (OMX) modules. Each OMX module is a passive device that can multiplex up to 4 optical wavelengths into one fiber path; the OMX modules are wavelength specific and are identified by their band (1 to 8). The shelf contains up to 20 active circuit cards of different types as it is shown in Figure 3.12. The FSP 2000 from Adva has similar features as the Optera 5200; but is much smaller in size and power dissipation.



OCM - Optical Channel Manager
OCI - Optical Channel Interface
OLCD - Optical Channel Laser and Detector
OMX - Optical Multiplexers
SP - Shelf processor

Figure 3.12 Card types in the Optera 5200 shelf

One shelf processor (SP) card; a programmable processor, not for data, but provides management and IP addressing for the shelf. The SP card monitors all circuit cards in the shelf, using feedback from each card to provide performance monitoring, software and configuration management, and alarm reporting. It has only an electrical connection to the shelf backplane.

Eight Optical Channel Interface (OCI) cards; which connects to the client equipment. It performs optical to electrical conversion (O/E) of the data prior to multiplexing and electrical to optical conversion (E/O) after demultiplexing. There are different types of OCI cards available; supporting protocols up to 1.25Gbps, a 4:1TDM card that puts up to 4-signals at data rates of 270Mbps or less over a single 1.25Gbps wavelength channel, and a protocol-specific card for Parallel Sysplex coupling links (all these operate at 1300nm wavelength). These cards are typically use SC duplex connectors, except for the 4TDM card, which uses MT-RJ interfaces.

Eight Optical Channel Laser and Detector (OCLD) cards; these perform E/O and O/E conversion of the data onto the ITU grid long-wavelength. They use a pair of FC optical connectors to attach to the OMX modules.

Two optical Channel Manager (OCM) cards; these are dual redundant, and provide switching functions from the fully cross-connected backplane for backup protection switching of data. All of the data to be multiplexed flows through one or both OCM cards, which allow any OCI card to map to any OCLD in the same shelf. The OCM stores configuration and provisioning data, as well as copies of the IP address information for the shelf. The OCM have only an electrical connection to the shelf backplane.

The shelf can be divided roughly in half, with channels corresponding to either the "East" or "West". The two halves of the shelf act as dual redundant data paths in protected or high availability mode. In unprotected or base mode, there are up to 8 duplex channels per shelf. The output of each shelf is a single fiber link on the east and west sides, carrying a multiplex of up to 4 wavelengths. If there is a card failure, that channel is lost; if there is a fiber cut on either the east or west side, 4 channels are lost. By contrast, in the protected or high availability configuration only 4 channels are used, but the data is split after passing through the OCI card and travels over dual redundant OCLD cards and fiber paths. There is no single point of failure in this configuration; and equipment failure or fiber break results in data being switched to the redundant path within 50ms. The system is complete "3R" repeater (***repeats, retimes, and regenerates the signal***). A single shelf thus support up to 8 base and 4 high available channels without using TDM; with TDM, the capacity is increased by a factor of 4 (*note the 4TDM channels are treated as a single wavelength for protection purposes*). Up to 4 models (8 shelves) can be daisy-chained together with optical fibers, which allows a maximum of 32 full duplex links to be multiplexed over a single pair of optical fibers (*32 wavelengths are compliant with the ITU grid, half in*

C-band and half in L-band, and for convenience are grouped into 8 bands of 4 wavelengths each). In this way, a FS network contains up to 32 high availability or 64 base channels, without TDM; using the 4TDM OCI card increases the capacity by a factor of 4. The daisy chain for a hubbed-ring configuration is shown in Figure 3.13 as an example.

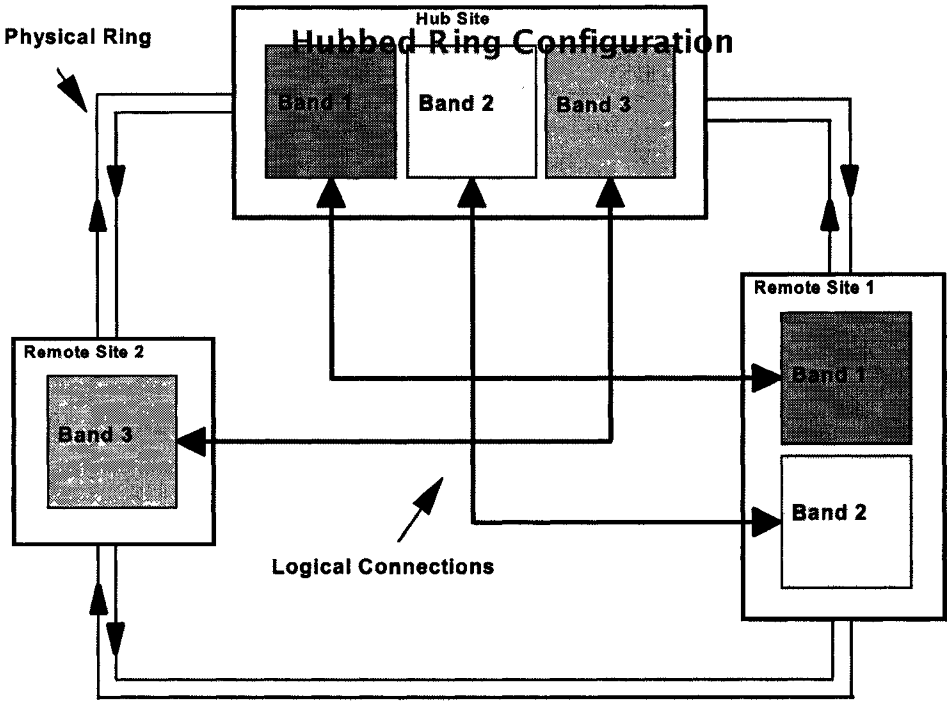


Figure 3.13 Daisy chain Hubbed-ring configuration

The maximum distance for point-to-point links is 50 km (15-dB), while the maximum distance between any two nodes on a hub-ring or dual hub-ring is 35 km

(10.5–dB). The difference is due to inclusion of additional Mux/Demux stages in ring topologies to allow for passive add/drop of individual channels at any point on the ring, an optical pass through for wavelengths destined for other nodes (shelves).

Unidirectional switching is employed in high-availability mode at transmit and receive fiber separately to ensure that there are no single points of failure in a protected channel. Some interfaces such as HiperLinks and Sysplex timer, should rely on link redundancy for continuous application availability. There is also switched base mode protection; this uses a dual optical fiber switch to detect fiber breaks and switch traffic to a redundant backup path. The switch is intended as a lower cost option than high availability for environments in which fiber breaks are more common than equipment failures, given that the dual fiber switch protects only fiber path and not the equipment cards. The switch also implements bi-directional switching, meaning that it can support some protocols, such as Sysplex Timer links, which may not function properly in high availability mode. There are 2 switches on each side for the East and West side of the network [18]. Because of the proprietary nature of many new protocol signals, overlay networks must be implemented to support the full range of services; mapping all of the desired protocols to SONET is not always possible because many digital types are not compatible with SONET (*for example, FICON and Parallel Sysplex links*).

The FS supports native attachments of all industry standard protocols up to a maximum data rate of 1.25 Gbps, including ESCON, FICON, Fibre Channel, Parallel Sysplex links (*HiPerLinks, ETR, and CLO*), ATM 155 and 622 (*OC-3 and OC-12*), FDDI, Fast Ethernet, and Gigabit Ethernet (*LX and SX*). Propagation of OFC protocols on HiPerLinks is supported using proprietary signaling between FS devices; because GDPS protocols remain IBM proprietary as of today, the FS is the only currently available product tested and supported by IBM for Parallel Sysplex and GDPS applications.

The description we have provided has been on the Nortel Optera 5200 DWDM. A joint work of Nortel and IBM created a system called the IBM fiber saver 2029. It is an eight-shelf solution. Adva has a similar product called FSP 2000 [83]; so does Cisco with its OTN 15540 EPS [15]. Adva and Cisco's product are more compact.

DATA CENTER APPLICATIONS

In this section our main focus will be in the description of two data center applications, the Geographically Dispersed Parallel Sysplex (GDPS) and the Storage Area Networks (SANs) where DWDM systems play an important role by extending the distance limitations of traditional technologies. First, we are briefly going to list the other applications with a short description, more detailed information can be found in the literature [1], [18] and [82].

Remote Control Units and LANs:

Some installations have a second site to implement remote backups to tapes, remote DASD access, remote printers or remote LANs. ESCON channels (without ESCON directors) are limited to 3 km and FICON native Channels to 10 km. Even with Directors or remote channels extenders the distance is limited to 20 km unless there is an intermediate site. By making use of fiber extenders such as the FS or FSP 2000 we can extend the site locations up to 50 km or more. Examples of two-sites (point-to-point) and three-sites (hubbed-ring topology) are shown in Figure 3.14 and Figure 3.15.

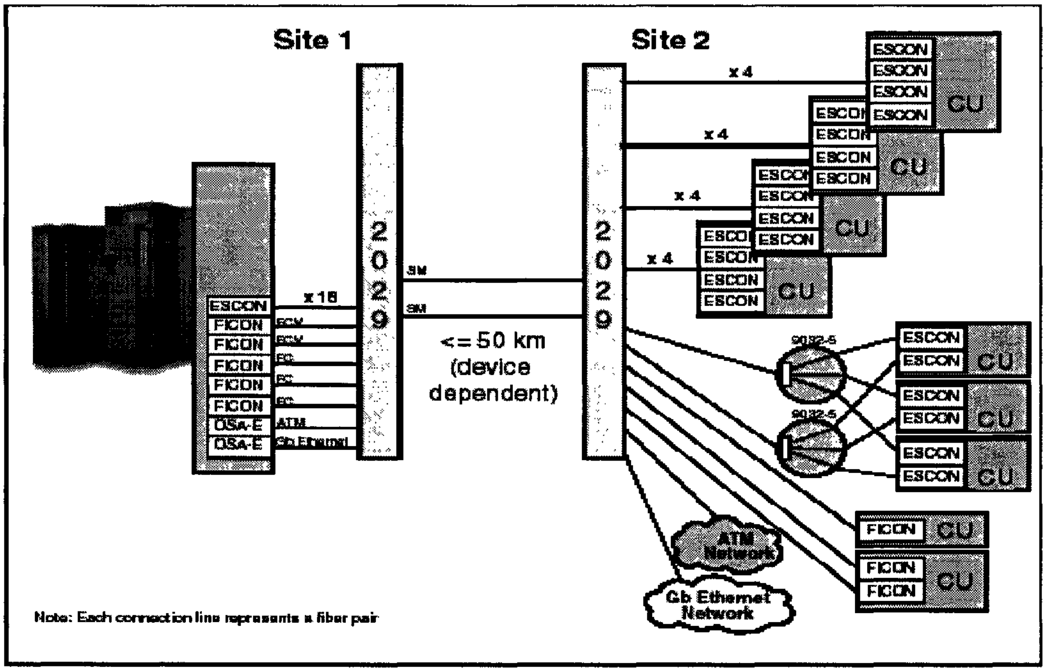


Figure 3.14 FS in a remote control unit and LAN point-to-point configuration

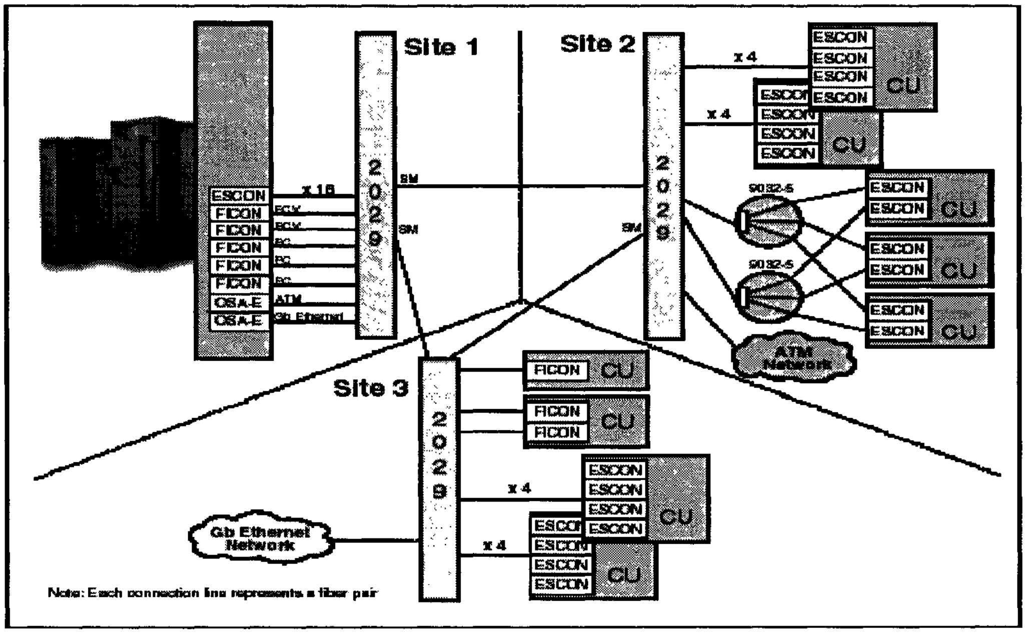


Figure 3.15 FS in a remote control unit and LAN hubbed-ring configuration

Multi-Site Parallel Sysplex:

Multi-site Parallel Sysplex is a very attractive way to share resources and distribute across CPCs at multiple sites. Usually 2 sites are involved, as shown in Figure 3.16, each having its own CPC (one or more), Sysplex Timer unit, Coupling Facility (CF). Some DASD sharing is also required. To avoid one of the sites of becoming a single point of failure for all systems, there must be some shared DASD at each site. ESCON channel-to-channel connections between sites are also common [18].

Using fiber savers the distance gets extended up to 40 km in a point-to-point configuration, and only two single mode fiber pairs are required between sites.

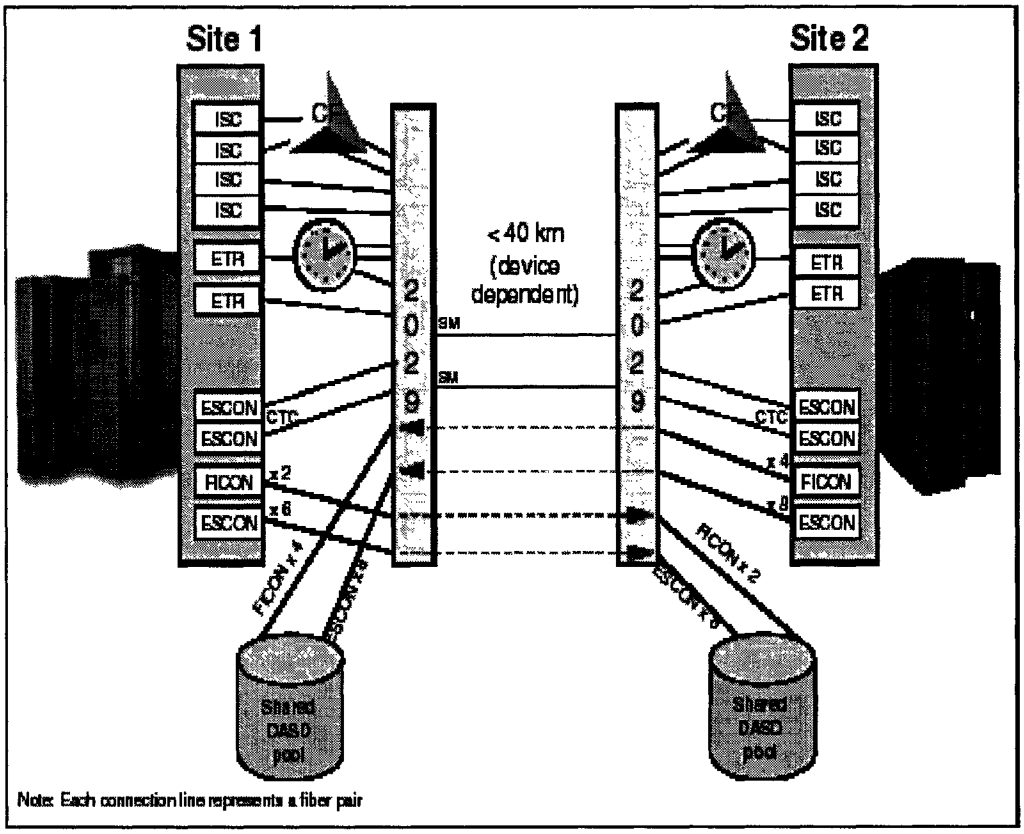


Figure 3.16 FS in a multi-site Parallel Sysplex configuration

Peer-to-Peer Remote Copy (PPRC):

DASD PPRC is a storage subsystem mirroring technique in which updates at the primary DASD subsystem are synchronously copied to a secondary subsystem, usually located at a remote site. This results in a mirrored volume pairs between the sites. The copy process is independent of the host systems.

PPRC is very useful for backup site implementations. If a disaster occurs at the primary site, no data is lost and full data integrity is expected at the backup site. PPRC is implemented by connections between primary and secondary DASD subsystems. The total number of connections between sites depends on the number of DASD subsystems and their update data rates. A point-to-point configuration is shown in Figure 3.17.

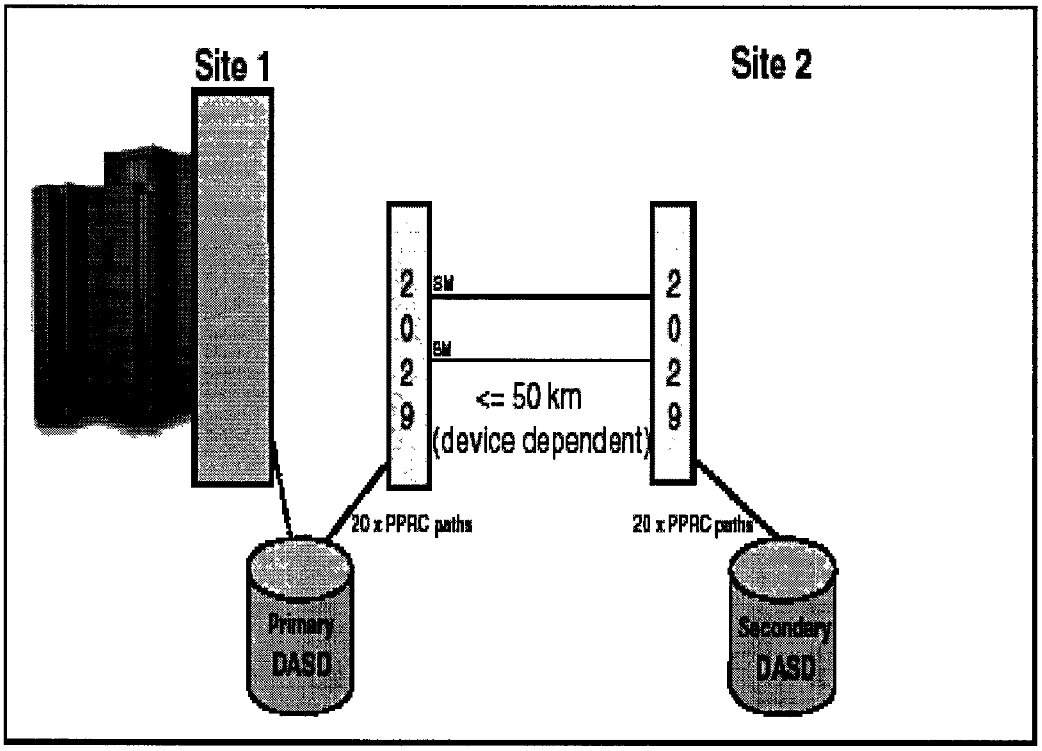


Figure 3.17 FS in a DASD peer-to-peer Remote Copy configuration

Geographically Dispersed Parallel Sysplex (GDPS):

Geographically Dispersed Parallel Sysplex (GDPS) is an IBM service solution to implement a multi-site management facility designed to minimize and potentially eliminate the impact of a disaster or planned site outage. The GDPS is a widely adopted architecture for clustered mainframe computing. This architecture uses high-speed fiber optic data links to couple processors together in parallel [9], [11], [84]; in this manner increasing capacity and scalability. Processors are interconnected via a coupling facility, which provides data caching, locking, and queuing services; it may be implemented as a logical partition rather than a separate physical device. The gigabit links; known as IterSystem Channel (ISC), HiperLinks, or Coupling Links, use long-wavelength (1300nm) lasers and single mode fiber to operate at distances up to 10 km with a 7 dB link budget. If good quality fiber is used, the link budget of these channels allows the maximum distance to be increased to 20 km.

The physical layer design is similar to the ANSI Fiber Channel Standard, operating at a data rate of 1.0625 Gbps, except for the use of open fiber control (OFC) laser safety on long-wavelength (1300nm) laser links.

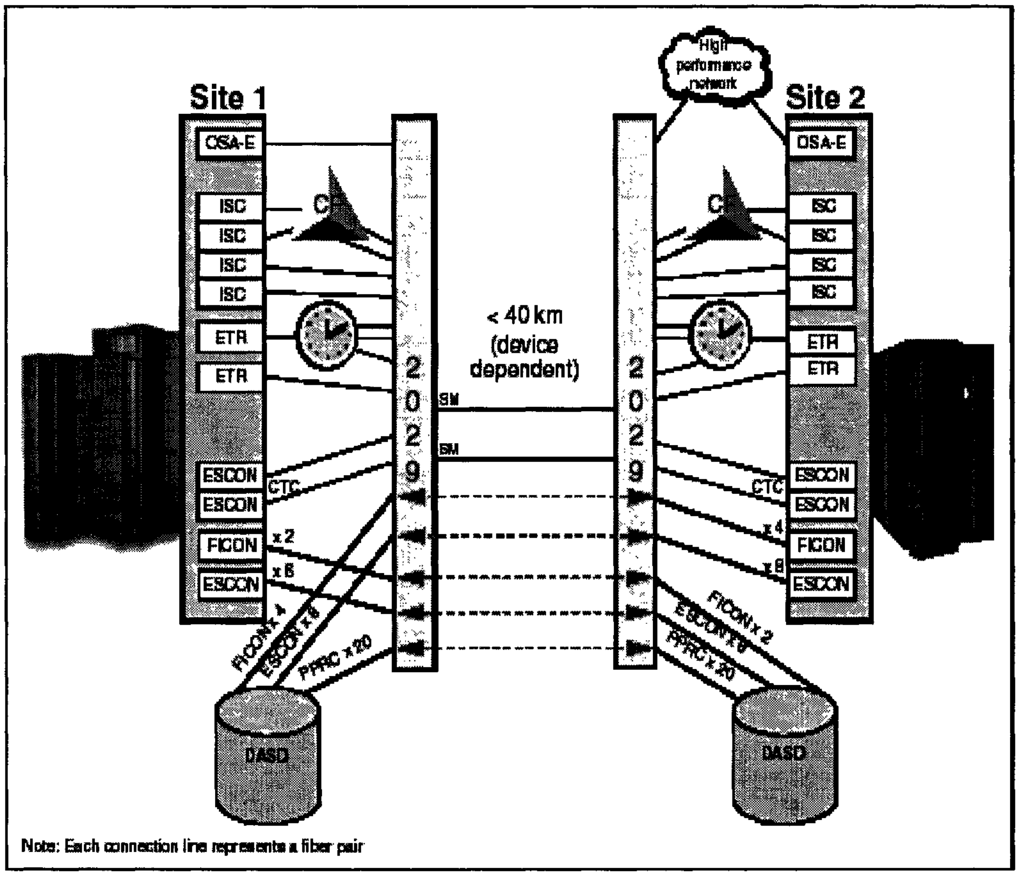
Because all processors in a GDPS must operate synchronously with each other, they all require a multimode fiber link to a common reference clock known as a Sysplex Timer; called the External Reference Timer. The ETR uses the same physical layer as an ESCON link, except that the data rate is 8 Mbps. The timer is the critical component of the Parallel Sysplex; the Sysplex will continue to run with degraded performance if a processor fails, but failure of the ETR will disable the entire Sysplex. For this reason, it is highly recommended that two redundant timers be used, so that if one fails the other can continue uninterrupted operation of the Sysplex. For this reason the timers must be synchronized with each other; this is accomplished by connecting them with two separate, redundant fiber links called the Control Link Oscillator (CLO). Physically, the CLO link is the same as an ETR link except that it carries timing information to keep the pair of timers synchronized.

There are three possible configurations for a Parallel Sysplex; first, the entire Sysplex may reside in a single physical location, within one data center. Second, the Sysplex can be extended over multiple locations with remote fiber optic data links. Finally, a multi-site Sysplex in which all data is remote, copied from one location to another, is known as a Geographically Dispersed Parallel Sysplex or GDPS. The GDPS also provides the ability to manage remote copy configurations, automated both planned and unplanned system reconfigurations, and provides rapid failure recovery from a single point of control. GDPS is a combination of system code and automation that utilizes the capabilities of Parallel Sysplex technology, storage subsystem mirroring and databases.

By making use of Parallel Sysplex and PPRC, GDPS requires all the connection types shown in their respective scenarios: (i) Sysplex Timer links, (ii) CF links, (iii)

ESCON and/or FICON channels for Channel-to-Channel connections, DASD and other control unit sharing links, (iv) PPRC links, OSA-Express Gigabit Ethernet, enabling the high performance network.

The total number of links depends on the number of ESCON, FICON, PPRC, OSA and CF links required [1], [9], [84]. An illustration of a GDPS is shown in Figure 3.18.



Note: Each connection line represents a fiber pair

Figure 3.18 FS in a GDPS configuration

Storage Area Network (SAN):

A Storage Area Network (SAN) is a dedicated, centrally managed, secure information infrastructure enabling any-to-any interconnection of servers and storage systems. Consolidation of storage hardware and management offers significant business benefits, including more efficient hardware utilization along with reduced management and administration costs [18].

Aside from offering advanced technology for storage needs, SANs also reduce costs when deploying highly scalable storage versus traditional direct-attached storage (DAS). Therefore, Storage Area Networks (SANs) represent the latest stage in the evolution of mass data storage for enterprises and other large institutions. With the advent of client-server environments, information that was previously centralized became distributed across the network.

A SAN is Composed of servers, storage devices (tapes, disk arrays), and network devices (multiplexers, hubs, routers, switches, and so on), constitutes an entirely separate network from the LAN. The SAN can relieve bottlenecks in the LAN by providing the resources for applications such as data mirroring, transaction processing; and backup and restoration [15].

FICON and Fiber Channel (FC) switches and directors are central to the SAN fabric. The distance limitations can and is overcome by transporting data between one or more enterprise locations and one or more SANs over the optical layer using

DWDM. Figure 3.19 shows an example of how the FS could be used to extend the distance between FICON and FC servers and shared storage hardware.

This example shows a hubbed-ring configuration. The FS is used to provide connectivity to the shared storage devices via FICON and FC through an Enterprise Director. The FICON and fiber channel servers are located at different remote sites.

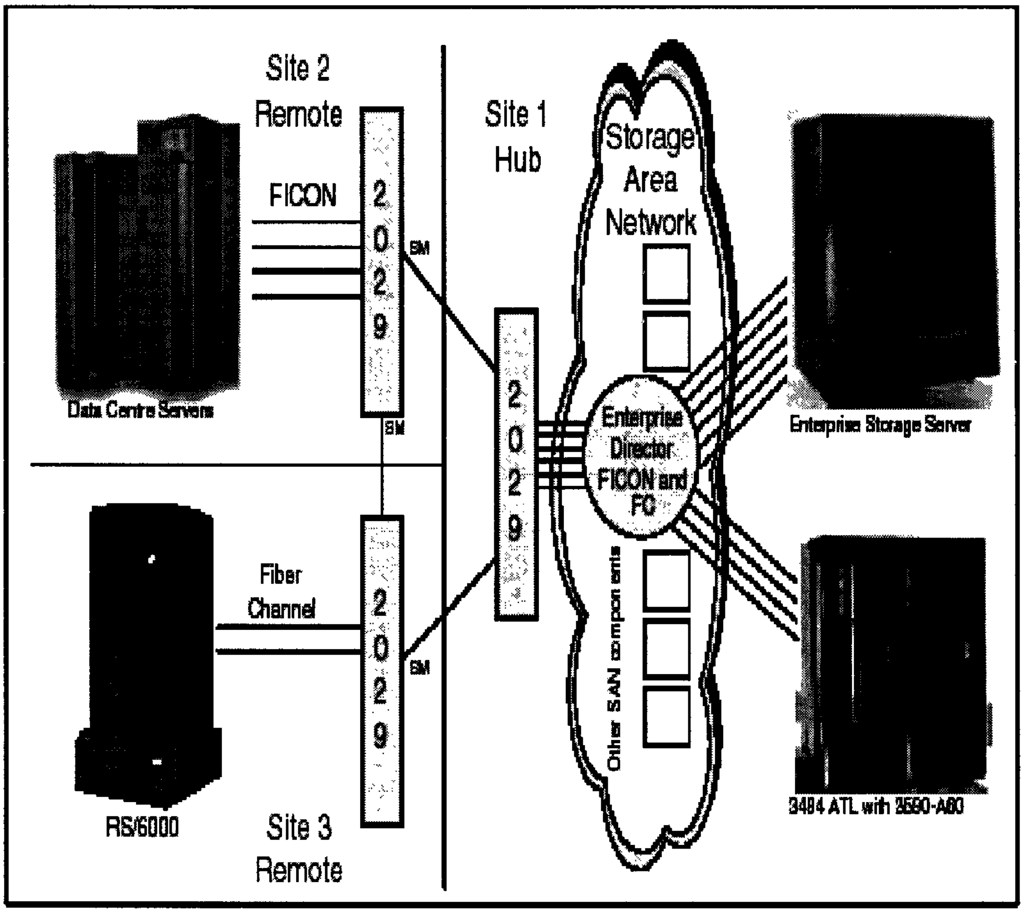


Figure 3.19 FICON and FC channels extended with FS in a SAN environment

CHAPTER 4

DESIGN AND MODELING OF DENSE WAVELENGTH DIVISION MULTIPLEXING (DWDM) NETWORKS

Because of the huge demand for bandwidth to support new data processing applications, WDM has found applications in storage area networks (SANs) over extended distances (tens to hundreds of km). Some of these SANs can encapsulate data in a SONET [2] frame structure using the recently standardized Generic Frame Procedure (GFP). Another option is the direct transport of storage data over Ethernet protocols, as advocated by the Ethernet last-mile consortium and other standard bodies. A third option, which has been widely deployed prior to the introduction of GFP and metro Ethernet, is the use of enterprise virtual private networks (VPNs) with either dark fiber or wavelength-based services. These networks employ a wide range of protocols, reflecting the mixed environment in typical Fortune 500 data centers. For example, it is not unusual for a mixture of ESCON, FICON, Fibre Channel, ATM (Asynchronous Transfer Mode), and Ethernet protocols to be used on the same network with vendor-proprietary protocols such as those used in a Parallel Sysplex architecture for disaster recovery of clustered enterprise servers; the details of Parallel

Sysplex design and protocols have been reported previously [1], [85]. Not all of these protocols can be readily encapsulated in SONET or Ethernet networks, and many have protocol specific requirements for recovery and performance that are not addressed using GFP. For example, many enterprises rely on storage applications such as synchronous data mirroring between two sites, using a Parallel Sysplex configuration with Peer-to-Peer Remote Copy (PPRC) and Sysplex Timer connections to provide data integrity; these requirements will continue to be addressed through wavelength-based dark fiber services for the foreseeable future.

Despite strong interest in enterprise VPNs, there has not previously been an effort to model the design and optimize the function of these networks. Various software tools are available for SONET based applications, including software packages such as VPI Corporation's TransmissionMaker software [86], but none of the current modeling tools addresses the requirements of dark fiber services over WDM as described earlier. Furthermore, some WDM vendors such as Adva, Lucent, Nortel, and Cisco offer their own network modeling tools, but only for their specific products; this makes it difficult to compare solutions from multiple vendors or to design heterogeneous multi-vendor environments. Therefore, we address the need for vendor-independent WDM network design and modeling tools in this environment by developing computer models for physical layer design of enterprise VPNs.

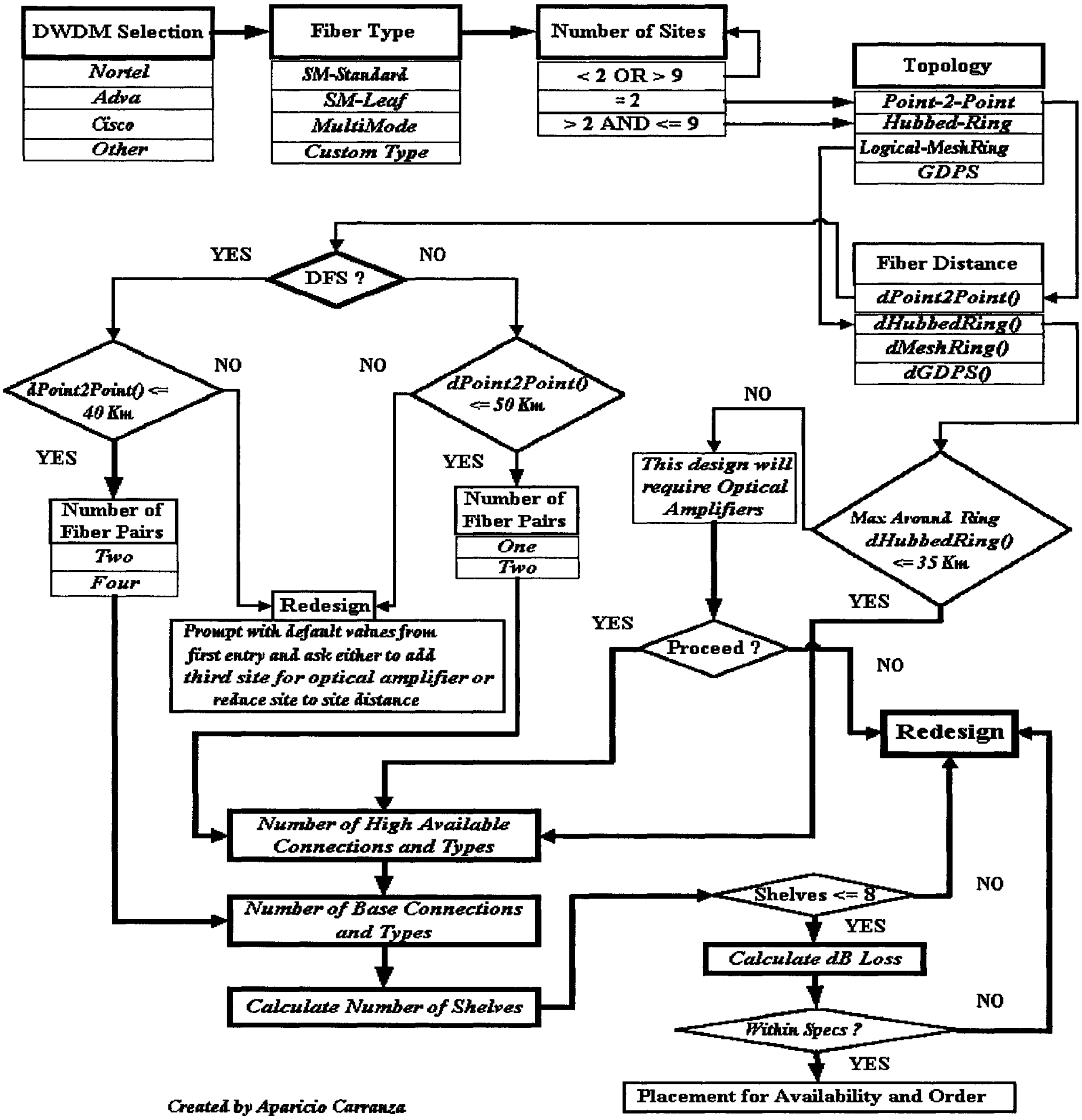
These networks must support a variety of topologies, including point-to-point, hubbed-rings, and meshed rings. There may be protocol-specific requirements, such as maximum distances which can be supported to achieve desirable performance; these should be enforced by the network design. Optical link budgets are an important restriction in the MAN, where it is desirable to avoid the use of expensive optical amplifiers for distances on the order of 50 -100 km. Longer distances can be achieved by using recently developed dispersion-compensating fiber, such as the large effective area (LEAF) fibers [1]; however, it is expensive to install new fiber in this environment, so there is an interest in modeling the ability of legacy single-mode fibers to support the required distances. These networks must also offer intelligent quality of service (QoS) features such as dual redundant physical pathing and protection switching or fiber trunk switching; users will often require a mixture of protected (high availability) and unprotected traffic in their systems. These requirements will translate into different equipment designs depending on the choice of WDM equipment; it is desirable to estimate how a given network topology will scale with respect to cost, physical size, power consumption, and other factors as the network grows. These estimates can be used to compare different network equipment designs and tradeoffs to help future-proof the WDM systems.

NETWORK MODELING APPROACH

The planning and designing of a particular network design, is a complex task, it requires many parameters to take in consideration. Our work contribution in this thesis has been to develop a set of computer simulation tools for the design of dark fiber optical networks; which accounts for the unique distinguishing features of this environment and that are independent of the choice of DWDM networking equipment. The models were developed using MATLAB version 6.5 [23], [24], [25]. MATLAB is a scientific programming language that runs on most major platforms. The models are capable of automatically designing a network configuration based on minimal input about the network environment, such as the number of locations to be connected by WDM networks, the fiber type and distance between locations, the number and type of protocols used at each location, and whether each channel is protected or unprotected. The number of sites is limited by supported configurations on commercially available WDM equipment (up to 9 sites maximum on a hubbed or meshed ring). Both standard single-mode and LEAF fibers are supported. Currently the model supports any mixture of ESCON, FICON, Fibre Channel, ATM, Gigabit Ethernet, and Parallel Sysplex protocols, at data rates ranging from 200 Mbps to 10 Gbps. Specific details about each of these protocols and their applications has been presented previously [1], [2]. In particular, we note that a Parallel Sysplex contains several non-standard protocols, including Inter-System Channel (ISC), External Time

Reference (ETR), and Control Link Oscillator (CLO). All of these are supported by the model, which automatically checks for protocol distance restrictions such as the 40 km maximum limitation on CLO links.

A high level flowchart of the model is shown in Figure 4.1. The models are capable of validating the design against any protocol-specific requirements; suggesting alternative configurations; and optimizing the design based on metrics including performance of the network (efficient use of bandwidth to support the attached computing devices), reliability (searching the proposed topology for single points of failure), scalability (based on user input of potential future upgrade paths), and cost of the associated networking equipment. The model calculates optical link budgets for different fiber types. The network can be modeled for various types of WDM equipment; initially, we have modeled both the Nortel Optera Metro 5200 and the Adva FSP 2000 systems, since these were readily available in the testbed used to validate our simulations. Additional vendor equipment can easily be added in a modular fashion for future simulations. We assume the maximum possible use of sub-rate time division multiplexing supported by the WDM equipment, in order to minimize cost by sharing several lower data rate links over a single high speed link. However, this is subject to the restriction that high availability channels must use a second, physically redundant wavelength in the network. The model supports both "1+1" protection switching and trunk switch options, including the link budget restrictions associated with using a trunk switch in point-to-point networks. Large networks which employ many of these features at once (for example, a multi-site meshed ring with amplifiers, sub-rate multiplexing, and a variety of protocol specific requirements, fiber types, and protection options) cannot be readily evaluated without a model such as this. The design of new networking equipment and protocols can also be evaluated, and suggestions made to improve their performance on a wavelength multiplexed MAN, based on result of these simulations.



Created by Aparicio Carranza

Figure 4.1 Flowchart of design process

Before presenting explanations of some of the features of the flowchart let us present some key contributions of this thesis; these are the hubbed-ring and logical mesh-ring equations and implementations. We begin with a hubbed-ring configuration, then, we present several case studies of logical-mesh-ring.

HUBBED RING DESIGN

In a hubbed-ring topology the communication is between the hub and the remote sites only. There is no remote-to-remote site communication. For the hubbed-ring we use matrices to represent the separation between sites that the user will input and consequently it will be used for calculating the maximum distance from the hub to the furthest remote site; including the clockwise and counter clockwise distances. A hubbed-ring network with 6 remote sites and a hub (total of 7 locations) is shown in figure 4.2

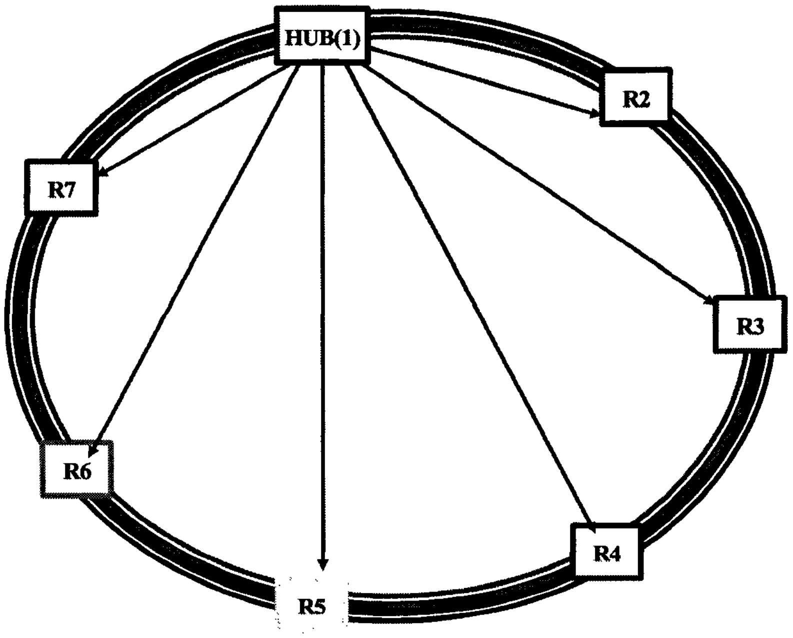


Figure 4.2 - Hubbed-ring network with a hub and 6 remote sites

The user must provide the following information: S[1,2], S[2,3], S[3,4], S[4,5], S[5,6], S[6,7] and S[1,7]. For a general case of N sites (locations); including the hub, the maximum distance clockwise direction is given by:

$$distCW_{\max} = \sum_{i=1}^{N-1} S[i,i+1] \tag{4.1}$$

The maximum distance in the counter clockwise direction is represented by:

$$distCCW_{\max} = distCW_{\max} + S[1,N] - S[1,2] \tag{4.2}$$

Equation (4.1) and (4.2) are directly derived using Figure 4.2.

After computations, if the resultant distances (clockwise or counter clockwise); is greater than the maximum hub to furthest remote distance allowed; the user should opt for redesigning the network with new parameters. If the resultant distances fall within the maximum allowed value, then the next step is to input the number and type of protocols from the hub to each of the remote sites. The user is allowed to run applications in either base (unprotected) of high available (protected) modes from the hub to each individual node. Finally, the number of shelves is determined for the hub to each remote site and then the total number of shelves for the entire configuration.

LOGICAL MESH RING DESIGN

Let **S** be an MxM square matrix representing the separation distance matrix, where **S**[i,j]$_,$ is the separation from site **i** to site **j** in the clock wise direction and **S**[j,i], represents the separation from site **i** to **j** in the counter clockwise direction, **i**=1,2, ...N and **j**=1,2,...,N. **S**[i,j] = 0, for **i** = **j**; since it represents connecting a location to itself; as a consequence all the elements from the main diagonal of the separation matrix will be 0. A matrix **S** for N-sites is shown below.

$$S = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1j} & \cdots & S_{1,N-1} & S_{1N} \\ S_{21} & S_{22} & \cdots & S_{2j} & \cdots & \cdots & S_{2N} \\ \cdots & \cdots & & \cdots & \cdots & \cdots & \cdots \\ S_{i1} & S_{i2} & \cdots & S_{ij} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & S_{N-1,N} \\ S_{N1} & S_{N2} & \cdots & \cdots & \cdots & S_{NN-1} & S_{NN} \end{bmatrix}$$

The ring's circumference R can be calculated using equation (4.3)

$$R = \sum_{i=1}^{N-1} S[i, i+1] + S[1, N] \tag{4.3}$$

The clock wise and counter clock wise distances from node *k* to node *l*; $1 \le k, l \le N$, $k < l$ are given by equations (4.4) and (4.5) respectively.

$$S[k, l] = \sum_{i=k}^{l-1} S[i, i+1] \tag{4.4}$$

$$S[l, k] = R - S[k, l] \tag{4.5}$$

To determine the maximum distance from node *k* to node *l* on either direction equation (4.6) is used.

$$D[i, j] = Max\{S[i, j], S[j, i]\} \tag{4.6}$$

$$i, j \in \{1, 2, \ldots, N\}$$

If $D[i,j] \le Rx$, where Rx is determined a priori, then our design meets the distance requirements, the next step is to select the number and type of protocols to connect from site to site, else if $D[i,j] > Rx$ we have to redesign.

Nine Locations

A logical mesh ring network with 9 locations (sites) is shown in figure 4.3,

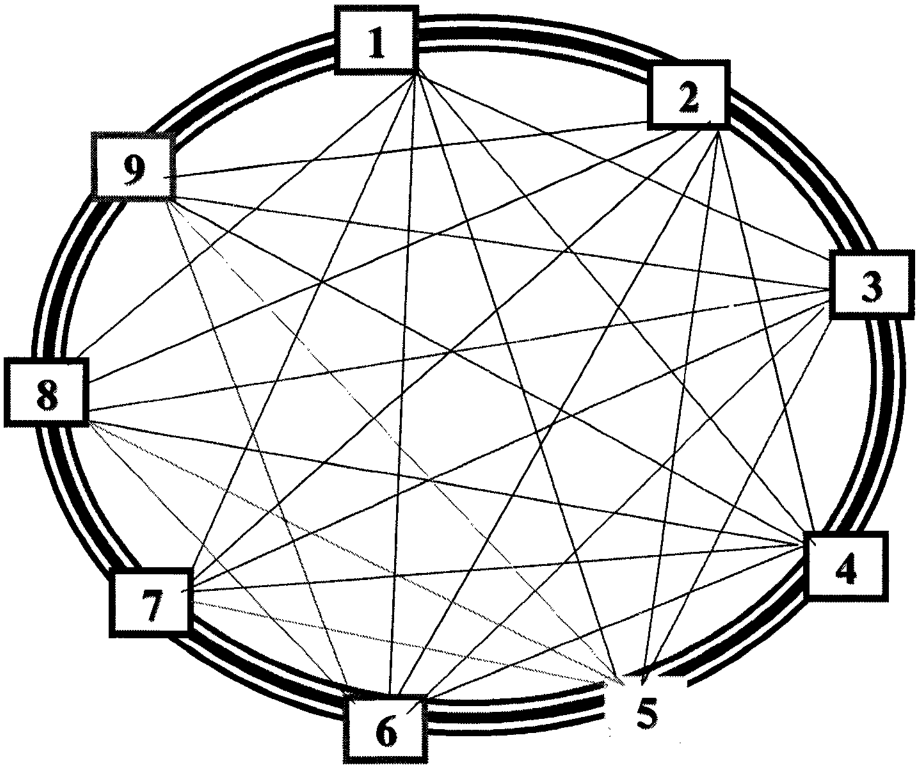


Figure 4.3 Logical mesh network with 9 sites

The matrix S for N = 9 is shown below. Analogous to the hubbed-ring networks the site to site distance around the ring must be provided. These distances are: S[1,2], S[2,3], S[3,4], S[4,5], S[5,6], S[6,7], S[7,8], S[8,9] and S[1,9].

$$S = \begin{pmatrix} 0 & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} & S_{19} \\ S_{21} & 0 & S_{23} & S_{24} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} \\ S_{31} & S_{32} & 0 & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} & S_{39} \\ S_{41} & S_{42} & S_{43} & 0 & S_{45} & S_{46} & S_{47} & S_{48} & S_{49} \\ S_{51} & S_{52} & S_{53} & S_{54} & 0 & S_{56} & S_{57} & S_{58} & S_{59} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & 0 & S_{67} & S_{68} & S_{69} \\ S_{71} & S_{72} & S_{73} & S_{74} & S_{75} & S_{76} & 0 & S_{78} & S_{79} \\ S_{81} & S_{82} & S_{83} & S_{84} & S_{85} & S_{86} & S_{87} & 0 & S_{89} \\ S_{91} & S_{92} & S_{93} & S_{94} & S_{95} & S_{96} & S_{97} & S_{98} & 0 \end{pmatrix}$$

After hubbed-ring and logical-mesh-ring designs have been presented, key points of flowchart in Figure 4.1; such as number of sites and purpose, device distance limitations, fiber distances, topology, number of fiber pairs, number of high availability connections and type, number of base availability and connections, calculation of number of shelves, calculation of dB loss, placement for availability, change on number of shelves; and finally redesign or order are presented next

LINK MODEL FLOWCHART DESCRIPTION

There are certain design rules to consider when planning a network configuration. Below we present some of the important points such as:

- The minimum number of shelf pair for a point-to-point or hubbed-ring configuration.
- The maximum number of shelves per site in a point-to-point configuration.
- The maximum number of remote shelves & hub shelves in hubbed-ring configuration.
- In a point-to-point or hubbed-ring configuration, each remote and hub shelf pair uses a unique wavelength band (Band 1 – Band 8) of four wavelengths.
- In a point-to-point or hubbed-ring configuration, the same wavelength band cannot be used for more than one remote and hub shelf pair.
- The maximum end-to-end distance is 50 km in a point-to-point configuration.
- The maximum end-to-end distance is 40 km when Fiber Switches are used.
- In a hubbed-ring the maximum distance is 35 km from the hub to the furthest remote shelf.

Number of Sites and Purpose:

We should have a clear picture of what we are trying to achieve, before we start planning our Dense Wavelength Division Multiplexing network (services supported).

Device Distance Limitations:

We need to know if there are any distance limitations imposed by selected devices. There are a number of examples of ESCON distance limitations [18]. There is also a restriction of 40 km for ETR links and coupling facility channels.

Fiber Distances:

Length of the fiber cables that will be connected between the shelves must be known.

Topology:

The decision to implement a hubbed-ring or point-to-point configuration will depend on the number of sites and distances between sites.

Number of Fiber Pairs:

A DWDM network may be implemented with just one fiber pair connecting two sites. The decision on the number of fibers to use between sites will probably be dependent on costs and possibly the number of connections already available. We must ascertain that the decision we make at this point allows a configuration that will support our availability requirements.

Number of High Availability Connections and Types:

At this point it is time to make a decision of how many connections will be provisioned as high availability channels at each remote site. This decision should be based on the availability and performance requirements [18].

Number of Base Connections and Types:

Base channels are the only option in a number of instances; so all links will be configured as base channels. The number of high availability channels was determined in the previous step. The remaining links will be base channels [18].

Calculation of Number of Shelves:

After deciding on the number of high and/or base availability channels required, we can now determine the number of shelves required at each site. The calculation will vary, depending on how we arrived at this task in the flowchart. Results of each calculation must be rounded up. If we are using a hubbed-ring configuration, we need to go through this process for each remote site.

Calculation of dB Loss:

The optical link budget calculation is required to determine whether attenuation (dB loss) in the network is within the acceptable range. Assistance from the dark fiber service provider will probably be needed to determine dB loss on the inter-site fibers. The loss calculation must also include losses on patch cables and connections within the sites [18].

Placement for Availability:

Now that we know how many shelves will be installed at each site, we can decide how the channels will be provisioned within the shelves. The first priority for base channels is to make certain links that provide redundancy for each other; use different fiber pairs (East or West). Second priority is to spread links, which provides redundancy for each other across different shelves.

Change in Number of Shelves

When we decide in our channel placement we may find that we cannot configure the shelves to provide the diversity that we need. Configuring additional links or converting some base channels to high availability channels could resolve this, but may also increase the number of shelves required.

Redesign:

The arrival to this point in the flowchart means that our DWDM network design will not satisfy all configuration requirements. The options to consider at this point depend on the reason for needing to redesign our configuration; and they might be:

- Point-to-point configuration exceeding 50Km:
- Hubbed-Ring configuration exceeding 35Km:
- More than eight shelf pairs in the network:
- Attenuation not within link budget:

Order:

The final design has now been decided and we are ready for the hardware to be ordered. Detailed planning will ensure that are no surprises with device restrictions or link budget requirements.

FIBER OPTIC LINK REQUIREMENTS

Most data links are full duplex, permitting two-way communication between attached devices; a separate transmitter/receiver pair is typically used for each direction. Data communication systems do no make efficient use of the fiber bandwidth; one user per link is typical. Data Link Design is not driven by optimization of fiber bandwidth but rather by cost of optoelectronic transceivers and adapters. By contrast, the telecom world makes extensive use of multiplexing to support multiple users on a single fiber. The number of electronic transceivers per kilometer of fiber is much higher in datacom applications that in telecom systems. A comparison of datacom and telecom requirements is shown in Table 4.1

Table 4.1 Comparison of Datacom and Telecom Requirements

	Datacom	Telecom
BER	$10^{-12} - 10^{-15}$	10^{-9}
Distance	20 – 50 Km	Varies with repeaters
Number of transceivers/Km.	Large	Small
Signal Bandwidth	0Mb – 1Gb	3 – 5Kb
Field Service	Untrained users	Trained staff
Number of fiber re-plugs	250 - 500	< 100 over lifetime

BIT ERROR RATE (BER)

All fiber optic channels consist of an optical source or transmitter, the cable plant, and optical receiver. The interaction of these components must be taken in account when designing a fiber optic link. The transmitter is capable of launching a limited amount of optical power into the fiber, and there is a limit to the weakness of a signal that can be detected by the receiver in the presence of noise. Thus, a fundamental consideration is the optical link power budget, or the difference between the transmitted and received optical power levels. Some power will be lost due to *connections*, *splices*, and *bulk attenuation* in the fiber. There may also be optical power penalties due to *dispersion*, *modal noise*, or *other effects* in the fiber and electronics. The optical power levels define the signal-to-noise ratio at the receiver; represented by Q - this is related to the bit error rate by the well-known Gaussian integral as shown:

$$BER = \frac{1}{\sqrt{2\pi}} \int_Q^{\infty} e^{-\frac{Q^2}{2}} dQ \cong \frac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}} \tag{4.7}$$

An important fact to mention is that the receiver sensitivity is specified at a given BER, which is often too low to measure directly in a reasonable amount of time. For example, a 200 Mbps link operating at a BER of 10^{-15} will take only one error every 57 days on average, and several hundred errors are recommended for a reasonable BER measurement. For practical reasons, the BER is typically measured at much higher error rates, where data can be collected more quickly (*such as* 10^{-4} *to* 10^{-8}) and then extrapolated to find the sensitivity at low BER. The relationship between optical input power, in watts, and the BER, is the complimentary Gaussian error function.

$$BER = \frac{1}{2} errorFunction(P_{out} - \frac{P_{signal}}{RMS_{noise}}) \tag{4.8}$$

The error function is an open integral that cannot be solved directly. Several approximations have been developed for this integral, which can be developed into transformation functions that yield a linear least squares fit to the data. The resulted fitted equation can then be used to extrapolate the receiver sensitivity [47]. Further information on curve fitting of low BER can be obtained in the literature [47] -- [49]. A curve of the BER as a function of Signal to Noise Ratio (Q) is shown in Figure 4.4.

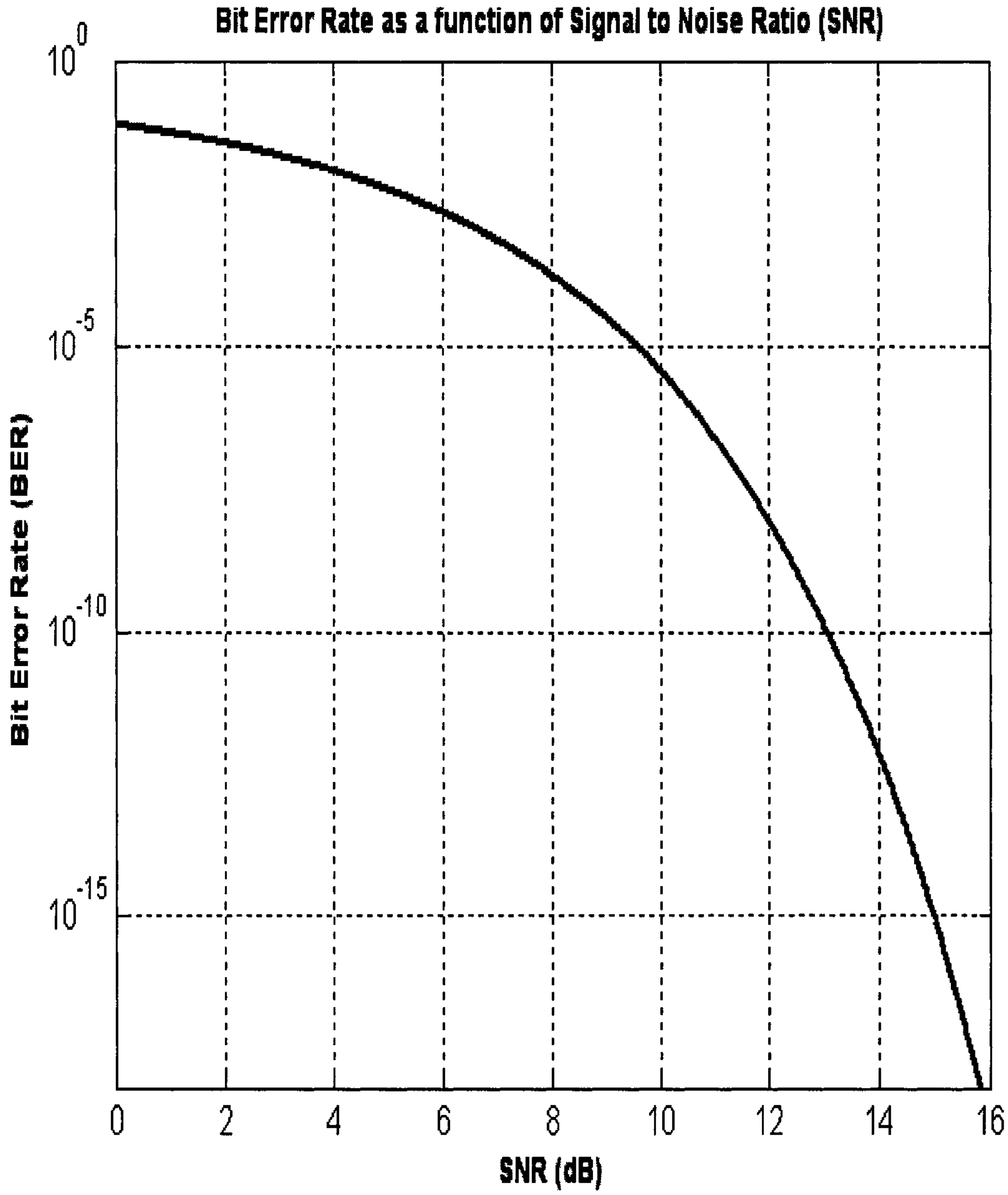


Figure 4.4 Bit Error Rate vs. SNR (Q)

In order to design a proper optical data link, the contribution of different types of noise sources should be assessed when developing a link budget. There are two basic approaches to link budget modeling. One method is to design the link to operate at the desired BER when all the individual link components assume their worst-case performance. This conservative approach is desirable when very high performance is required or when it is difficult or inconvenient to replace failing components near end of their useful lifetimes. The resulting design has a high safety margin; in some cases, it may be over designed for the required level of performance. Because it is very unlikely that all the elements of the link will assume their worst-case performance at the same time, an alternative is to model the link budget statistically. For this method, distributions of transmitter power output, receiver sensitivity, and other parameters are either obtained from vendors or estimated by measuring a small sample of parts. They are then combined statistically using an approach as the Monte Carlo method, in which many possible link combinations are simulated to generate an overall distribution of the available link optical power. The industry standard is a $3-\sigma$ design, in which the combined variations of all link components are not allowed to extend more than 3 standard deviations from the average performance target in either direction. The statistical approach results in greater design flexibility and generally increased distance compared with the worst-case model at the same BER. The statistical approach is only valid as the input data, however, this can be difficult to obtain and many vendors consider such data proprietary. A good design compromise is to use a combination of both methods.

OPTICAL LINK BUDGET MODELS

We now present important factors in the modeling and design of fiber optic data link, with emphasis on the link budget requirements [50]. The optical link budget consists of two components, cable plant loss and available power budget. The cable plant loss is a worst case calculation which includes attenuation of the fiber (dB/km), splice loss, and connector loss at patch panels or distribution facilities. The available power budget is given by the difference between the worst case optical transmitter power and receiver sensitivity, minus any link budget power penalties. The model currently incorporates power penalties due to dispersion, modal noise, relative intensity noise (RIN), and mode partition noise; additional penalties can be added in a modular fashion.

A typical point-to-point fiber optic link connecting two devices is shown in Figure 4.5, consisting of both trunk and jumper cables. A single trunk cable may contain many individual fibers. Jumper cables are used for short connections between devices that are close together or between devices and a distribution panel; they typically contain only one or two fibers, while trunk cables are for long distances. Jumper cables are allowed to have slightly higher attenuation loss than trunk cable. Typical trunk cable will have a loss of 0.5dB/km near 1300nm to 1500nm, whereas jumper cable in this range may average 0.8dB/km or more. Fibers are available as low as 0.2dB/km for some applications.

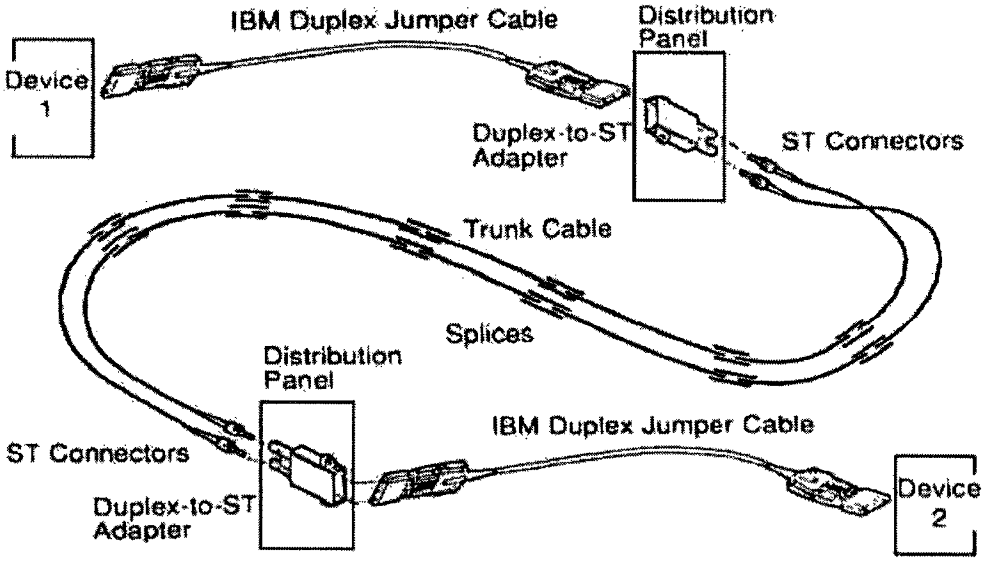


Figure 4.5 Example of point-to-point data link, ESCON environment [2]

Transmission loss is perhaps the most important property of an optical fiber or cable; it affects the link budget and maximum unrepeated distance. The number and separation between optical repeaters and regenerators are largely determined by this loss. Although wavelength-dependent attenuation data are available from most fiber manufactures, it is often not practical to perform measurements of the fiber at each wavelength of interest, especially during repair activity. An accurate model for fiber loss as a function of wavelength; has been developed by Walker [51]; this model accounts for the effects of linear scattering, macro-bending, material absorption due to ultraviolet and infrared band edges, hydroxide (OH) absorption, and absorption from common impurities such as phosphorus. Using this model, it is possible to calculate the fiber loss as a function of wavelength for different impurity levels. Optical fiber with a pure silica core is least susceptible to radiation damage; however, almost all-commercial fiber is intentionally doped to control the refractive index of the core and cladding as well as dispersion properties.

There are also installation losses associated with fiber optic connectors and splices; both of these are inherently statistical in nature. There are many different kinds of standardized optical connectors [2]. Generally, higher variability has been observed for screw-type connectors compared with push-pull of bayonet-type designs. By "making and braking" the connection many times, a connector loss distribution can be measured, for large number of connections, the distribution is often approximately Gaussian and can be characterized by a mean (μ) and a standard deviation (σ) values [2].

There are many different models that have been published for estimating connection loss due to fiber misalignment [52] – [57]; most of these treat loss due to misalignments of fiber core, offset of fibers on either side of the connector, and angular misalignment of fibers. The loss of these effects is then combined into an overall estimate of the connector performance. Optical splices are also required for longer links, because fiber is usually available in spools of 1 – 5 km, or to repair broken fibers. There are two basic types, mechanical splices and fusion splices. Fusion splices have become much more common because of their low loss and the advent of new portable tools for efficiently performing fusion splices in the field.

At this stage we present the several types of losses that affect the link budget of our system design. The more pertinent effects we have used in our model are penalties due to chromatic dispersion, mode partition; reflection induced relative intensity (RIN) and modal noise. In addition, there are other penalties such as timing jitter noise, stimulated Raman & Brillouin scattering; and frequency chirping penalties. They are more prominent in Long-Haul applications in which high power levels and amplifiers are required; these high levels of power introduce non-linear effects, such as the scattering effects. In view of the fact that our model deals with Metropolitan Area Networks, in which the distances are not great of concern; and the power levels are reasonably low; the effects of scattering is very minimal so we can disregard them completely without any effect in our modeling. The other penalties from the timing jitter and frequency chirping effects is taken care by the DWDM equipment itself.

Chromatic Dispersion and Inter-Symbol Interference Penalty:

The most important fiber characteristic after transmission loss is dispersion, which refers to the broadening of optical pulses as they propagate along the fiber. As pulses broaden, they tend to interfere with adjacent pulses; this limits the data rate and BW of optical link. In multimode fibers, there are two dominant kinds of dispersion, modal and chromatic, Modal dispersion refers to the fact that light can propagate along many different paths, or modes, in a multimode fiber; because not all these paths are the same length, different mode will travel at different velocities and cause pulse broadening. The fiber manufacturer will measure and specify modal bandwidth of the fiber in units of MHz/Km, this has been characterized by:

$$BW_{\text{mod}al} = \frac{BW_1}{L^{\gamma}} \tag{4.9}$$

Where $BW_{\text{mod}al}$ is the total bandwidth for a length L of fiber, BW_1 is the manufacturer specified modal bandwidth of a 1-Km section of fiber, and γ is a constant known as the modal bandwidth concatenation length-scaling factor, $0.5 \le \gamma \le 1$. The other major contribution is chromatic dispersion, BW_{chrom}, which occurs because different wavelengths of light propagate at different velocities in the fiber. For multimode fiber, this is given by an empirical model of the form:

$$BW_{chrom} = \frac{L^{\gamma c}}{\sqrt{\lambda_{\omega}}(a_0 + a_1 \mid \lambda_c - \lambda_{eff} \mid)} \tag{4.10}$$

Where L is the fiber length in Km, λ_c is the center wavelength of the source in nm; λ_{ω} is the source full width and half maximum spectral width in nm; γ^c is the chromatic bandwidth length, which combines length scaling coefficient, an constant; λ_{eff} is the effective wavelength , which combines the effects of the fiber zero dispersion wavelength and spectral loss signature; and the constants a_0 and a_1 are determined by a regression fit of measured data [60]. This is only one possible model, for more information refer to [61] and [62]. The total bandwidth capacity of multimode fiber BW_t is obtained with the modal and chromatic dispersion contributions according to:

$$\frac{1}{BW_t^2} = \frac{1}{BW_{chrom}^2} + \frac{1}{BW_{\mathrm{modal}}^2} \tag{4.11}$$

Once the total bandwidth is known, the dispersion penalty can be calculated for a given data rate. Single-mode fiber does not suffer modal dispersion. More detailed models of dispersion penalty have been proposed [64], [66] taking into account the design detail of the receiver and equalizer circuits and the inclusion of effects of the laser diode spectrum, pulse shaping, transmitter extinction ratio; and statistics of the data stream. By keeping a close match between the operating and zero dispersion wavelengths, this penalty can be kept to a tolerable 0.5 – 1.0 dB in most cases.

We model chromatic dispersion in single-mode fiber as the first derivative of group velocity with respect to wavelength, given by:

$$D = \frac{d\tau_g}{d\lambda} = \frac{S_0}{4}(\lambda_c - \frac{\lambda_0^4}{\lambda_c^3}) \tag{4.12}$$

Where D is the Dispersion in $ps/km.nm$ and λ_c is the laser center wavelength. The fiber is characterized by its zero dispersion wavelength λ_0 and zero dispersion slope S_0. Usually, both center and zero dispersion wavelengths are specified over a range of values; it is necessary to consider both upper and lower bounds in order to determine the worst-case dispersion penalty. The largest absolute value of D occurs at the extremes of this region. Once the dispersion is determined, inter-symbol interference penalty as a function of link length, L, can be determined to a good approximation from a model proposed by Agrawal et al. [63]:

$$P_d = 5\log(1 + 2\pi(BD\Delta\lambda)^2 L^2) \tag{4.13}$$

Where B is the bit rate and $\Delta\lambda$ is the RMS spectral width of the source.

Mode Partition Penalty:

As light propagates through a fiber with wavelength-dependent dispersion or attenuation, which deforms the pulse shape, each mode is delayed by a different amount due to group velocity dispersion in the fiber; this leads to additional signal degradation at the receiver in addition to the inter-symbol interference caused by chromatic dispersion alone. This is known as mode partition noise; it is capable of generating bit error rate floors, such that additional optical power into the receiver will not improve the link BER. This is because mode partition noise is a function of laser spectral fluctuation and wavelength-dependent dispersion of the fiber, so the signal-to-noise ratio due to this effect is independent of the signal power. The power penalty due to mode partition noise was first calculated by Ogawa [30], [65] as:

$$P_{mp} = 5\log(1 - Q^2\sigma_{mp}^2) \tag{4.14}$$

Where, $\sigma_{mp}^2 = \frac{1}{2}k^2(\pi B)^4[A_1^4\Delta\lambda^4 + 42A_1^2A_2^2\Delta\lambda^6 + 48A_2^4\Delta\lambda^8]$ (4.15a)

$$A_1 = DL, \quad \text{and} \quad A_2 = \frac{A_1}{2(\lambda_c - \lambda_0)} \tag{4.15b}$$

The mode partition coefficient, $k \in [0,1]$, and describes how much on the optical power is randomly shared between modes; it summarizes the statistical nature of mode partition noise. According to Ogawa k depends on the number of interacting modes and root mean square (rms) spectral width of the source.

Campbell showed that mode partition noise is data dependent as well. Recent work based on this model [60] has re-derived the signal variance:

$$\sigma_{mp}^2 = E_{av}(\sigma_0^2 + \sigma_{+1}^2 + \sigma_{-1}^2) \tag{4.16}$$

Where the mode partition noise contributed by adjacent baud periods is defined by:

$$\sigma_{+1}^2 + \sigma_{-1}^2 = \frac{1}{2}k^2(\pi B)^4[1.25A_1^4\Delta\lambda^4 + 40.95A_1^2A_2^2\Delta\lambda^6 + 50.25A_2^4\Delta\lambda^8] \tag{4.17}$$

And the time-average extinction ratio E_{av}= $10\log(p_1 / p_0)$, where P_1 and P_0 represent the optical power by a "1" and "0", respectively. If the operating wavelength is far away from the dispersion wavelength, the noise variance simplifies to:

$$\sigma_{mp}^2 = 2.25\frac{k^2}{2}E_{av}(1 - e^{-\beta L^2})^2 \tag{4.18}$$

Which is valid provided that,

$$\beta = (\pi BD\Delta\lambda)^2 << 1 \tag{4.19}$$

Mode partition effects deserve careful consideration because they can often limit the performance of a link or generate BER floors. However, many diode lasers have been observed to exhibit mode hopping or mode splitting in which the spectrum appears to split optical power between two or three mode for brief periods of time. It is still not fully understood the exact mechanism, but stable Gaussian spectra are generally only observed for continuous wave operation and temperature-stabilized lasers [67].

Reflection Induced Relative Intensity Noise (RIN) Penalty:

When stray light is reflected into a Fabry-Perot-type laser diode, it gives rise to intensity fluctuations in the laser output. This is a complicated phenomena, strongly dependent on the type of laser; it is known as reflection-induced relative intensity noise (RIN). Because the reflected light is measured at a specified signal level, RIN is data rate dependent, although it is independent of link length. There have been several attempts to characterize RIN [2], [69], [70], [71]; typically, the RIN noise is assumed Gaussian in amplitude and uniform in frequency over the receiver bandwidth of interest. One approximation for the RIN power penalty is given by:

$$P_{rin} = -5\log[1 - Q^2(BW)(1+M_r)^{2g}(10^{\frac{RIN}{10}})(\frac{1}{M_r})^2] \qquad (4.20)$$

Where, the RIN value is specified in *dB/Hz,* BW is the receiver bandwidth, M_r is the receiver modulation index, and the exponent $g \in [0,1]$ that relates the magnitude of RIN noise to the optical power levels. We assume that optical power levels in this application are below the threshold for nonlinear effects, such as Raman or Brillouin scattering.

Modal Noise Penalty:

Because high-capacity optical links use highly coherent laser transmitters, different modes propagating in the fiber may interfere with one another. Random coupling between fiber modes causes fluctuations in the optical power coupled through lossy splices and connectors; this phenomena is known as modal noise [55]. Assuming that the only significant interaction occurs between the two lowest order longitudinal modes for a sufficiently coherent laser, then for N sections of fiber, each of length L in a single-mode link, the worst-case σ for modal noise is given by:

$$\sigma_m = \sqrt{2}N\eta(1-\eta)e^{-aL} \tag{4.21}$$

Where a is the attenuation coefficient of the LP11 mode, and η is the splice transmission efficiency, given by:

$$\eta = 10^{-(\frac{\eta_0}{10})} \tag{4.22}$$

Where η_0 is the mean splice loss (typically, splice transmission efficiency will exceed 90%). The corresponding optical power penalty due to modal noise is given by:

$$P = -5\log(1 - Q^2\sigma_m^2) \tag{4.23}$$

Where, Q corresponds to the desired BER.

Total Power Availability:

The total available power will be:

$$P_{available} = [Tx_{(output)} - Rx_{(sensitivity)}] - Penalties \tag{4.24}$$

The presented solutions have only been estimated. It should be apparent that link design requires not only the latest valid performance models but also a good amount of engineering judgment in how to best apply these tools. Besides, real-world problems are not often clear-cut representations. A link designer must be able to manage the trade-off involved in frequently working with incomplete information.

A summary of the important link budget loss sources and link power penalties is given in tables (4.2) and (4.3); more detailed descriptions of link budget modeling, including equations for all the link noise parameters and examples of a complete link budget calculation, are available in the literature [50], [60], [61].

Table 4.2: Link Budget Loss Sources

Sources	Typical Loss
Fiber attenuation	$0.5 dB / Km$
Connector loss	$0.25 - 0.50 dB$
Splice loss	$0.15 - 0.40 dB$
Transmitter/Receiver end-of-life degradation	$0.5 - 1.0 dB$

Table 4.3: Typical Link Power Penalties

Penalty	Typical at $20\,Km$, $200\,Mbps$ (dB)
Chromatic dispersion	1.2
Mode partition	1.5
RIN	0.8
Multi-path	0.25

CHAPTER 5

EXPERIMENTAL RESULTS

In this chapter we present experimental results of our simulation models. We have validated the model using a 2 site point-to-point WDM network designed for disaster recovery, using both synchronous and asynchronous backup solutions; similar to those described previously [84]. The WDM testbed consisted of two IBM zSeries 900 model 106 enterprise servers and two enterprise storage servers (ESS) 2015 model F20 (*commonly known by their trade name "Shark"*). The storage control units were configured with 3.6 Tbyte capacities each, running Linux and DB2 database management software version 7.1. The two locations were interconnected with cascaded 20 km spools of Corning SFM-28 grade single-mode fiber, using flat polished ST connectors. Two network configurations were evaluated.

CASE A: *Basic GDPS Designs Using Nortel Optera 5200 and Adva FSP 2000:*

The first configuration is a 2 site Parallel Sysplex with PPRC remote copy, using redundant Sysplex Timer links (2 ETR, 2 CLO links) and 2 ISC links, with PPRC traffic carried by a combination of 8 protected ESCON links and 4 protected FICON links; to support network management, 1 Gigabit Ethernet link and 1 ATM link were also included.

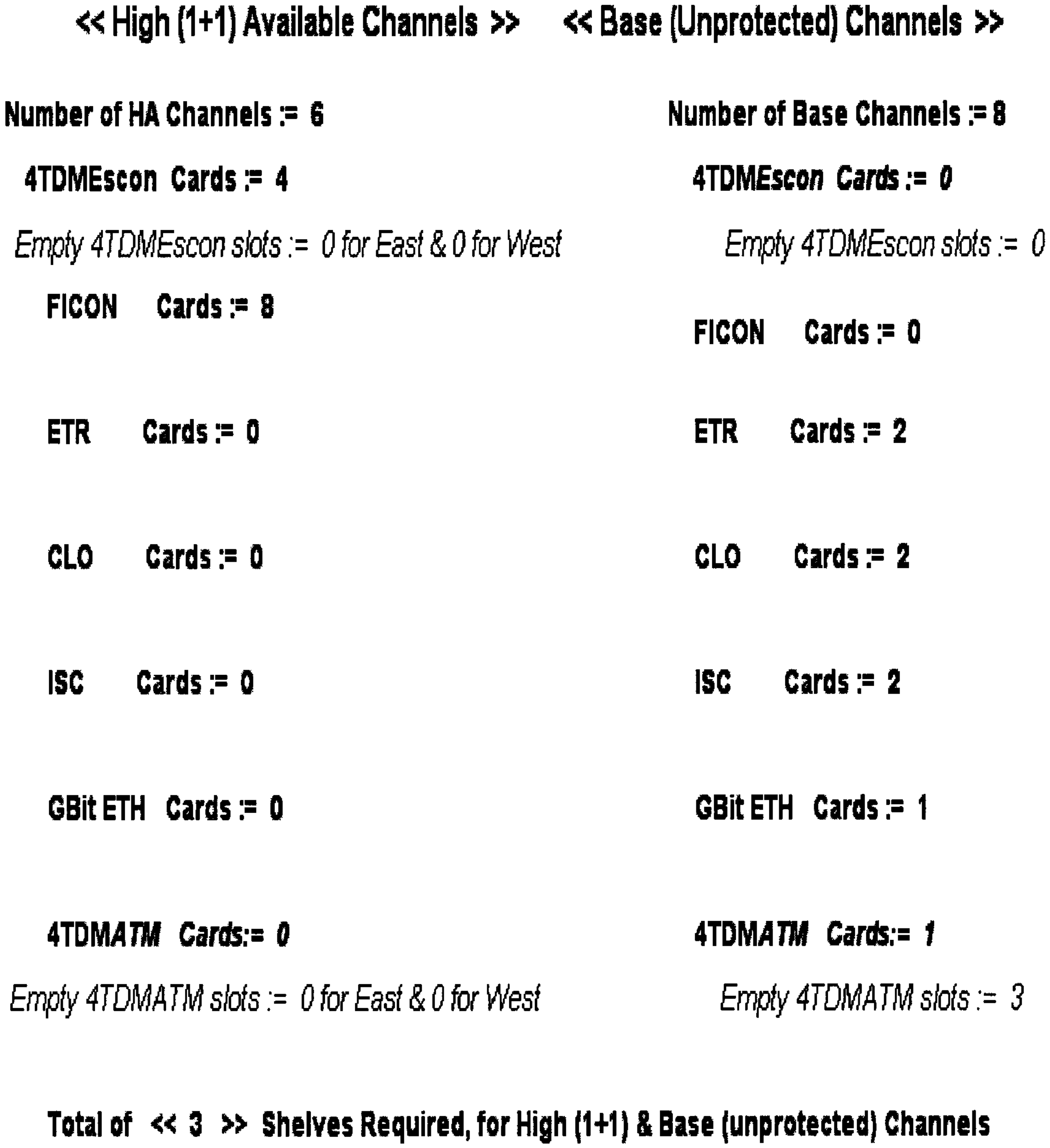
Case B: ***Storage Area Network Design Using Nortel Optera 5200 and Adva FSP 2000:***

The second configuration was a storage disk mirroring system which required 16 channels each of ESCON and FICON traffic.

We first compute the required number of WDM equipment shelves and contents of each shelf, assuming the Optera Metro 5200 equipment [1]. Like most WDM products, the Optera is a modular design based on a rack-mounted equipment shelf as illustrated in Figure 5.1.

Figure 5.1 – Nortel Optera Metro WDM shelf

This shelf is populated with various types of interface cards, which convert optical signals from the subtended equipment into electronic signals, implement management functions (such as protection switching), remodulate the data onto an ITU grid wavelength, and combine multiple wavelength channels into a single optical fiber. Optional adapter cards implement time division multiplexing (TDM) for lower data rates; for example, combining 4 ESCON channels into a single 1 Gbps wavelength channel. Each shelf is self-contained, with its own power and cooling, and provides optional protection switching by redundantly transmitting data on the east and west sides of the shelf, as shown. When presented with a network requirement, such as transporting a certain number of ESCON channels between two sites, it is first necessary to determine how many shelves and what types of cards are required at each location.



```
<< High (1+1) Available Channels >>      << Base (Unprotected) Channels >>

Number of HA Channels := 6                    Number of Base Channels := 8

 4TDMEscon Cards := 4                          4TDMEscon Cards := 0

 Empty 4TDMEscon slots := 0 for East & 0 for West   Empty 4TDMEscon slots := 0

  FICON    Cards := 8
                                               FICON    Cards := 0

  ETR      Cards := 0                          ETR      Cards := 2

  CLO      Cards := 0                          CLO      Cards := 2

  ISC      Cards := 0                          ISC      Cards := 2

  GBit ETH  Cards := 0                         GBit ETH  Cards := 1

  4TDMATM  Cards:= 0                           4TDMATM  Cards:= 1

 Empty 4TDMATM slots := 0 for East & 0 for West    Empty 4TDMATM slots := 3

  Total of << 3 >> Shelves Required, for High (1+1) & Base (unprotected) Channels
```

Figure 5.2 Nortel system detailed simulation result (case A)

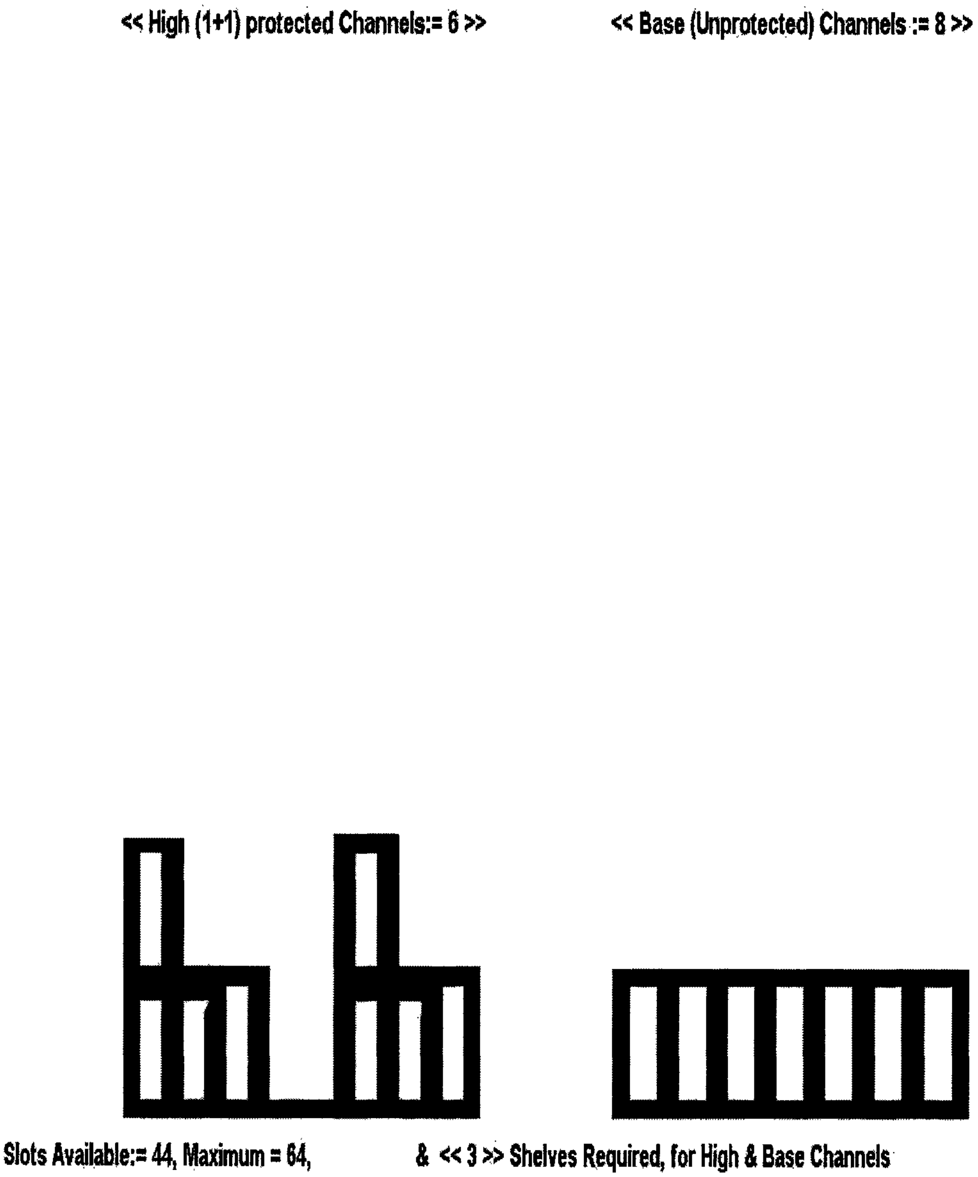
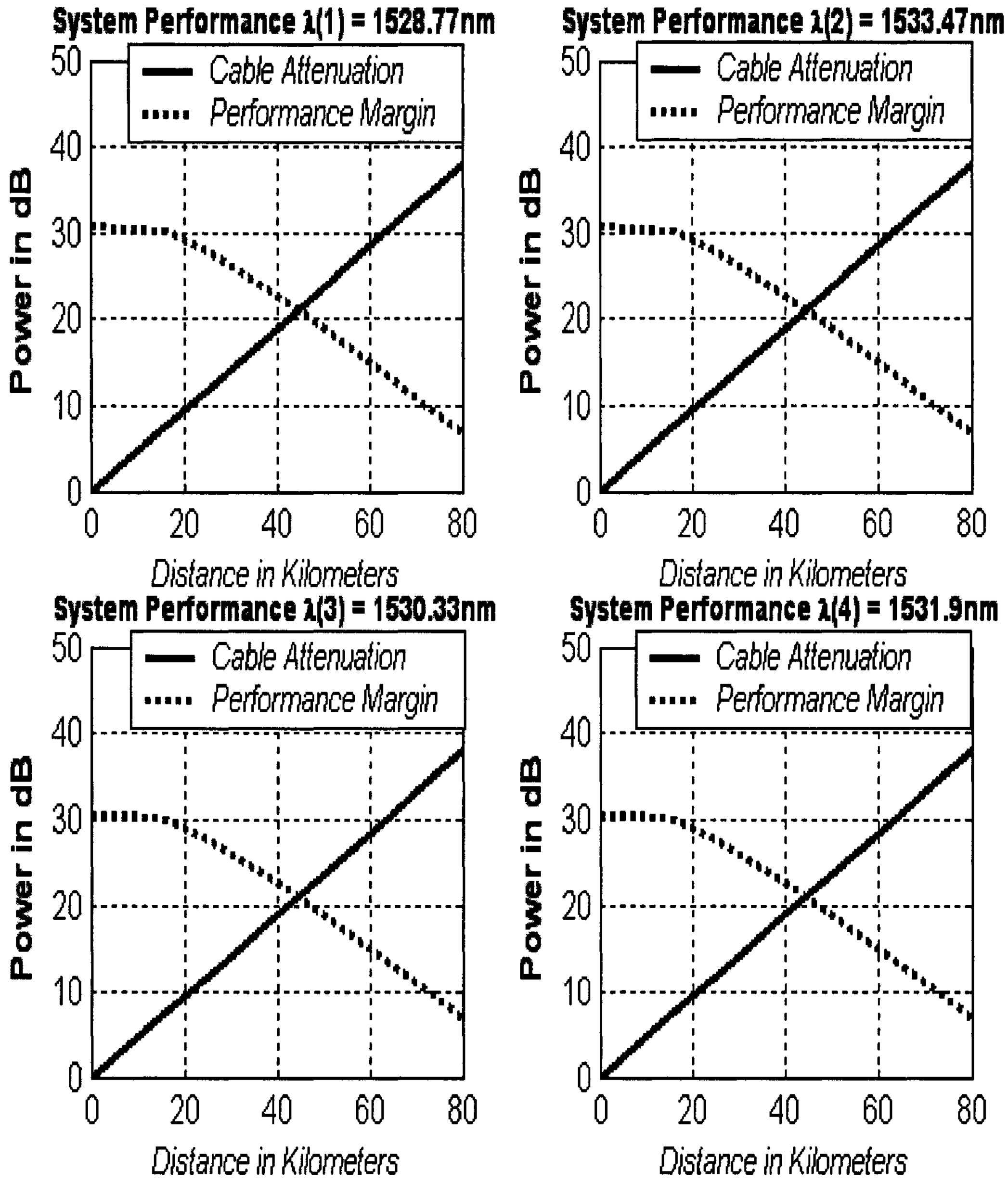


Figure 5.3 Nortel system shelves configuration (case A)

The model correctly predicted that this configuration would require a total of 3 Optera shelves, (see Figure 5.2 and Figure 5.3) populated with a combination of different adapter cards to accommodate the data. This feature can save considerable time when designing a network, and can potentially be linked into the order fulfillment system which generates purchase orders for the required hardware.

Since the Optera uses a combination of C-band and L-band wavelengths with 1.6 nm spacing (twice the ITU grid), this configuration allows us to compute the link budgets for each WDM wavelength and data rate per wavelength. Results are summarized in Figure 5.4 (a) & (b), which shows the optical link budgets as a function of distance and wavelength assuming LEAF fiber at two different data rates, 200 Mbps (ESCON traffic) and 1.06 Gbps (FICON traffic). Cable plant loss increases linearly with distance, while available optical power decreases; the intersection of these 2 curves gives the maximum supported distance of 40 km. We constructed this network using the model's recommended shelf provisioning, and validated the link budget model by operating the testbed error free for 48 hours at 40 km. As the distance was increased beyond this point, link errors were logged on the servers.



System Performance λ(1) = 1528.77nm

System Performance λ(2) = 1533.47nm

System Performance λ(3) = 1530.33nm

System Performance λ(4) = 1531.9nm

Figure 5.4 (a) Nortel system link budget for 200 Mbps bit rate

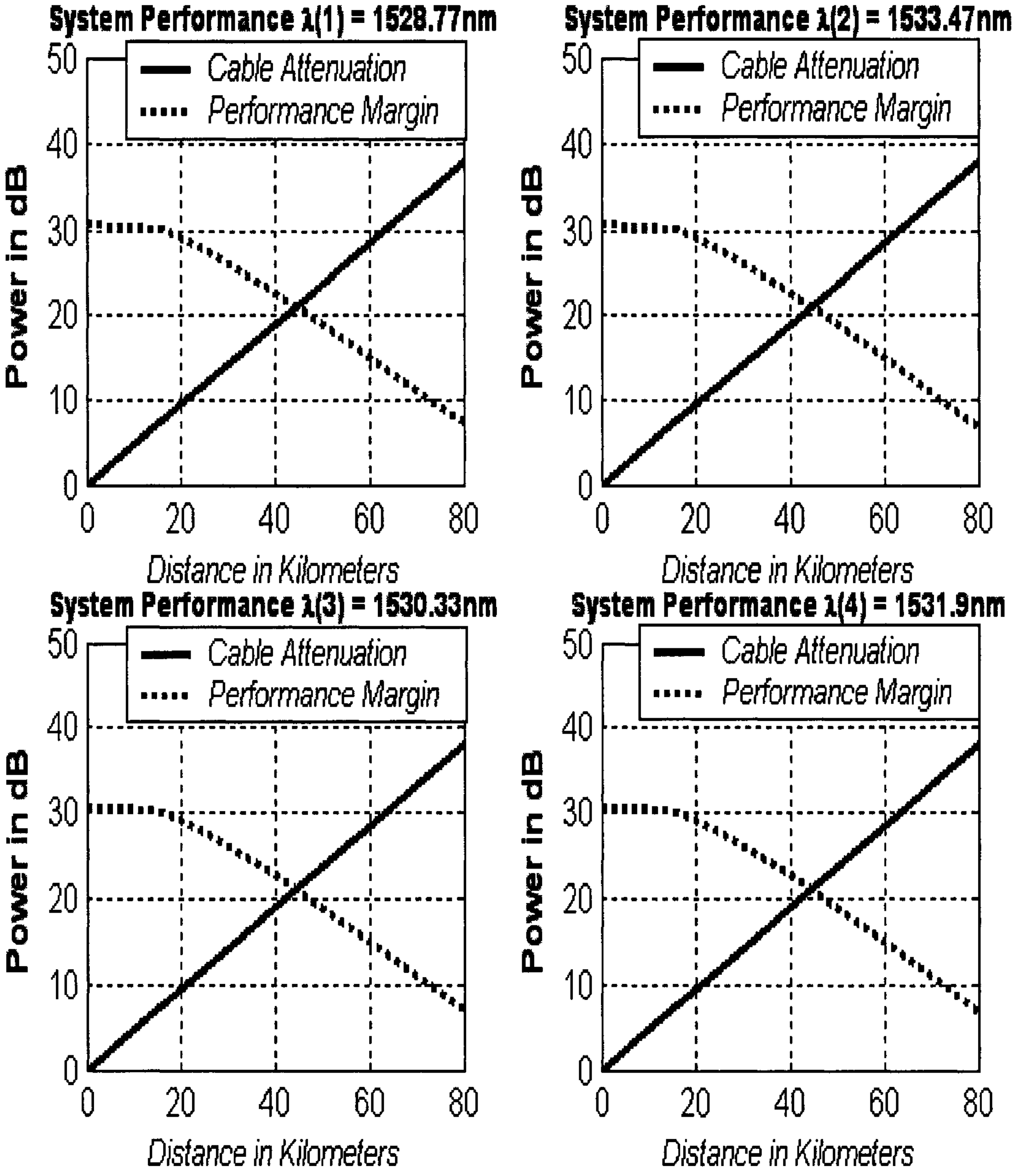


Figure 5.4 (b) Nortel system link budgets for 1.06 Gbps bit rate

Then, we redesigned the same configuration using different equipment, the FSP 2000 platform from Adva Optical Networking [83], [87], [88], [90]. This equipment is also based on a modular shelf design; however the shelf is not as large as an Optera shelf as seen in Figure 5.5. Each shelf can accommodate up to eight (8) adapter cards, which contain transponders for conversion of client signals to ITU grid wavelengths.

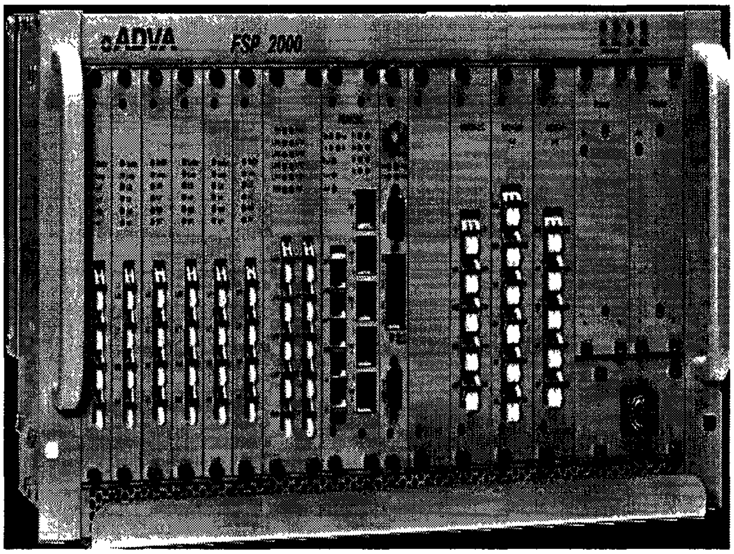
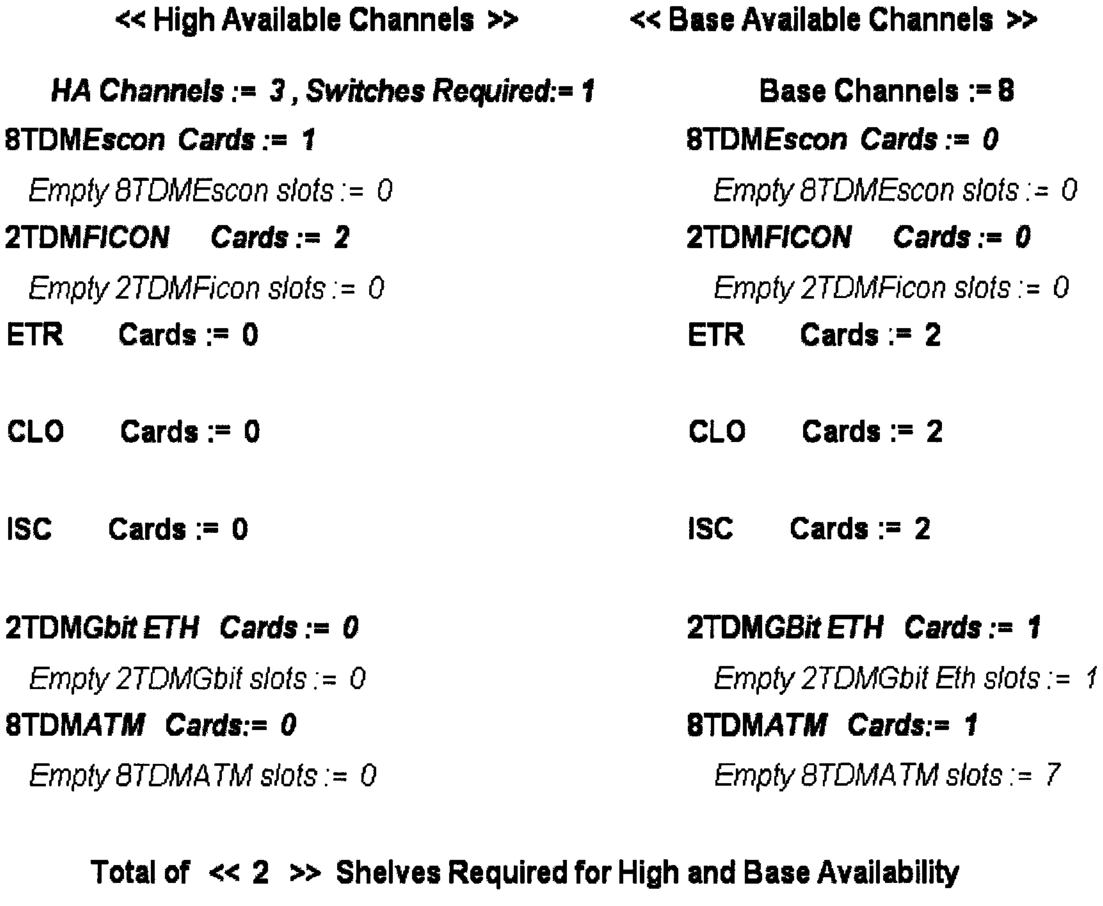


Figure 5.5 – Adva FSP 2000 WDM shelf

The FSP 2000 designs we considered use only C-band wavelengths at the minimum ITU grid spacing of 0.8 nm. As before, each shelf also contains a multiplexing card for combining the wavelengths, a management card, power supply, and cooling. An optional optical protection switch can be used in the shelf to provide redundant transmission over two physically redundant paths. As before, the model correctly predicted the required hardware configuration (2 FSP 2000 shelves as it is seen in Figure 5.6 and Figure 5.7).

Then, we validated the link budgets shown previously by operating the testbed for 48 hours error free at 40 km maximum distance as shown in Figure 5.8 (a) & (b).



<< High Available Channels >>	<< Base Available Channels >>
HA Channels := 3 , Switches Required:= 1	**Base Channels := 8**
8TDM*Escon Cards := 1*	**8TDM*Escon Cards := 0***
Empty 8TDMEscon slots := 0	*Empty 8TDMEscon slots := 0*
2TDM*FICON Cards := 2*	**2TDM*FICON Cards := 0***
Empty 2TDMFicon slots := 0	*Empty 2TDMFicon slots := 0*
ETR Cards := 0	**ETR Cards := 2**
CLO Cards := 0	**CLO Cards := 2**
ISC Cards := 0	**ISC Cards := 2**
2TDM*Gbit ETH Cards := 0*	**2TDM*GBit ETH Cards := 1***
Empty 2TDMGbit slots := 0	*Empty 2TDMGbit Eth slots := 1*
8TDM*ATM Cards:= 0*	**8TDM*ATM Cards:= 1***
Empty 8TDMATM slots := 0	*Empty 8TDMATM slots := 7*

Total of << 2 >> Shelves Required for High and Base Availability

Figure 5.6 Adva system detailed simulation result (Case A)

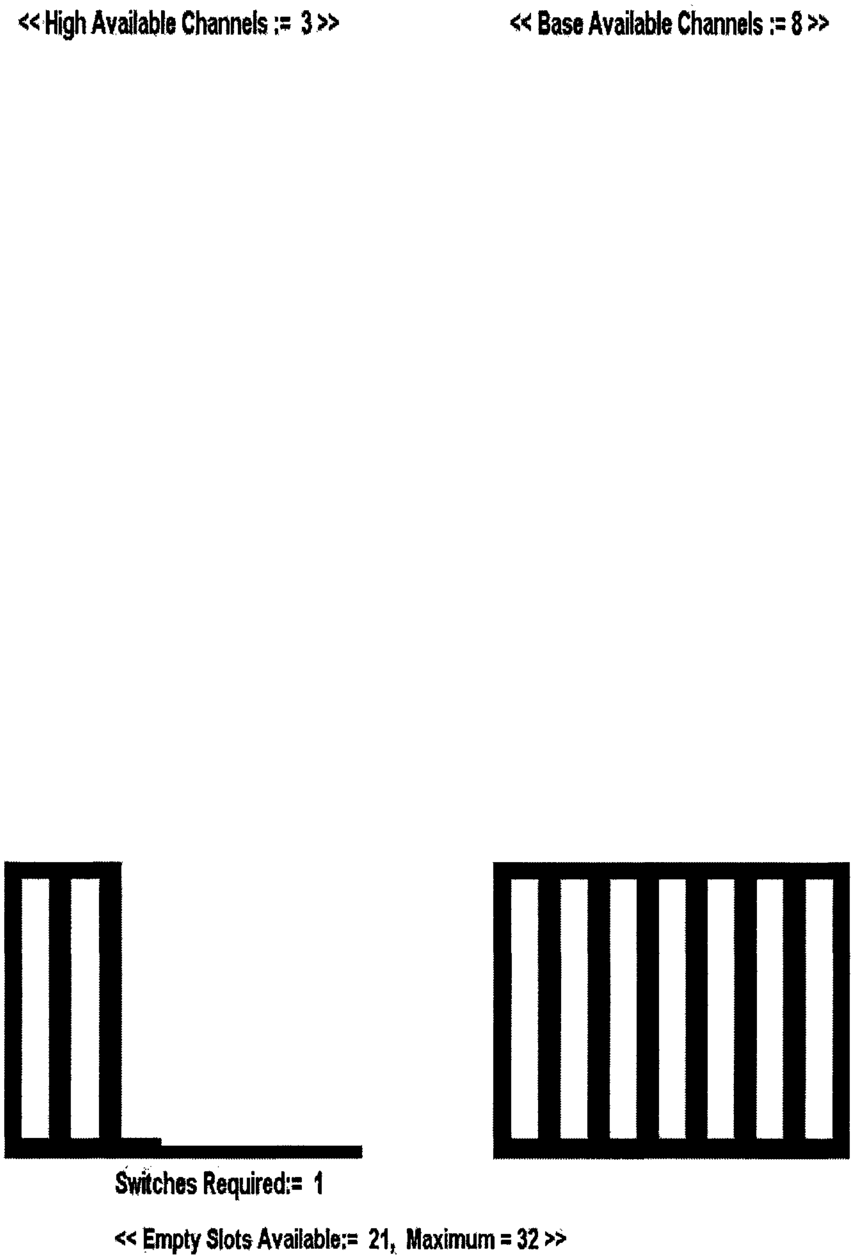
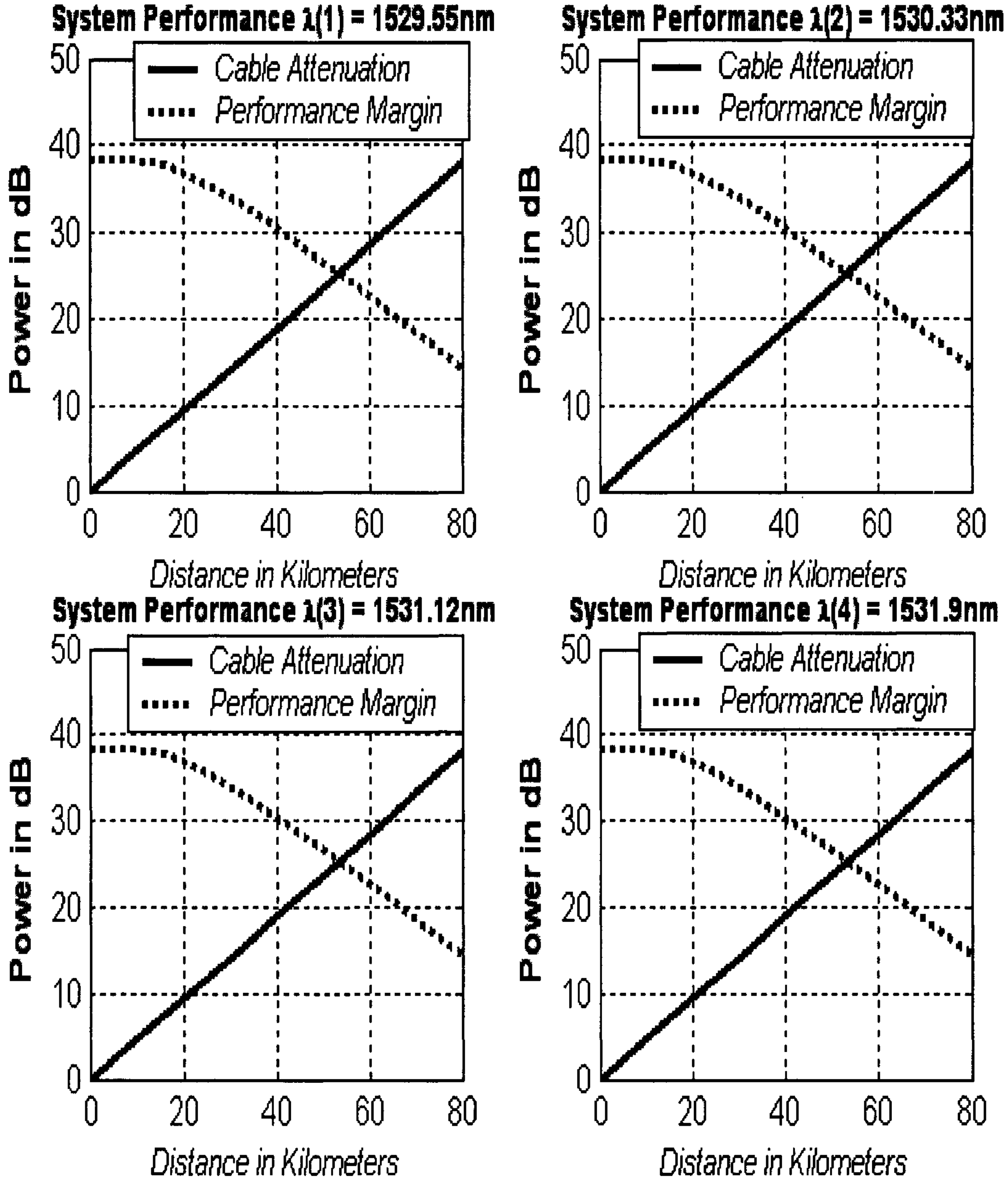


Figure 5.7 Adva system shelves configuration (case A)



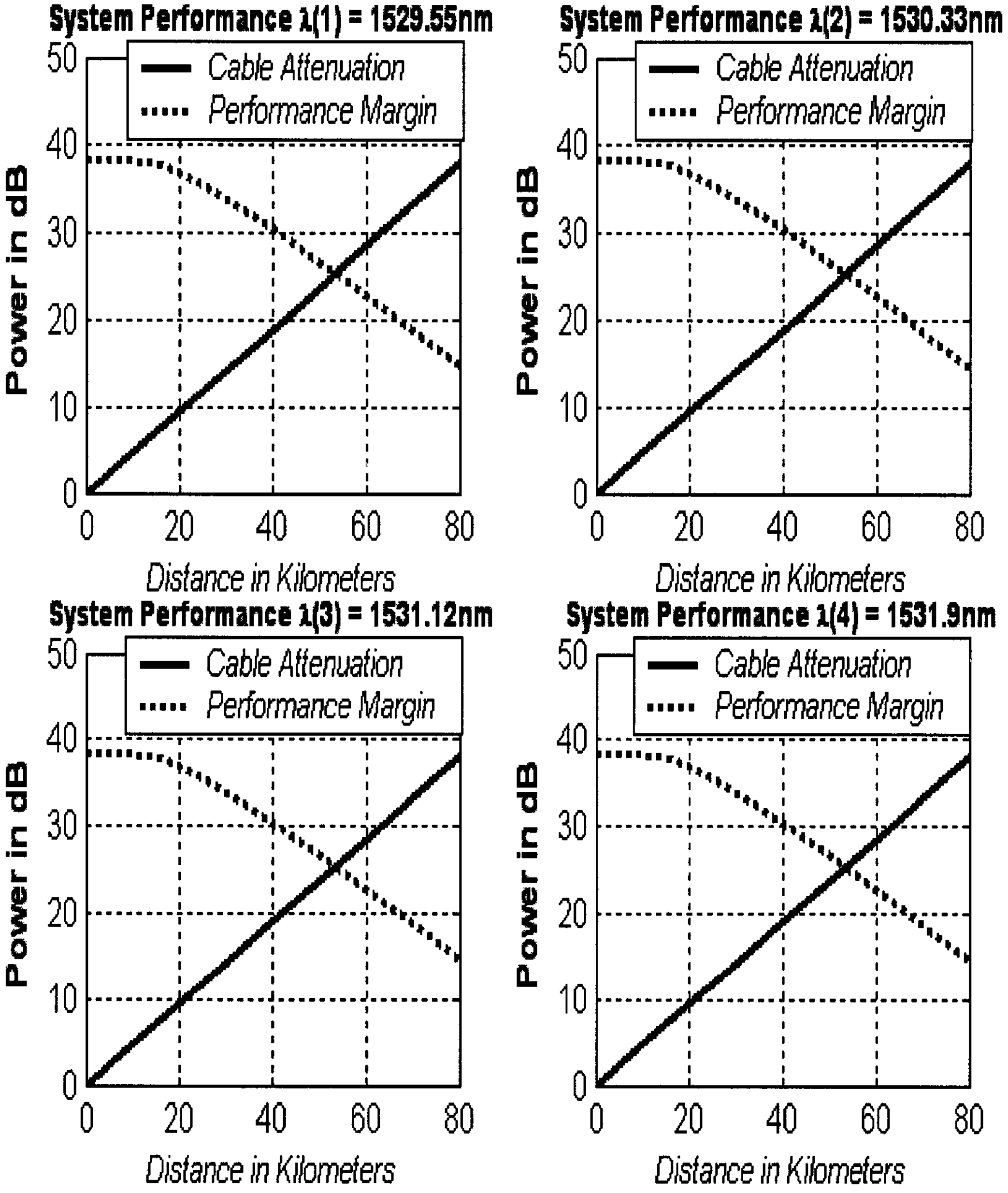
System Performance λ(1) = 1529.55nm

System Performance λ(2) = 1530.33nm

System Performance λ(3) = 1531.12nm

System Performance λ(4) = 1531.9nm

Figure 5.8 (a) Adva system link budget for 200 Mbps bit rate


System Performance λ(1) = 1529.55nm

System Performance λ(2) = 1530.33nm

System Performance λ(3) = 1531.12nm

System Performance λ(4) = 1531.9nm

Figure 5.8 (b) Adva system link budgets for 1.06 Gbps bit rate

The previous experiments allow for a comparison of different WDM equipment designs for the same network topology. Given the current unit cost of the different adapter cards and equipment shelves, we can then compute the total equipment cost, physical size, and power consumption of each solution. It should be noted that while this information is a useful design guideline, the selection of equipment for a given application may depend on many other factors, as well. For example, it is useful to see how the configuration will scale if we assume a compounded 10 % growth rate and the same mix of traffic; this result is shown in Figure 5.9 and Figure 5.10 as a function of cost per channel for both WDM networks.

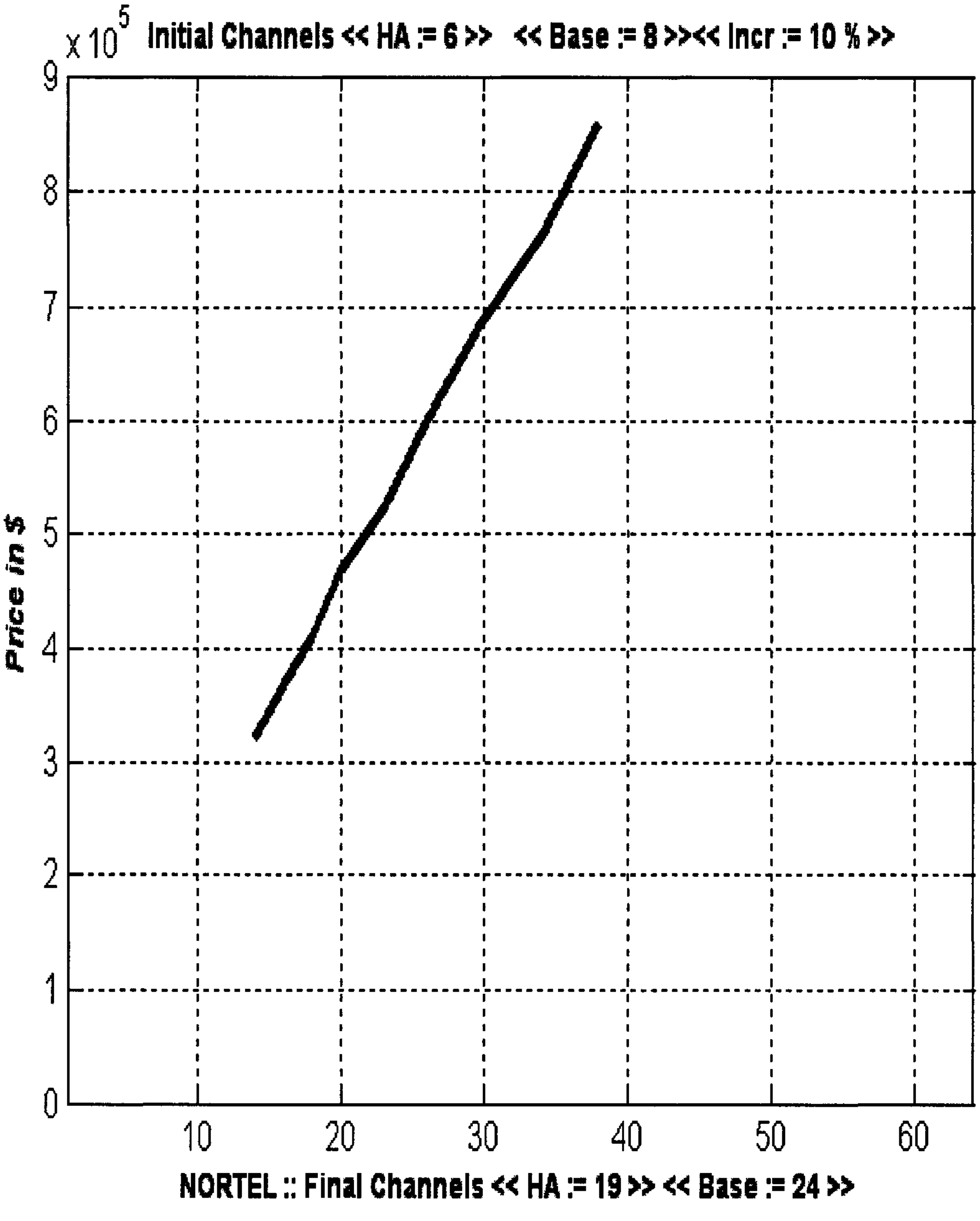


Figure 5.9 cost per channel, Nortel configuration (case A)

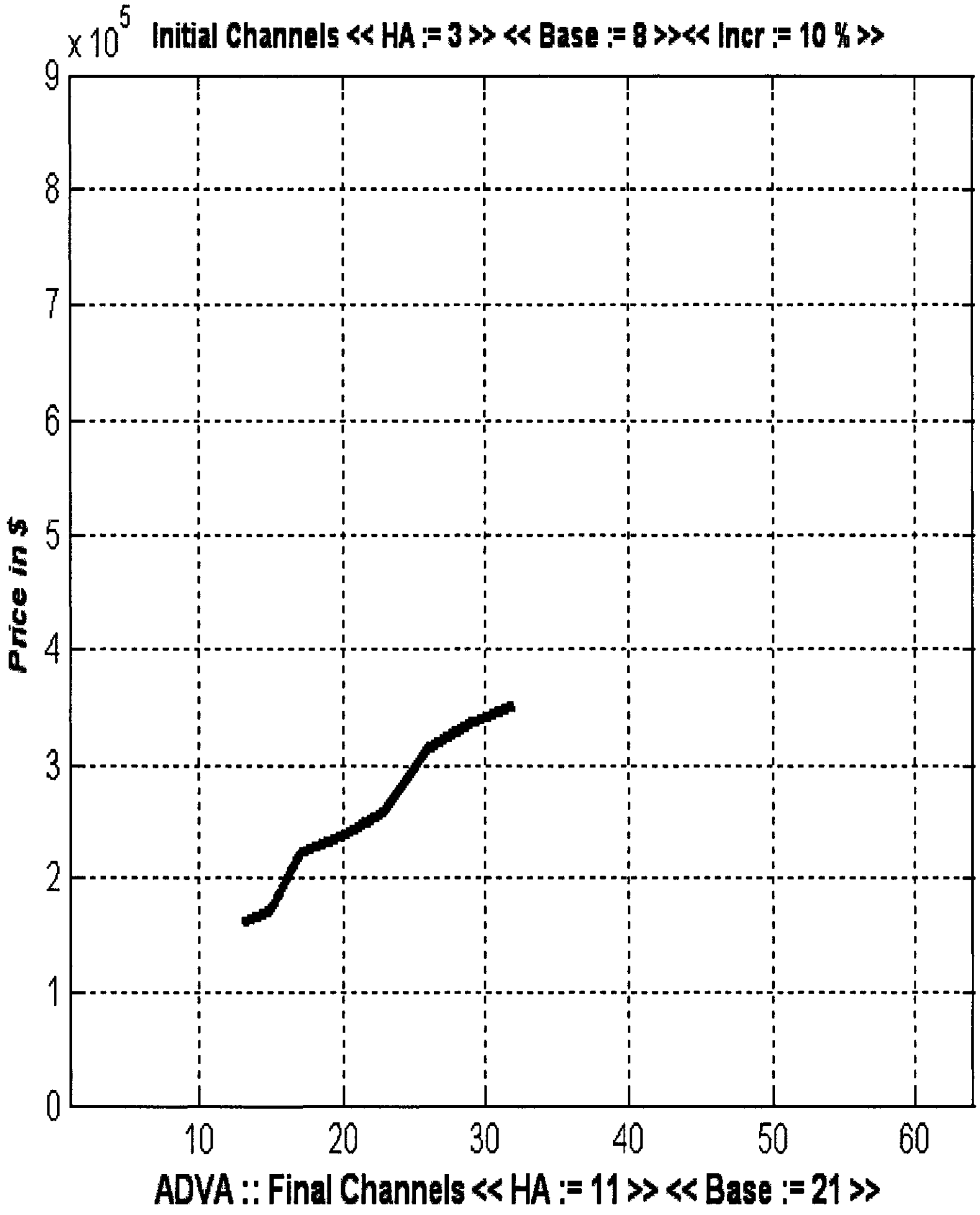


Figure 5.10 cost per channel, Adva configuration (case A)

We may also define our own dimensionless performance metrics, for example the product of total system cost, size, and power consumption, M;

$$M = (power)(\cos t)(physicalSize) \tag{9}$$

The scaling of M vs. number of channels is shown in Figure 5.11 and Figure 5.12 for each of the two WDM configurations tested.

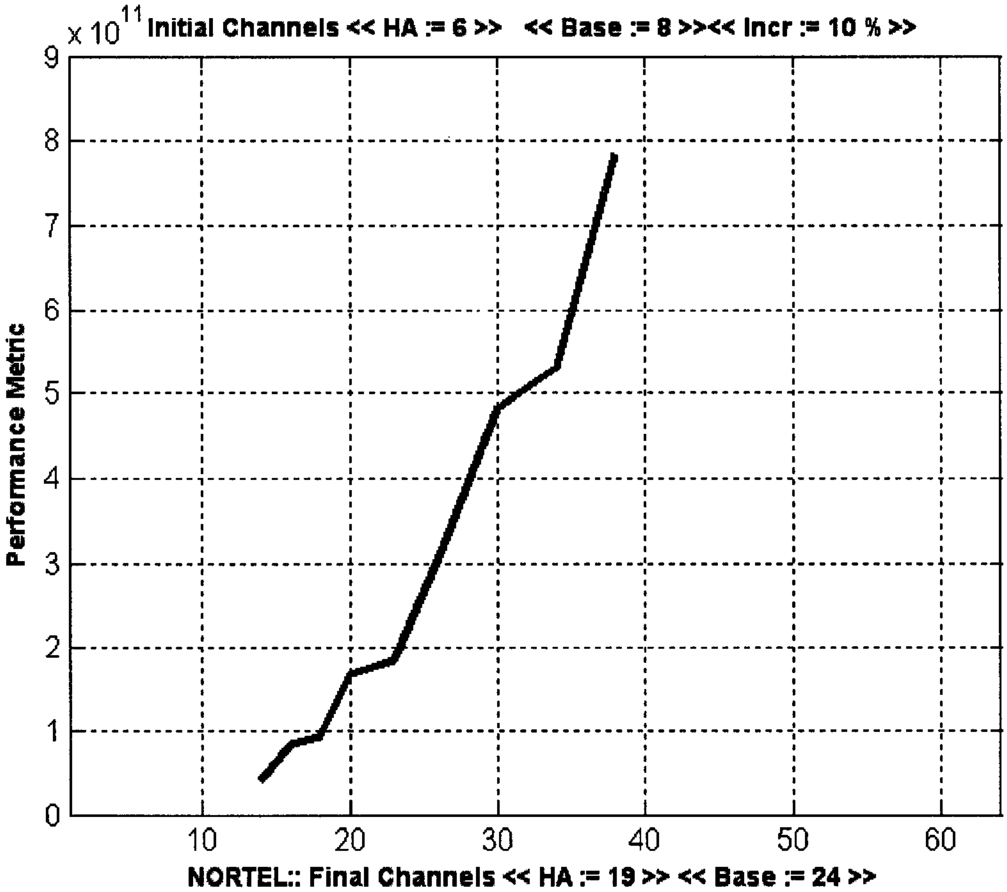


Figure 5.11 – performance metric, Nortel platform (case A)

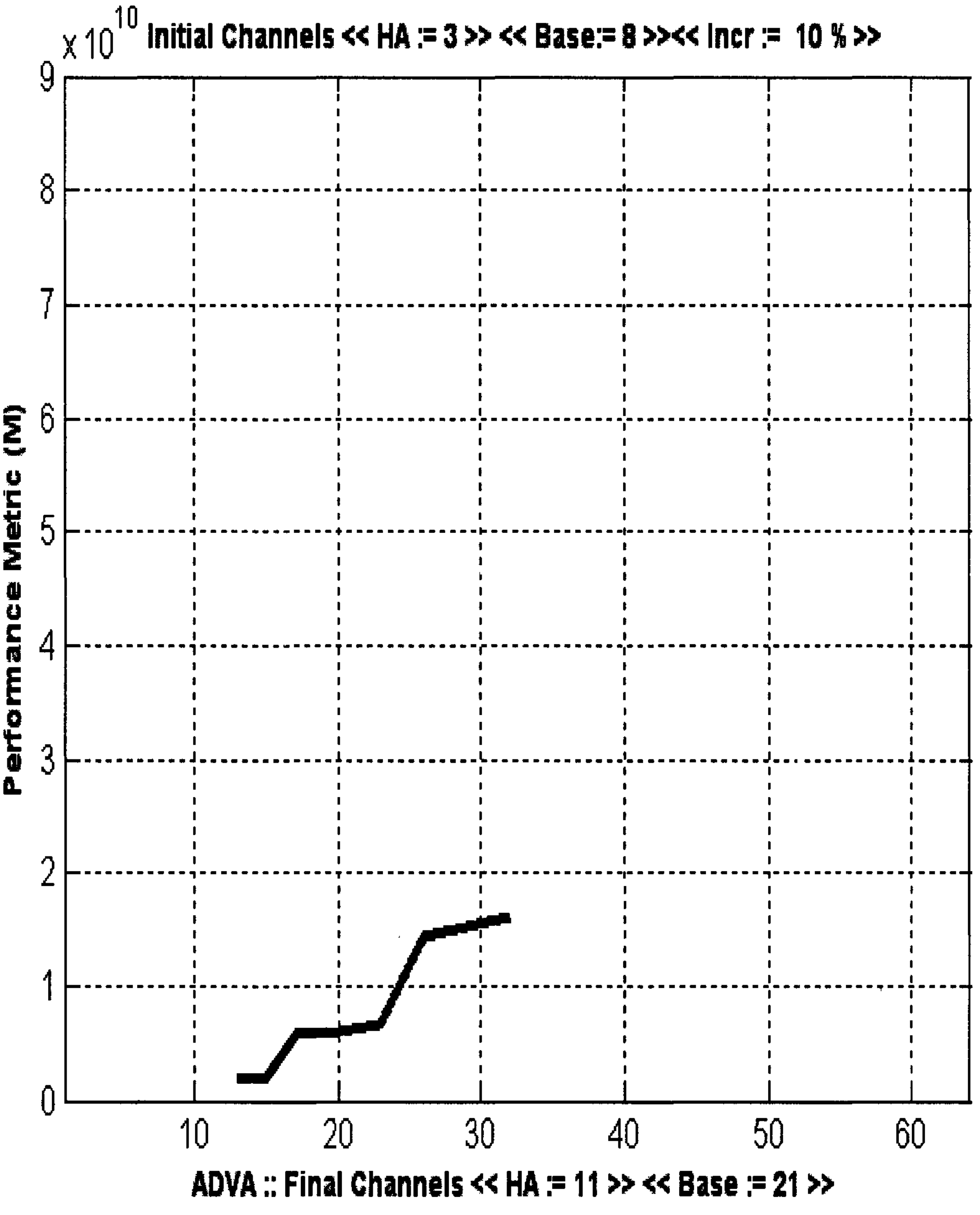
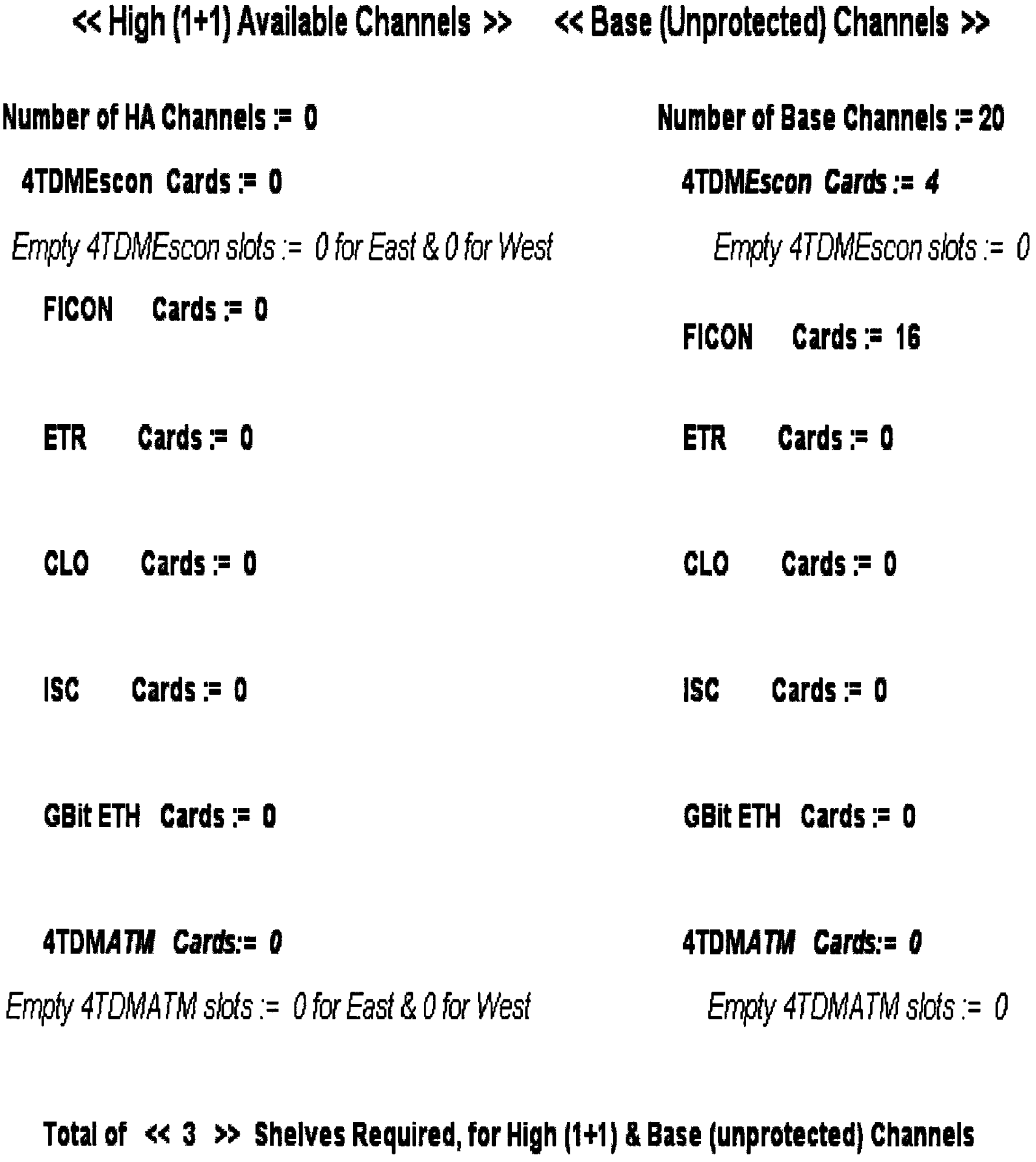


Figure 5.12 – performance metric, Adva platform (case A)

Note the discontinuities which occur whenever the growing configuration must add another equipment shelf. This suggests that alternative designs with fewer shelves would scale better using this particular metric. We can also see the advantage of using TDM whenever possible for lower data rate traffic, provided that the cost, size, and power consumption of the TDM card are less than the comparable factors for multiple individual cards. It is desirable for the scaling curves to increase as slowly as possible over a large number of channels.

The results for Case B; are presented in Figure 5.13 for Nortel simulation; and Figure 5.14 shows for Adva's simulation. Figure 5.15 shows a joint result of cost and performance metric for Nortel solution; and Figure 5.16 presents Adva's cost and performance metric solution.



```
     << High (1+1) Available Channels >>      << Base (Unprotected) Channels >>

Number of HA Channels := 0                       Number of Base Channels := 20
 4TDMEscon Cards := 0                              4TDMEscon Cards := 4
 Empty 4TDMEscon slots := 0 for East & 0 for West    Empty 4TDMEscon slots := 0
   FICON    Cards := 0
                                                   FICON    Cards := 16

   ETR     Cards := 0                              ETR     Cards := 0

   CLO     Cards := 0                              CLO     Cards := 0

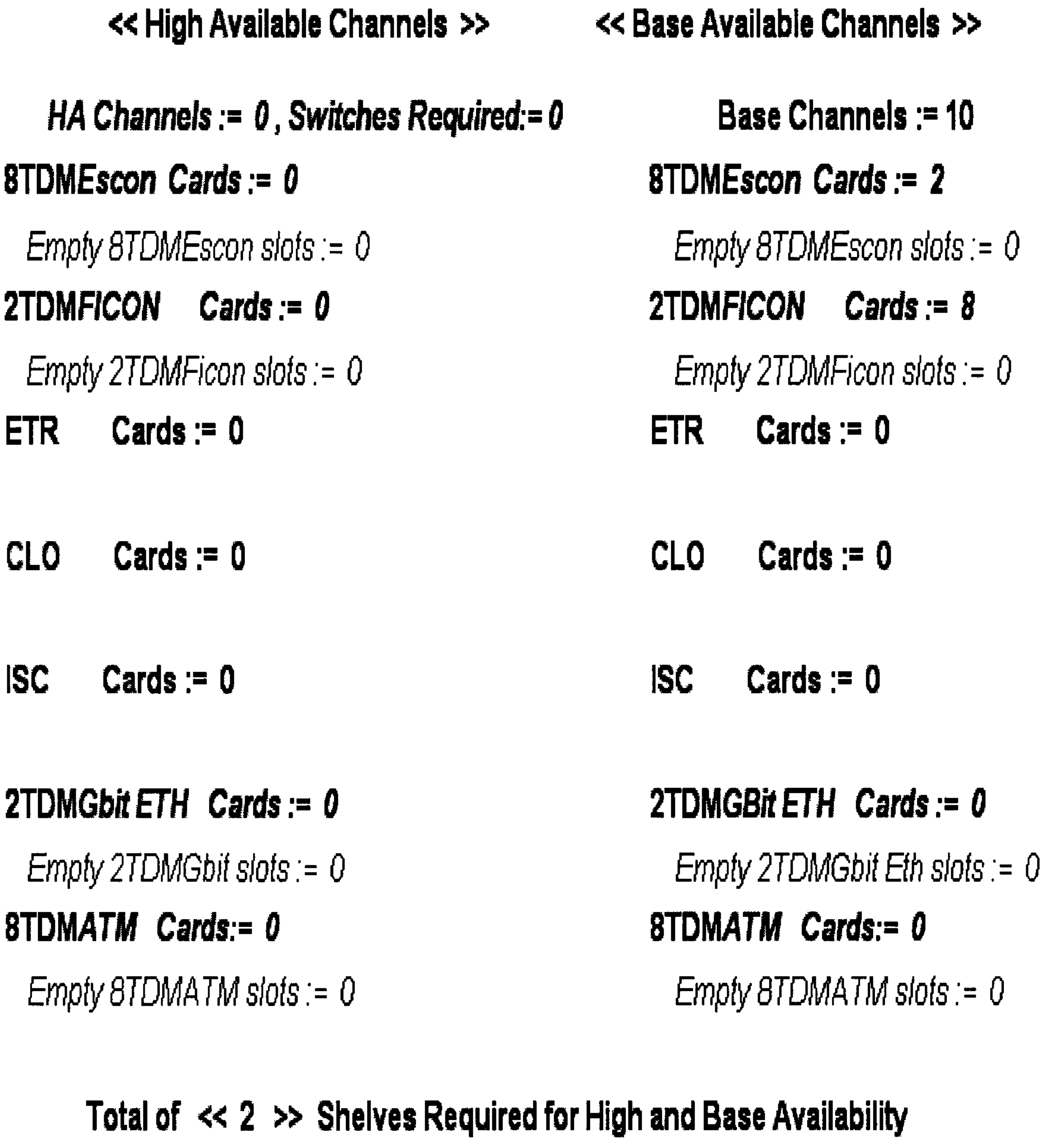
   ISC     Cards := 0                              ISC     Cards := 0

   GBit ETH  Cards := 0                            GBit ETH  Cards := 0

   4TDMATM  Cards:= 0                              4TDMATM  Cards:= 0
 Empty 4TDMATM slots := 0 for East & 0 for West     Empty 4TDMATM slots := 0

   Total of  << 3 >>  Shelves Required, for High (1+1) & Base (unprotected) Channels
```

Figure 5.13 Nortel system detailed simulation result (case B)



```
   << High Available Channels >>          << Base Available Channels >>

   HA Channels := 0 , Switches Required:= 0        Base Channels := 10
8TDMEscon Cards := 0                      8TDMEscon Cards := 2
  Empty 8TDMEscon slots := 0                Empty 8TDMEscon slots := 0
2TDMFICON    Cards := 0                   2TDMFICON    Cards := 8
  Empty 2TDMFicon slots := 0                Empty 2TDMFicon slots := 0
ETR      Cards := 0                       ETR      Cards := 0


CLO      Cards := 0                       CLO      Cards := 0


ISC      Cards := 0                       ISC      Cards := 0


2TDMGbit ETH  Cards := 0                  2TDMGBit ETH  Cards := 0
  Empty 2TDMGbit slots := 0                 Empty 2TDMGbit Eth slots := 0
8TDMATM  Cards:= 0                        8TDMATM  Cards:= 0
  Empty 8TDMATM slots := 0                  Empty 8TDMATM slots := 0

     Total of  << 2  >>  Shelves Required for High and Base Availability
```

Figure 5.14 Adva system detailed simulation result (case B)

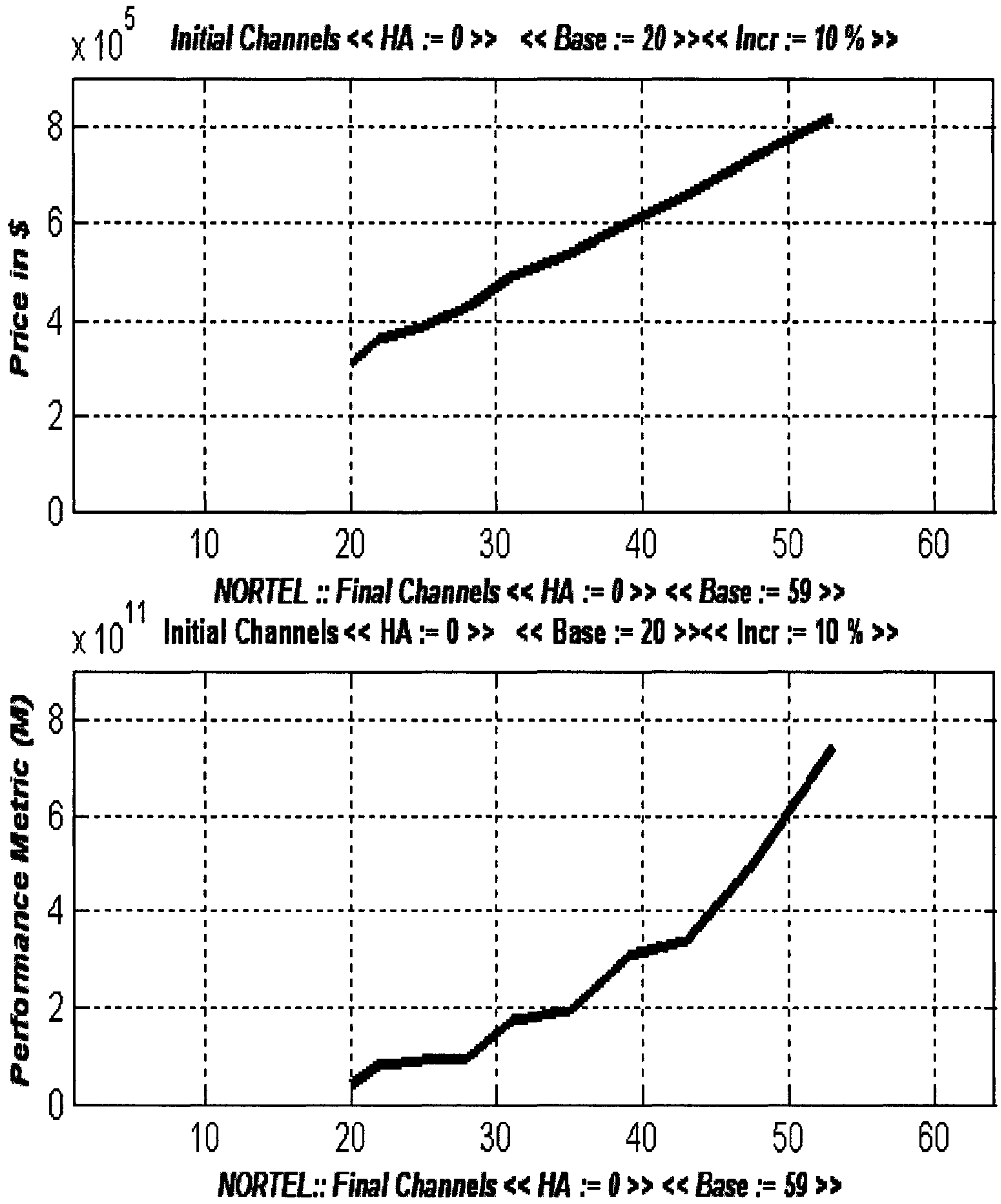


Figure 5.15 Nortel cost and performance metric (case B)

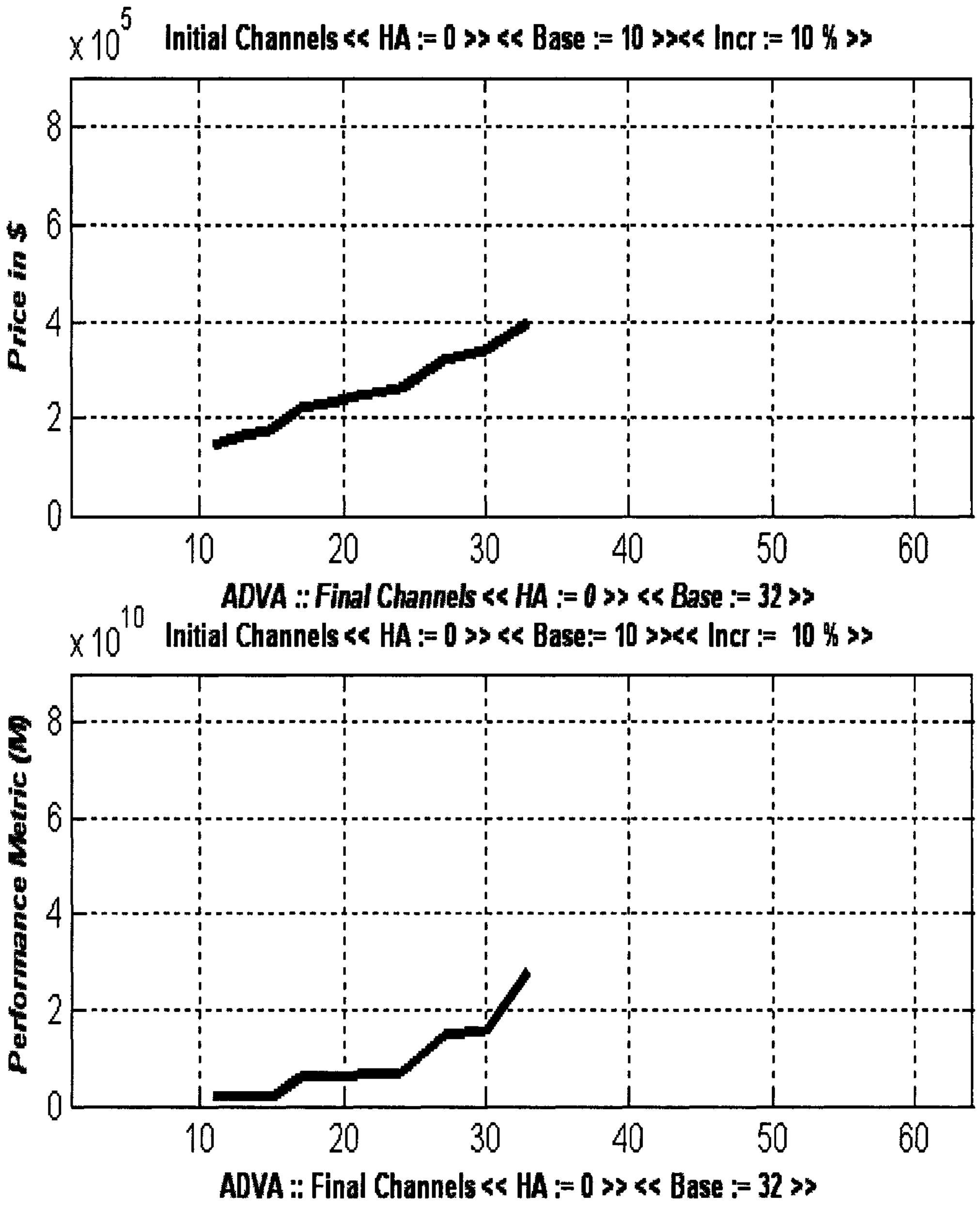


Figure 5.16 Adva cost and performance metric (case B)

Case C: Initial 2 Channels and Scaling at 10% Growth

For comparison, we have also modeled the effect of starting with a very simple configuration of 2 protected and 2 unprotected channels and scaling to a maximum configuration, as shown in Figure 5.17. Additional WDM platforms could also be modeled and computed in a modular fashion by adding extensions to the existing simulation program.

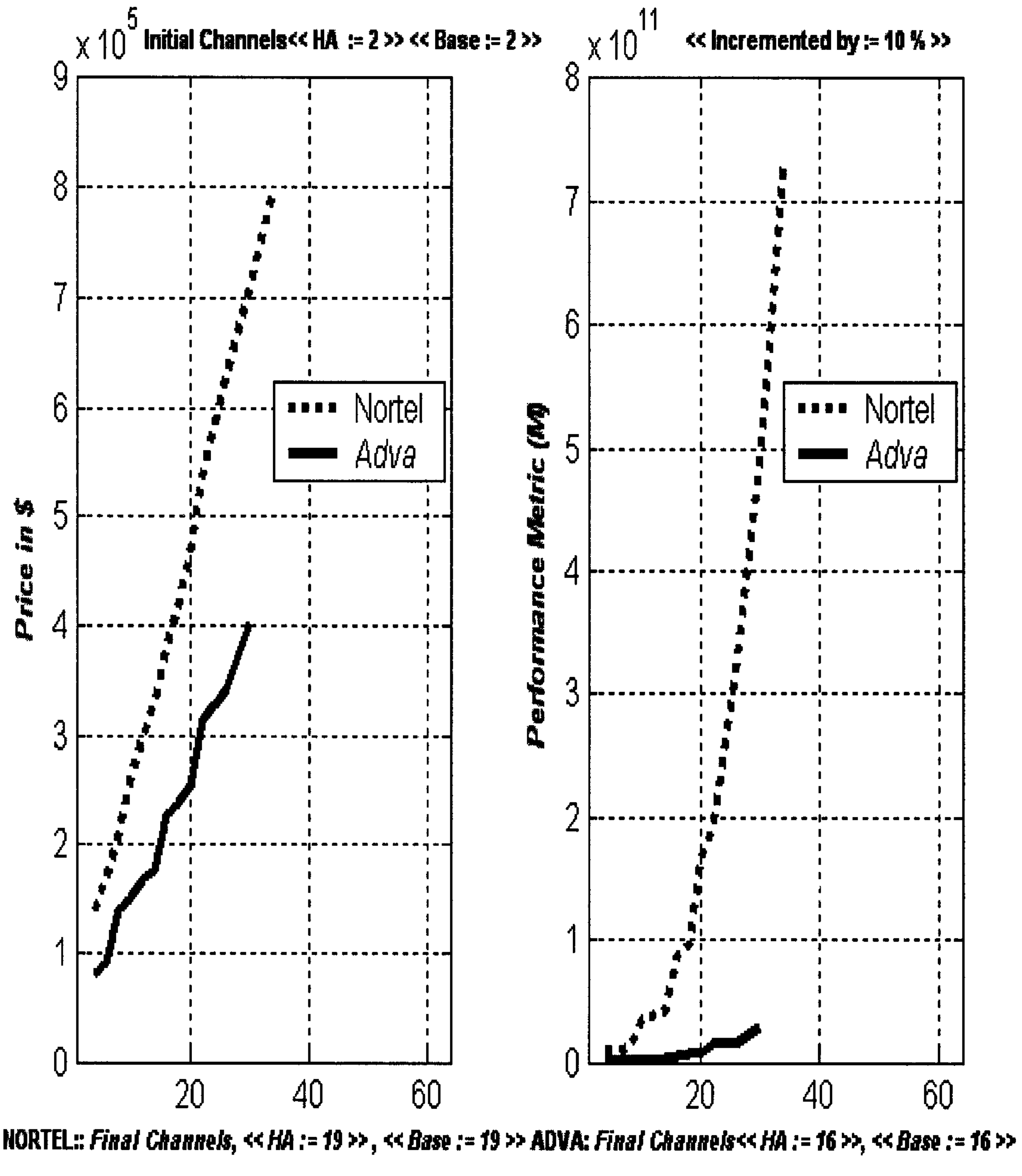


Figure 5.17 – scaling of an initial 2 channel configuration

CONCLUSIONS

The metropolitan optical networking environment includes a significant amount of dark fiber, for which wavelength based solutions had not been previously modeled. Using a matrix based approach; we have simulated several topologies using equipment designs from multiple vendors. These results have been validated against actual networks assembled at the IBM WDM testbed in Poughkeepsie NY. Then, our models can be used for the design and validation of new DWDM equipment before it is built.

FUTURE RESEARCH DIRECTIONS

Future extensions of this work are expected to incorporate OADM (Optical Add/Drop Multiplexers) for networks that will span over 50 km; thus include other penalties in a modular fashion to tackle the effects of nonlinearity. It will also include additional vendors and features such as wavelength reuse and the proposed MPLS protocols [26], [89].

GLOSSARY

ADM (Add/Drop Multiplexer): Digital multiplexing equipment that provides interfaces between different signals in a network.

Architecture: The specifications of a system and how its components interconnect; interact and cooperate.

ATM (Asynchronous Transfer Mode): A high speed multiplexing and switching method that uses fixed-length cells of 53 octets to support multiple types of traffic. As specified in international standards, ATM is asynchronous in the sense that cells carrying user data need not be periodic.

Attenuation: The decrease in signal strength in an optical fiber caused by absorption and scattering. Attenuation can be calculated to express: (1) *Signal loss between two points*; (2) *Total signal loss of a telecommunications system or segment.*

Backbone Network: A primary conduit for traffic that is often both coming from, and going to, other networks.

BER (Bit Error Rate): The ratio of the number of bit errors in the received signal to the total number of bits transmitted.

Brillouin Scattering: The scattering of photons (light) by acoustic phonons (sound waves). A special case of Raman scattering.

Channel: A communication path or the signal sent over that path by multiplexing several channels, voice channels can be transmitted over one optical channel.

Channel Assignment: Is a mapping of an OCI facility to either one (*unprotected*) or two (*protected*) OCLD facilities.

Chirp: A pulsed signal whose frequency lowers during the pulse.

Cladding: In fiber optic cable, a colored material with a low refractive index that surrounds the core and provides optical insulation and protection to the core.

Core: The light-conducting central portion of an optical fiber; composed of material with a higher refractive index than the cladding.

Cross-talk: The leaking of or interference between signal in two nearby pixels, wires, or fibers.

Dark Fiber: An inactive optical fiber; a fiber without connected transmitters, receivers, amplifiers, and so on.

DataCom (Data Communications): The transfer of digital or analog data using digital or analog signals.

Data Rate: The maximum number of bits of information that can be transmitted per second, as in a data transmission link, typically expressed in Mbps or Gbps.

Decibel (dB): A unit of measure indicating relative optical power on a logarithmic scale. It is often expressed to a fixed value, such as dBm (*1 milliwat*) or dBμ (*1 microwatt*).

Demultiplexing: The inverse of multiplexing; which consists on separating optical channels.

Dispersion: The broadening of input pulses as they travel the length of an optical fiber. There are three major types of dispersion: (1) *modal dispersion*, which is caused by the many optical path lengths in a multimode fiber; (2) *chromatic dispersion*, which is caused by the differential delay at various wavelengths in the optical fiber; (3) *wave-guide dispersion*, which is caused by light traveling through both the core and cladding materials in single-mode fibers.

Duplex SC: Two SC-type connectors that physically joined so they can be plugged or unplugged at the same time.

DWDM (Dense Wavelength Division Multiplexing): A type of multiplexing used with fiber optic systems that involves the transfer of multiple streams of data over a single optical fiber using multiple-colored laser transmitters.

E/O and O/E: Electrical to Optical and Optical to Electrical Conversion.

ESCON (Enterprise Systems Connection): A duplex optical connection used for computer-to-computer data exchange.

FA (Fiber Amplifier): An all-optical amplifier using erbium or other doped fibers and pump lasers to increase signal output power without electronic conversion.

FC (Fiber Channel): A technology for transmitting data between computer devices at a rate up to 1 Gbps.

Fiber Loss: The attenuation of the light signal in optical fiber transmission.

Fiber Optic Link: A combination of transmitter, receiver, and fiber-optic cable capable of transmitting data.

FICON: Fiber Channel Connection.

Frequency Agile: Capable of being easily adjusted over a range of operating frequencies.

GbE (Gigabit Ethernet): A LAN transmission standard that provides a data rate of 10^9 bits per second (Gbps).

Graded Index: A fiber with a refractive index that varies with radial distance from the center.

Hubbed Ring: Optical network architecture in which all data traffic flows through a single common location or hub.

Insertion Loss: Additional loss in a system when a device such as a connector is inserted, equal to the difference in signal level between the input and output.

Interface: A shared boundary between two functional units, defined by specific attributes, such as functional characteristics, common physical interconnection characteristics, and signal characteristics.

ITU (International Telecommunication Union) Grid: Standard wavelength designation. It is based on optical frequency with 100GHz spacing. The anchor optical frequency is 193.1THz, corresponding to 1552.52nm wavelength.

Legacy Product: A product an organization has already invested in, or has currently installed. New technology must be compatible with legacy products.

Light: Electromagnetic radiation visible to the human eye at 400nm to 700nm. The term is also applied to electromagnetic radiation with properties similar to visible light, including the invisible near-infrared radiation in most fiber optic communication systems.

LASER (Light Amplification by Stimulated Emission of Radiation): One of the wide ranges of device that generate light by that principle. Laser light is directional, covers a narrow range of wavelengths, and is more coherent than ordinary light. Semiconductor laser diodes are the standard light sources in fiber optic systems.

LED (Light-Emitting Diode): A semiconductor device that accepts electrical signals and converts the energy to a light signal with lasers. The main light source for optical transmission; used mainly with multimode fiber.

LAN (Local Area Network): A data communications network geographically limited to 1Km radius, allows easy interconnection of terminals, microprocessors, and computers within adjacent buildings. Most notable LAN topologies are Ethernet, token ring, and FDDI.

Link Loss Analysis: A calculation of all losses (attenuation) on a link.

MAN (Metropolitan Area Network): It consists of LANs interconnected within a radius of approximately 80Km (50mi). MANs typically use fiber optic cable to connect LANs.

Meshed Rings: Network topology in which any node may be connected to any other node

Metropolitan Area Network: Interconnected LANs with a radius of less than 80 Km.

Mode: An independent light path through and optical fiber.

Mode Partition Noise: Within a laser diode, the power distribution between different longitudinal modes will vary between pulses. Each mode is delayed by a different amount due to the chromatic dispersion and group velocity dispersion in the fiber, which causes pulse distortion.

MPLmS: Multi-protocol Lambda Switching.

MM Fiber (Multimode fiber): A fiber optic medium in which light travels in multiple modes. Typical core/cladding sizes are 50µm/125µm, 62.5µm/125µm and 100µm/140µm.

Multiplexer: A device that combines two or more signals into a single composite data stream for transmission on a single channel.

NZDSF (Non-Zero Dispersion Shifted Fiber): A type of optical fiber optimized for high bit-rate and dense wavelength division multiplexing.

OC (Optical Carrier): Series of physical protocols defined for SONET optical signal transmissions. OC signal levels put STS frames onto fiber optic line at a variety of speeds. The base rate is 51.84Mbps (OC-1); each signal level thereafter operates at a speed divisible by that number (thus, OC-3 runs at 155.52 Mbps).

Optical Channel: A wavelength band foı WDM optical communication.

OCI (Optical Channel Interface): The circuit card that interfaces with the customer equipment in an IBM 2029 network. A non-WDM card in the IBM 2029 node that provides an interface to the WDM fiber. Types of OCI cards are OC-3, OC-12, GEthernet, FDDI, etc.

OCLD (Optical Channel Laser and Detector): The optical channel transmitter and receiver circuit card that interfaces with the WDM ring through the OMX in an IBM 2029 network.

OCM (Optical Channel Manager): The circuit card that does protection switching for the IBM 2029 network.

Optical Fiber: A thing filament of glass that consists of a core and a cladding that is capable of carrying information in the form of light.

OMX (Optical Multiplexer): A module that does optical add/drop operations to the various IBM 2029 nodes.

Path: An end-to-end unidirectional connection from a source OCI to a destination OCI. There are separate paths for each direction; for working and protection.

Path Protection: It relates to the OCM card switching from one input to another to maintain traffic.

Protocol: The procedure used to control the orderly exchange of information between stations on a data link or on a data communications network or system. Protocols specify standards in three areas: ***the code set***, usually ASCII or EBCDIC; ***the transmission mode***, usually asynchronous or synchronous; and the ***non-data exchanges of information*** by which the two devices establish contact and control, detect failures or errors, and initiate corrective action.

Raman Scattering: Scattering of phonons (quanta of vibration). A special case of Brillouin scattering, which is when an acoustic phonon (sound wave) in involved.

Rx (Receiver): A terminal device that includes a detector and signal processing electronics. It functions as an optical-to-electrical converter.

Reflection: The abrupt change in direction of a light beam at an interface between two dissimilar media so the light beam returns into the media form which it originated.

Refractive Index: The ratio of the speed of light in a vacuum to the speed of light in a material at a given wavelength.

Reshaping: Removes pulse distortion caused by dispersion.

Ring Network: A network topology in which terminals are connected serially point-to-point in an unbroken circle.

Scalable: Is the ability to add power and capability to an existing system without significant expense or overhead.

SP (Shelf Processor): The circuit pack that provides alarm consolidation, software and configuration management, node visibility, and other features for the IBM 2029 system.

SM Fiber (Single Mode Fiber): An optical fiber that supports only one mode of light propagation above the cutoff wavelength. Core diameters are usually between 5μm to 10μm and claddings are usually ten times the core diameter. These fibers have a potential bandwidth of 50GHz to 100GHz per Kilometer.

SC (Subscriber Connector): A push-pull type of fiber optic connector with a square barrel.

SONET/SDH (Synchronous Optical Network/Digital Hierarchy): Interface standards for synchronous optical fiber transmission (USA/Europe).

Storage Area Network (SAN): A high speed network, or section of an enterprise network, of storage devices, for access by local area networks (LAN) and wide area networks (WAN).

TDM (Time Division Multiplexing): It is a digital multiplexing in which two or more apparently simultaneous channels are derived from a given frequency spectrum, i.e., bit stream, by interleaving pulse representing bits from different channels.

TeleCom (Telecommunications): The study of telephones and the systems that transmit telephone signals.

Topology: The physical layout of a network.

TX (Transmitter): A device that includes a LED or LASER source and signal conditioning electronics that is used to inject a signal into optical fiber.

APPENDIX

MODEL CODE LISTING

modelPoint2Point.m

```
% modelPoint2Point.m  by Aparicio Carranza
% Procedure for designing a Point to Point DWDM network
choice = 'Y'; clc;
while (choice == 'Y' | choice == 'y')% Looping to stop or continue <******.....
fprintf('Select Dense Wavelength Division Multiplexing (DWDM) Vendor:\n');
selectDWDM = input(' << Nortel = 1 >>, or << Adva = 2 >>: ');
if (selectDWDM == 1)
fprintf('\nNortel OPTera 5200 System Option\n');
% Fiber Type Selection
fprintf('Select a Fiber Type:\n');
selectFiber = input('<<1 =SM >>,<<2 =LEAF>>,<<3 =Custom>>: ');
switch(selectFiber)
case{1, 2, 3', } % Fiber Type Selection
if(selectFiber == 1) fprintf('<< Standard Single-Mode Fiber selected >>\n');
elseif(selectFiber == 2) fprintf('<< Leaf Single-Mode Fiber Selected >>\n');
else fprintf('Custom Made Fiber Selected \n'); end
% Number of Sites, Topology Selection
numberOfSites = 2;
fprintf('\n<==== Simple Point2Point or GDPS Topology Support ====>\n');
hubToRemoteDistance = input('distance: Hub-to-Remote in Kilometers (Km): ');
dualFiberSwitch = input(' Will you use DFS in your Design (Y/N) ?: ','s');
switch(dualFiberSwitch)  %< DFS SELECTION ***....
case{'N','n'} % <No DFS Used case begins *****......
if(hubToRemoteDistance > 50.0)
fprintf('Hub2Remote dist. %4.2f Km out of Specs\n', hubToRemoteDistance);
elseif(hubToRemoteDistance >= 0.00 & hubToRemoteDistance <= 50.00)
fprintf('Hub2Remote dist. %4.2f Km within Specs & no DFS maxDist = 50
Km. \n',hubToRemoteDistance);
numberFiberPair = input('<< Fiber pairs: << 1 >> or << 2 >> pairs? >>: ');
switch(numberFiberPair)
case(1)
fprintf('<< %d pair of fibers chosen >>',numberFiberPair);
fprintf('\nNo HA (1+1) protection configuration is possible\n');
fprintf('Only Base (Unprotected) configuration possible\n');
fprintf(' Please enter the following information below: \n');
```

```
[baseEscon,baseFicon,baseEtr,baseClo,baseIsc,baseGbEth,baseAtm] = baseChannels;
% NumberShelvesBase() function call
[baseCards4TDMEscon, baseCards4TDMAtm, totalOCIBaseChannels, numberOfShelves] = ...
NumberShelvesBase(baseEscon,baseFicon,baseEtr,baseClo,baseIsc,baseGbEth,baseAtm);
fprintf('This Config. requires <<%d>> shelves at each site\n',ceil(numberOfShelves));
case(2)
fprintf('<< %d pair of fibers chosen >>',numberFiberPair);
fprintf('\n HA (1+1) and Base configuration protection is possible\n');
fprintf('In this case Line and Path protection is supported\n');
fprintf(' Please enter the following information below: \n');
 [highAvEscon,highAvFicon,highAvEtr,highAvClo,highAvIsc,highAvGbEth,highAvAtm] =
...  highAvChannels;
 [baseEscon, baseFicon, baseEtr, baseClo, baseIsc, baseGbEth, baseAtm] = baseChannels;
% NumberShelvesBaseHigh() function call
[baseCards4TDMEscon, baseCards4TDMAtm, totalOCIBaseChannels,
highAvCards4TDMEscon, ...
    highAvCards4TDMAtm, totalOCIHighAvChannels, numberOfShelves] = ...
    NumberShelvesBaseHigh(baseEscon, baseFicon, baseEtr, baseClo, baseIsc,baseGbEth,...
  baseAtm,highAvEscon,highAvFicon,highAvEtr,highAvClo,highAvIsc,highAvGbEth,
highAvAtm);
fprintf('This Config. requires << %d >> shelves at each site\n',ceil(numberOfShelves));
otherwise
fprintf('<< %d pair of fibers chosen, not supported >>\n',numberFiberPair);
end
end % No DFS Used case ends ******>
case{'Y','y'} % < When DFS Used case begins *******...
if(hubToRemoteDistance > 40.0)
fprintf('Hub2Remote dist. %4.2f Km out of Specs when DFS used, maxDistance = 40 Km. \n',
hubToRemoteDistance); fprintf('         Need to Redesign\n');
elseif(hubToRemoteDistance >= 0.00 & hubToRemoteDistance <= 40.00)
fprintf('Hub2Remote dist. of %4.2f Km within Specs with DFS\n',hubToRemoteDistance);
numberFiberPair = input('<< Fiber pairs: << 2 >> or << 4 >> pairs? >>: ');
switch(numberFiberPair)
case{2,4}
fprintf('<< 2 pairs provide Half Path Protection \n');
fprintf('   4 pairs provide Full Path Protection >>\n');
fprintf('<< %d pair of fibers chosen >>',numberFiberPair);
fprintf('\nNo HA (1+1) protection configuration is possible when DFS is used\n');
fprintf('Only Base (Unprotected) configuration possible\n');
fprintf(' Please enter the following information below: \n');
 [baseEscon, baseFicon, baseEtr, baseClo, baseIsc, baseGbEth, baseAtm] = baseChannels;
[baseCards4TDMEscon, baseCards4TDMAtm, totalOCIBaseChannels, numberOfShelves] = ...
```

```
NumberShelvesBase(baseEscon, baseFicon, baseEtr, baseClo, baseIsc, baseGbEth,baseAtm);
fprintf('This Config. requires << %d >> shelves at each site\n',ceil(numberOfShelves));
otherwise fprintf('<< %d pair of fibers chosen, not supported >>\n',numberFiberPair);
end; end % When DFS Used case ends ******>
otherwise
fprintf('press Y, y, N or n for choosing DFS, you pressed %c\n',dualFiberSwitch);
end % DFS SELECTION ***>
end
elseif (selectDWDM == 2)
fprintf('\nAdva FSP 2000 System Option\n');
else % Future Support selection
fprintf('\nNot supported yet at this time \n\n');   end
choice = input('Do you want to continue? (Y/N) : ', 's'); clc;
end
```

baseChannels.m

```
function [baseEscon,baseFicon,baseEtr,baseClo,baseIsc,baseGbEth,baseAtm] = baseChannels()
% By Aparicio Carranza
% Function that will allow to enter the number of base channels
% for each protocols
  baseEscon = input('Number of Base ESCON      channels : ');
  baseFicon = input('Number of Base FICON      channels : ');
  baseEtr   = input('Number of Base ETR        channels : ');
  baseClo   = input('Number of Base CLO        channels : ');
  baseIsc   = input('Number of Base ISC        channels : ');
  baseGbEth = input('Number of Base GbEthernet channels : ');
  baseAtm   = input('Number of Base ATM        channels : ');
```

highAvChannels.m

```
function
[highAvEscon,highAvFicon,highAvEtr,highAvClo,highAvIsc,highAvGbEth,highAvAtm]=...
  highAvChannels()
% By Aparicio Carranza
% Function that will allow to enter the number of HA (1 + 1) protection channels
% for each protocols
  highAvEscon = input('Number of High Avaible ESCON      channels : ');
  highAvFicon = input('Number of High Avaible FICON      channels : ');
  highAvEtr   = input('Number of High Avaible ETR        channels : ');
  highAvClo   = input('Number of High Avaible CLO        channels : ');
  highAvIsc   = input('Number of High Avaible ISC        channels : ');
  highAvGbEth = input('Number of High Avaible GbEthernet channels : ');
  highAvAtm   = input('Number of High Avaible ATM        channels : ');
```

numberShelvesBase.m

```
function
[baseCards4TDMEscon,baseCards4TDMAtm,totalOCIBaseChannels,numberOfShelves] = ...
   NumberShelvesBase(baseEscon,baseFicon,baseEtr,baseClo,baseIsc,baseGbEth,baseAtm)
% By Aparicio Carranza
% function to calculate the number of shelves when only base or unprotected
% configuration is considered.
baseCards4TDMEscon = baseEscon / 4;
baseCards4TDMAtm   = baseAtm / 4;
totalOCIBaseChannels = baseCards4TDMEscon + baseFicon + baseEtr + baseClo +...
   baseIsc + baseGbEth + baseCards4TDMAtm;
numberOfShelves = totalOCIBaseChannels / 8;
```

numberShelvesHigh.m

```
function
[highAvCards4TDMEscon,highAvCards4TDMAtm,totalOCIHighAvChannels,numberOfShel
ves]= NumberShelvesHigh(highAvEscon,highAvFicon,highAvEtr,highAvClo,highAvIsc,...
   highAvGbEth, highAvAtm)
% By Aparicio Carranza
% function to calculate the number of shelves when
% high availability (1+1) configuration are considered.
highAvCards4TDMEscon = highAvEscon / 4;
highAvCards4TDMAtm = highAvAtm / 4;
totalOCIHighAvChannels = 2*(highAvCards4TDMEscon + highAvFicon + highAvEtr + ...
   highAvClo + highAvIsc + highAvGbEth + highAvCards4TDMAtm);
numberOfShelves = totalOCIHighAvChannels / 8;
```

numberShelvesBaseHigh.m

```
function
[baseCards4TDMEscon,baseCards4TDMAtm,totalOCIBaseChannels,highAvCards4TDMEscon
,highAvCards4TDMAtm, totalOCIHighAvChannels, numberOfShelves] =
NumberShelvesBaseHigh(baseEscon,baseFicon,baseEtr,baseClo,baseIsc,baseGbEth,
baseAtm,highAvEscon,highAvFicon,highAvEtr,highAvClo,highAvIsc,highAvGbEth,highAv
Atm)
% By Aparicio Carranza
% function to calculate the number of shelves when base (unprotected) and
% high availability (1+1) configuration are considered.
baseCards4TDMEscon = baseEscon / 4;
baseCards4TDMAtm   = baseAtm / 4;
totalOCIBaseChannels = baseCards4TDMEscon + baseFicon + baseEtr + baseClo + baseIsc + ...
   baseGbEth + baseCards4TDMAtm;
```

```
highAvCards4TDMEscon = highAvEscon / 4;
highAvCards4TDMAtm = highAvAtm / 4;
totalOCIHighAvChannels = 2*(highAvCards4TDMEscon + highAvFicon + highAvEtr + ...
   highAvClo + highAvIsc + highAvGbEth + highAvCards4TDMAtm);
numberOfShelves = (totalOCIBaseChannels + totalOCIHighAvChannels) / 8;
```

modelLinkBudget.m

```
% modelLinkBudget.m
% Procedure to calculate the link budget margin
% Created by Aparicio Carranza
%
hubToRemoteDistance = input('distance : ');
N = input('Number of wavelengths : ');
selectFiber = input('enter either 1, 2 or 3 to select Fiber type (SM) (LEAF) (MM): ');
selectDWDM = 'adva  ';
distance = hubToRemoteDistance;  cableDistance = 0:8:distance;
Q = input('Enter value of Q : ');
amplification = input('Enter the amplifier gain in (+dB) : ');
amp = amplification*ones(size(cableDistance));
%N = totalProtocols;
%
lossPerKmSM = -0.3;  lossPerKmLEAF = -0.2; lossPerKmMM = -0.5;
if (selectFiber == 1) lossPerKm = lossPerKmSM;
elseif (selectFiber == 2) lossPerKm = lossPerKmLEAF;
elseif (selectFiber == 3) lossPerKm = lossPerKmMM;
else lossPerKm = input('Please Enter a fiber loss per KM in dB: ');
end
totalFiberLoss = cableDistance * lossPerKm;
% Connector Loss
connectorLoss = -0.5; numbOfConectors = ceil(cableDistance/2);
totalConnectorLoss = connectorLoss * numbOfConectors;
% Splice Loss
spliceLoss = -0.1; numbOfSplices = ceil(cableDistance/4);
totalSpliceLoss = spliceLoss * numbOfSplices;
% Electronics Specifications
powerTxOutput  = 0.5;  minRxSensitivity = -38.0;
%
% Segment to load from file the 32 wavelengths
format long g
load advaData.dat;
lambda = advaData(:,2);
b = input('Please enter the Bit Rate in Mbps : ');
```

```
clf; i = 1;
while (i <= N)
 %*************************************************************************
 % Dispersion and Dispersion Penalty
 S0 = 0.095e-12; lambda0 = 1540; dLambda = 1.7; B = b*10^6;
 disper = (S0/4)*(lambda(i) - (lambda0^4)*(lambda(i)^-3));
 disperPenalty = 5*log10(1 + 2*pi*(disper^2*(B*dLambda)^2)*cableDistance.^2);
 %*************************************************************************
 % Mode Partition Variance and Mode Partition Penalty
 k = 0.5; A1 = disper*cableDistance; A2 = A1/(2*(lambda(i) - lambda0));
 sigmaMPSqr = 0.5*k^2*(pi*B)^4*((A1.^4)*(dLambda)^4 + 42*(A1.*A2).^2*(dLambda)^6 +
48*(A2.^4)*(dLambda)^8);
 modePartitionPenalty = 5*log10(1 - (Q^2)*(sigmaMPSqr));
 %*************************************************************************
 % Modal Noise Splice Standard Deviation and Modal Noise Splice Penalty
 L = 2; eta0 = 0.91; a = 0.01; spliceTxEff = 10^(-eta0/10);
 sigmaM = sqrt(2)*numbOfSplices*spliceTxEff*(1-spliceTxEff)*exp(-a*L);
 modNoiseSplicePenalty = -5*log10(1 - (Q^2)*(sigmaM.^2));
 %*************************************************************************
 % Reflection Induced Intensity Penalty
 QRin = Q; BW = 1e9; g  = 0.5; M = 2; RIN = -112;
 RINPenalty = -5*log10(1 - (QRin.^2)*BW*((1 + M)^(2*g))*(10^(RIN/10))*(1/M)^2);
 %=========================================================================
 % Total power Penalties (use the equations)
 powerPenalties = (disperPenalty + modePartitionPenalty + modNoiseSplicePenalty +
RINPenalty);
 repairMargin   = -0.3; totalPPenalty = powerPenalties + repairMargin;
 % Relationships to for our plotting
 cableAttenuation = totalFiberLoss + totalConnectorLoss + totalSpliceLoss;
 LinkBudget = (powerTxOutput - minRxSensitivity) - totalPPenalty;
 systemPerformance = LinkBudget - abs(cableAttenuation) + amp;
 switch(i)
 case{1,2,3,4}
    subplot(2,2,i);
   if (i == 1)
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'k:','linewidth'
,2)
 elseif (i == 2)
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'k:','linewidth'
,2)
   elseif (i == 3)
```

```
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'k:','linewidth'
,2)
  else
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'k:','linewidth'
,2)
    title(['\fontname{helvetica}\fontsize{9}\bfSystem Performance ','\lambda(',num2str(i),') =
',num2str(lambda(i)),'nm'])
    ylabel('\fontname{helvetica}\fontsize{10}\bfPower in dB');
xlabel('\fontname{helvetica}\fontsize{9}\itDistance in Kilometers')
    legend('\fontname{helvetica}\fontsize{9}\itCable
Attenuation','\fontname{helvetica}\fontsize{9}\itPerformance Margin ',0); axis([0 distance 0
50]); grid
    figure
  end
 % Other sections of code goes here  .....
 %
 otherwise
    subplot(2,2,i-28)
  if (i == 29)
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'r','linewidth',
2)
  elseif (i == 30)
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'g','linewidth',
2)
  elseif (i == 31)
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'b','linewidth',
2)
  else
plot(cableDistance,abs(cableAttenuation),'k',cableDistance,systemPerformance,'m','linewidth'
,2)
  end
 end
 title(['\fontname{helvetica}\fontsize{9}\bfSystem Performance ','\lambda(',num2str(i),') =
',num2str(lambda(i)),'nm'])
 ylabel('\fontname{helvetica}\fontsize{10}\bfPower in dB');
xlabel('\fontname{helvetica}\fontsize{9}\itDistance in Kilometers')
  legend('\fontname{helvetica}\fontsize{9}\itCable
Attenuation','\fontname{helvetica}\fontsize{9}\itPerformance Margin ',0); axis([0 distance 0
50]); grid
 pause(0.5)
 i = i + 1;
```

```
hold on
end
grid on
```

modelShelvesNortel.m

```
% modelShelvesNortel.m
% By Aparicio Carranza
% This procedure allows the assignment of channels for the following protocols:
% ESCON, FICON, ETR, CLO, ISC, GbitEthernet, & ATM when Nortel DWDM box is used.
% The user will enter the number of channels as unprotected & protected modes,
% then it will perform the appropriate computation to fill the shelves with
% corresponding cards based on each protocol according to the number of channels
% that was input. The ouptut will be the shelves in High (1 + 1) & base (unprotected)
% channel configurations; the user will view the number of slots still available.
% ======================================================================
clear; clc;
shelvesEH = zeros(10,5); shelvesWH = zeros(10,5);
shelvesEWb = zeros(10,10);
format long g
% Base (unprotected) Channels assignment
baseEscon = input('Enter Number of base ESCON Channels : ');
baseFicon = input('Enter Number of base FICON Channels : ');
baseEtr   = input('Enter Number of base ETR   Channels : ');
baseClo   = input('Enter Number of base CLO   Channels : ');
baseIsc   = input('Enter Number of base ISC   Channels : ');
baseGbEth = input('Enter Number of base GbEth Channels : ');
baseAtm   = input('Enter Number of base ATM   Channels : ');
% High (1 + 1) Available Channels assignment
highAvEscon = input('Enter Number of HA ESCON Channels : ');
highAvFicon = input('Enter Number of HA FICON Channels : ');
highAvEtr   = input('Enter Number of HA ETR   Channels : ');
highAvClo   = input('Enter Number of HA CLO   Channels : ');
highAvIsc   = input('Enter Number of HA ISC   Channels : ');
highAvGbEth = input('Enter Number of HA GbEth Channels : ');
highAvAtm   = input('Enter Number of HA Atm   Channels : ');
baseCards4TDMEscon = ceil(baseEscon/4); baseCards4TDMAtm   = ceil(baseAtm/4);
highAvCards4TDMEscon = 2*ceil(highAvEscon/4); highAvCards4TDMAtm =
2*ceil(highAvAtm/4);
totalBaseChannels = ceil(baseEscon/4) + baseFicon + baseEtr + baseClo + ...
   baseIsc + baseGbEth + ceil(baseAtm/4);
totalOCI_HA = 2*(ceil(highAvEscon/4) + highAvFicon + highAvEtr + ...
   highAvClo + highAvIsc + highAvGbEth + ceil(highAvAtm/4));
```

```
totalHighAvChannels = totalOCI_HA/2;
totalB = totalBaseChannels; totalHA = totalHighAvChannels;
totalShelves = ceil((totalOCI_HA + totalBaseChannels)/8);
if (totalShelves <= 8)
for i = 1:8;
   for j = 1:4;
      if (totalHA > 0 )
         shelvesEH(i,j) = 2;
         shelvesWH(i,j) = 2;
         totalHA = totalHA -1;
      end
   end
end
for i = 1:8;
   for j = 1:8;
      if (totalB > 0)
         if (shelvesEWb(i,j) == 0)
            shelvesEWb(i,j) = 1;
         end
         totalB = totalB -1;
      end
   end
end
slotsAvailableNortel = 64 - (totalOCI_HA + totalBaseChannels);
shelvesEWH = [shelvesEH shelvesWH];
[x,y] = meshgrid([1 :1:10]);
subplot(1,2,1)
mesh(x,y,shelvesEWH,'linewidth',12)
title(['\fontname{helvetica}\fontsize{10}\bf << High (1+1) protected Channels:=
',num2str(totalHighAvChannels),' >>']);
axis([0.85 9.1 1 8.9]); axis off
text(-2,0.7,['\fontname{helvetica}\fontsize{9}\bf Slots Available:=
',num2str(slotsAvailableNortel), ', Maximum = 64, ']);
subplot(1,2,2)
mesh(x,y,shelvesEWb,'linewidth',12)
title(['\fontname{helvetica}\fontsize{10}\bf << Base (Unprotected) Channels :=
',num2str(totalBaseChannels),' >>']);
axis([0.85 8.1 1 8.9]); axis off
text(-3.2,0.7,['\fontname{helvetica}\fontsize{9}\bf &  << ', num2str(totalShelves),...
   ' >> Shelves Required, for High & Base Channels ']);
figure
if (mod(baseEscon,4) == 0) emptyBaseEscon = 0;
```

```
else emptyBaseEscon = 4 - mod(baseEscon,4);
end
if (mod(baseAtm,4) == 0) emptyBaseAtm = 0;
else   emptyBaseAtm = 4 - mod(baseAtm,4);
end
if (mod(highAvEscon,4) == 0) emptyHighAvEscon = 0;
else emptyHighAvEscon = 4 - mod(highAvEscon,4);
end
if (mod(highAvAtm,4) == 0) emptyHighAvAtm = 0;
else emptyHighAvAtm = 4 - mod(highAvAtm,4);
end
highAvFiconCards = 2*highAvFicon; highAvEtrCards = 2*highAvEtr;
highAvCloCards = 2*highAvClo; highAvIscCards = 2*highAvIsc;
highAvGbEthCards = 2*highAvGbEth;
subplot(1,2,1)
title('\fontname{helvetica}\fontsize{10}\bf << High (1+1) Available Channels >>');
axis([0.85 9.1 1 8.9]); axis off
text(-2,8.5,['\fontname{helvetica}\fontsize{9}\bf Number of HA Channels :=
',num2str(totalHighAvChannels),' ']);
text(-1.5,8,['\fontname{helvetica}\fontsize{9}\bf 4TDMEscon  Cards :=
',num2str(highAvCards4TDMEscon),' ']);
text(-1.9,7.5,[' \fontname{helvetica}\fontsize{9}\it Empty 4TDMEscon slots :=
',num2str(emptyHighAvEscon),' for East & ',...
      num2str(emptyHighAvEscon),' for West ']);
text(-1,7,['\fontname{helvetica}\fontsize{9}\bf FICON     Cards :=
',num2str(highAvFiconCards),' ']);
text(-1,6,['\fontname{helvetica}\fontsize{9}\bf ETR   Cards :=  ',num2str(highAvEtrCards),' ']);
text(-1,5,['\fontname{helvetica}\fontsize{9}\bf CLO  Cards :=  ',num2str(highAvCloCards),' ']);
text(-1,4,['\fontname{helvetica}\fontsize{9}\bf ISC    Cards :=  ',num2str(highAvIscCards),' ']);
text(-1,3,['\fontname{helvetica}\fontsize{9}\bf GBit ETH   Cards :=
',num2str(highAvGbEthCards),' ']);
text(-1,2,['\fontname{helvetica}\fontsize{9}\bf 4TDM\itATM   Cards:=
',num2str(highAvCards4TDMAtm),' ']);
text(-1.9,1.5,['\fontname{helvetica}\fontsize{9}\it Empty 4TDM\itATM slots :=
',num2str(emptyHighAvAtm),' for East & ', num2str(emptyHighAvAtm),' for West ']);
text(-1,0.5,['\fontname{helvetica}\fontsize{9}\bf Total of  <<  ', num2str(totalShelves),...
   ' >> Shelves Required, for High (1+1) & Base (unprotected) Channels']);
subplot(1,2,2)
title('\fontname{helvetica}\fontsize{10}\bf << Base (Unprotected) Channels >>');
axis([0.85 8.1 1 8.9]); axis off
text(2,8.5,['\fontname{helvetica}\fontsize{9}\bf Number of Base Channels :=
',num2str(totalBaseChannels),' ']);
```

```
text(2.5,8,['\fontname{helvetica}\fontsize{9}\bf 4TDM\itEscon  Cards :=
',num2str(baseCards4TDMEscon),' ']);
text(3,7.5,['\fontname{helvetica}\fontsize{9}\it  Empty 4TDM\itEscon slots :=
',num2str(emptyBaseEscon),' ']);
text(2.5,6.8,['\fontname{helvetica}\fontsize{9}\bf FICON  Cards :=  ',num2str(baseFicon),' ']);
text(2.5,6,['\fontname{helvetica}\fontsize{9}\bf ETR        Cards :=  ',num2str(baseEtr),' ']);
text(2.5,5,['\fontname{helvetica}\fontsize{9}\bf CLO        Cards :=  ',num2str(baseClo),' ']);
text(2.5,4,['\fontname{helvetica}\fontsize{9}\bf ISC        Cards :=  ',num2str(baseIsc),' ']);
text(2.5,3,['\fontname{helvetica}\fontsize{9}\bf GBit ETH Cards :=  ',num2str(baseGbEth),' ']);
text(2.5,2,['\fontname{helvetica}\fontsize{9}\bf 4TDM\itATM   Cards:=
',num2str(baseCards4TDMAtm),' ']);
text(3,1.5,['\fontname{helvetica}\fontsize{9}\it Empty 4TDM\itATM slots :=
',num2str(emptyBaseAtm),' ']);
else
 fprintf('Maximum # of Shelves := 8, Current # of << %d >> Shelves exceed Availability
option\n',totalShelves);
end
```

modelShelvesCostNortel.m

```
% modelShelvesCostNortel.m
% By Aparicio Carranza
% Procedure to determine cost and performace plotting of a sytstem
% using the Nortel DWDM System
%======================================================================
clear; clc;
priceShelf = 25000; priceOCI_Card = 5000; priceOCLD_Card = priceOCI_Card;
priceCPU_Card = 4000; pricePowerCard = 2000; priceMUX_Card = 10000;
powerPerShelf = 750; sizeShelf = 19;
n = 1;
totalHighAvChannels = input('Enter Number of High Availability Channels ( <= 32 ): ');
totalBaseChannels   = input('Enter Number of Base Availability Channels ( <= 64 ): ');
incrCh = input('Enter the  Percentage Channel Increment: ');
totalOCI_HA = 2 * totalHighAvChannels; totalOCI_BA = totalBaseChannels;
totalHighBaseChannels = totalHighAvChannels + totalBaseChannels;
HaBaOCI = 2*totalHighAvChannels + totalBaseChannels;
totalShelves = ceil(HaBaOCI/8); w = totalHighAvChannels + totalBaseChannels;
if ((HaBaOCI >= 65) | (totalHighAvChannels >= 33) | (totalBaseChannels >= 65) | ...
       (totalHighBaseChannels >= 65) | (totalShelves > 8))
 fprintf('<<< Not possible to Design, out of specifications >>>\n');
elseif(((totalHighAvChannels <= 32) | (totalBaseChannels <= 64) | (w <= 64)))% | n == 1)
 %Calculation for extremes case  begins
 powerTotal = powerPerShelf * totalShelves; sizeTotal = sizeShelf * totalShelves;
```

```
costOCI = priceOCI_Card*HaBaOCI;   costOCLD = priceOCLD_Card*HaBaOCI;
costCPU = priceCPU_Card*(totalShelves*2);  costPCard = pricePowerCard*totalShelves;
costMUX = priceMUX_Card*ceil(HaBaOCI/4);
costShelves = costOCI + costOCLD + costCPU + costPCard + costMUX;
perfMetricM = (costShelves * sizeTotal * powerTotal);
if ((totalHighAvChannels == 32) | (totalBaseChannels == 64) | (w == 64))
  CS(n) = costShelves; PM(n) = perfMetricM; HBC(n) = totalHighBaseChannels;
   subplot(1,2,1)
  plot(HBC,CS,'r*','linewidth',3); hold on;
  title(['\bf\it                    << Initial HA Channels :=  ',num2str(totalOCI_HA/2),' >> ',...
       '\bf\it<< Incremented by := ',num2str(incrCh),'%> >']);
  ylabel('\bf\itPrice in $'); axis([1 64 0 9e5]); grid on;
  xlabel(['\bf\it<< HA Channels := ',num2str(totalHighAvChannels),' >>',...
       '\bf\it<< Base Channels := ',num2str(totalBaseChannels),' >>']);
  subplot(1,2,2)
  plot(HBC,PM,'r*','linewidth',3); hold on; grid on;
  title(['\bf\it<< Initial Base Channels := ',num2str(totalOCI_BA),' >>']);
  axis([1 64 0 9e11])
  xlabel(['\bf\it<< HA Channels := ',num2str(totalHighAvChannels),' >>',...
       '\bf\it<< Base Channels := ',num2str(totalBaseChannels),' >>']);
  ylabel('\bfPerformance Metric');
end
% Extremes case ends
 while ((HaBaOCI < 64) & (totalHighAvChannels < 32) & (totalBaseChannels < 64) & ...
        (totalHighBaseChannels < 64) & (totalShelves < 8))
  totalHighAvChannels  = totalHighAvChannels + ceil(totalHighAvChannels*incrCh/100);
  totalBaseChannels = totalBaseChannels + ceil(totalBaseChannels*incrCh/100);
  HaBaOCI = 2*totalHighAvChannels + totalBaseChannels;
  totalShelves = ceil(HaBaOCI/8);
  powerTotal = powerPerShelf * totalShelves;
  sizeTotal = sizeShelf * totalShelves;
  costOCI = priceOCI_Card*HaBaOCI;
  costOCLD = priceOCLD_Card*HaBaOCI;
  costCPU = priceCPU_Card*(totalShelves*2);
  costPCard = pricePowerCard*totalShelves;
  costMUX = priceMUX_Card*ceil(HaBaOCI/4);
  costShelves = costOCI + costOCLD + costCPU + costPCard + costMUX;
  perfMetricM = (costShelves * sizeTotal * powerTotal);
  CS(n) = costShelves; PM(n) = perfMetricM;
  HBC(n) = totalHighBaseChannels;
  n = n + 1;
  totalHighBaseChannels = totalHighAvChannels + totalBaseChannels;
```

```
end
 %subplot(1,2,1)
 plot(HBC,CS,'k','linewidth',3); hold on;
 title(['\fontname{helvetica}\fontsize{9}\bf Initial Channels << HA :=
 ',num2str(totalOCI_HA/2), ' >> ',' << Base := ',num2str(totalOCI_BA),' >>','<< Incr := '...
       ,num2str(incrCh),' % >>']);
 ylabel('\fontname{helvetica}\fontsize{9}\bf\itPrice in $'); axis([1 64 0 9e5]); grid on;
 xlabel(['\fontname{helvetica}\fontsize{9}\bfNORTEL :: Final Channels << HA :=
 ',num2str(totalHighAvChannels),' >>', '<< Base := ',num2str(totalBaseChannels),'>>']); hold on
 %subplot(1,2,2)
 figure
 plot(HBC,PM,'k','linewidth',3); hold on; grid on;
 title(['\fontname{helvetica}\fontsize{9}\bfInitial Channels << HA :=
 ',num2str(totalOCI_HA/2),' >> ',' << Base := ',num2str(totalOCI_BA),' >>','<< Incr := '...
       ,num2str(incrCh),' % >>']);
 axis([1 64 0 9e11])
 xlabel(['\fontname{helvetica}\fontsize{9}\bfNORTEL:: Final Channels << HA :=
 ',num2str(totalHighAvChannels),' >>',' << Base := ',num2str(totalBaseChannels),' >>']);
 ylabel('\fontname{helvetica}\fontsize{9}\bfPerformance Metric');
 end
```

modelMeshTopology.m

```
% modelMeshTopology.m
% Procedure to work with mesh configuration
% By Aparicio Carranza
%
clear; clc;
numberOfSites = input('How Many Site Locations? : ');
if(numberOfSites <= 1 | numberOfSites > 9)
 fprintf('Number of Sites supported Minimun = 2, Maximum = 9\n');
 fprintf('Number Of Sites You Entered = %d\n',numberOfSites);
elseif(numberOfSites >= 2 & numberOfSites <=9)
fprintf('You have chosen %d sites, then your design is feasible,\n',numberOfSites);
selectTopology = 4;
end
if(numberOfSites > 2 & numberOfSites <= 9 & selectTopology == 4)
fprintf('Mesh Ring Topology with << %d >> Sites selected\n',numberOfSites);
 for i = 1:numberOfSites;
   for j = 1:numberOfSites;
     if(i == j)
       s(i,j) = 0;
     end
```

```
    if((j == i + 1) & (j <= numberOfSites))
      fprintf('Enter Distance from << %d_%d ',i, j); s(i,j) = input('>> in Kilometers (Km) : ');
    end;   end; end;
fprintf('Enter Distance from << 1_%d ',i); s(1,i) = input('>> in Kilometers (Km) : ');
ringMax = 100;
switch (numberOfSites)
case(7)
  s(1,3) = s(1,2) + s(2,3);  s(1,4) = s(1,3) + s(3,4);  s(1,5) = s(1,4) + s(4,5);  s(1,6) = s(1,5) + s(5,6);
  s(2,4) = s(2,3) + s(3,4);  s(2,5) = s(2,4) + s(4,5);  s(2,6) = s(2,5) + s(5,6);  s(2,7) = s(2,6) + s(6,7);
  s(3,5) = s(3,4) + s(4,5);  s(3,6) = s(3,5) + s(5,6);  s(3,7) = s(3,6) + s(6,7);
  s(4,6) = s(4,5) + s(5,6);  s(4,7) = s(4,6) + s(6,7);  s(5,7) = s(5,6) + s(6,7);  s(2,1) = s(1,7) + s(2,7);
  s(3,1) = s(1,7) + s(3,7);  s(3,2) = s(1,2) + s(3,1);  s(4,1) = s(1,7) + s(4,7);  s(4,2) = s(1,2) + s(4,1);
  s(4,3) = s(2,3) + s(4,2);  s(5,1) = s(1,7) + s(5,7);  s(5,2) = s(1,2) + s(5,1);  s(5,3) = s(2,3) + s(5,2);
  s(5,4) = s(3,4) + s(5,3);  s(6,1) = s(1,7) + s(6,7);  s(6,2) = s(1,2) + s(6,1);  s(6,3) = s(2,3) + s(6,2);
           s(6,4) = s(3,4) + s(6,3);  s(6,5) = s(4,5) + s(6,4);
  s(7,1) = s(1,6) + s(6,7);  s(7,2) = s(1,2) + s(1,7);  s(7,3) = s(2,3) + s(7,2);  ....
           s(7,4) = s(3,4) + s(7,3);  s(7,5) = s(4,5) + s(7,4);  s(7,6) = s(5,6) + s(7,5);
  d12 = max(s(1,2),s(2,1));  d13 = max(s(1,3),s(3,1));  d14 = max(s(1,4),s(4,1));
           d15 = max(s(1,5),s(5,1));
  d16 = max(s(1,6),s(6,1));  d17 = max(s(1,7),s(7,1));
  d23 = max(s(2,3),s(3,2));  d24 = max(s(2,4),s(4,2));  d25 = max(s(2,5),s(5,2));  ...
           d26 = max(s(2,6),s(6,2));  d27 = max(s(2,7),s(7,2));
  d34 = max(s(3,4),s(4,3));  d35 = max(s(3,5),s(5,3));  d36 = max(s(3,6),s(6,3));  ...
           d37 = max(s(3,7),s(7,3));
  d45 = max(s(4,5),s(5,4));  d46 = max(s(4,6),s(6,4));  d47 = max(s(4,7),s(7,4));
  d56 = max(s(5,6),s(6,5));  d57 = max(s(5,7),s(7,5));  d67 = max(s(6,7),s(7,6));
  if(d12 > ringMax | d13 > ringMax | d14 > ringMax | d15 > ringMax | d16 > ringMax | d17 >
  ringMax |  d23 > ringMax | d24 > ringMax | d25 > ringMax | d26 > ringMax | d27 > ringMax |
       d34 > ringMax | d35 > ringMax | d36 > ringMax | d37 > ringMax | d45 > ringMax |
       d46 > ringMax | d47 > ringMax | d56 > ringMax | d57 > ringMax | d67 > ringMax)
    fprintf(' CW_Distance or CCW_Distance fails, Max = %4.2f Kms. allowed. \n',ringMax);
    fprintf('<<d12:= %4.2f Km.>>, <<d13:= %4.2f Km.>>, <<d14:= %4.2f Km.>>, <<d15:= %4.2f
Km.>> \n', d12,d13,d14,d15);
    fprintf('<< d16 := %4.2f Km. >>, << d17 := %4.2f Km. >> \n', d16,d17);
    fprintf('<d23 := %4.2f Km.>, <d24 := %4.2f Km.>, <d25 := %4.2f Km.>, <d26 := %4.2f
Km.> \n',d23, d24, d25, d26);   fprintf('<< d27 := %4.2f Km. >> \n', d27);
    fprintf('<d34 := %4.2f Km.>, <d35 := %4.2f Km.>, <d36 := %4.2f Km.>, <d37 := %4.2f
Km.> \n', d34, d35, d36, d37);
fprintf('<<d45 := %4.2f Km.>>, <<d46 :=%4.2f Km.>>,<<d47 :=%4.2f Km.>> \n', d45, d46, d47);
    fprintf('<<d56 :=%4.2f Km.>>,<<d57 :=%4.2f Km.>>,<<d67 :=%4.2f Km.>> \n', d56, d57,
d67);
    fprintf('            << Need to Redesign  >> \n');
```

```
else
    fprintf('NodeToNode CW_Distance and CCW_Distance within specs, Max = %4.2f Kms.
  \n', ringMax);
    fprintf('<d12 := %4.2f Km.>, <d13 := %4.2f Km.>, <d14 := %4.2f Km.>, <d15 := %4.2f
  Km.>\n', d12,d13,d14,d15);
    fprintf('<< d16 := %4.2f Km. >>, << d17 := %4.2f Km. >>\n', d16,d17);
    fprintf('<d23 := %4.2f Km.>, <d24 := %4.2f Km.>, <d25 := %4.2f Km.>, <d26 := %4.2f
  Km.>\n', d23, d24, d25, d26);
    fprintf('<< d27 := %4.2f Km. >>\n', d27);
    fprintf('<d34 := %4.2f Km.>, <d35 := %4.2f Km.>, <d36 := %4.2f Km.>, <d37 := %4.2f
  Km.>\n',d34, d35, d36, d37);
  fprintf('<<d45 :=%4.2f Km>>,<<d46 := %4.2f Km.>>, <<d47 := %4.2f Km.>> \n',d45, d46, d47);
  fprintf('<<d56 := %4.2f Km>>,<<d57 := %4.2f Km.>>, <<d67 := %4.2f Km.>> \n',d56, d57, d67);
    fprintf('        << Ready to enter Number and Types of connections between nodes >>\n');
    totalNumberOfShelves = 0;
    for m = 1:numberOfSites -1;
     for n = 2:numberOfSites;
      if (m < n)
    fprintf('Number of Base (Unprotected) Chanels from node_%d-to-node_%d\n',m,n);
        baseMeshEscon(m,n) = input('Number of Base ESCON      channels : ');
        baseMeshFicon(m,n) = input('Number of Base FICON      channels : ');
        baseMeshGbEth(m,n) = input('Number of Base GbEthernet channels : ');
        baseMeshAtm(m,n)   = input('Number of Base ATM        channels : ');
        fprintf('Number of High Available (1+1) protected Chanels from node_%d-to-
  node_%d\n',m,n);
        highAvMeshEscon(m,n) = input('Number of High Available ESCON      channels : ');
        highAvMeshFicon(m,n) = input('Number of High Available FICON      channels : ');
        highAvMeshGbEth(m,n) = input('Number of High Available GbEthernet channels : ');
        highAvMeshAtm(m,n)   = input('Number of High Available ATM        channels : ');
        baseCards4TDMEscon(m,n)    = baseMeshEscon(m,n)/4;
        baseCards4TDMAtm(m,n)      = baseMeshAtm(m,n)/4;
        totalOCIBaseChannels(m,n)  = baseCards4TDMEscon(m,n) + baseMeshFicon(m,n) + ...
            baseMeshGbEth(m,n) + baseCards4TDMAtm(m,n);
        highAvCards4TDMEscon(m,n)  = highAvMeshEscon(m,n) / 4;
        highAvCards4TDMAtm(m,n)    = highAvMeshAtm(m,n) / 4;
        totalOCIHighAvChannels(m,n) = 2*(highAvCards4TDMEscon(m,n) +
  highAvMeshFicon(m,n) + highAvMeshGbEth(m,n) + highAvCards4TDMAtm(m,n));
        numberOfShelves(m,n) = (totalOCIBaseChannels(m,n) +
  totalOCIHighAvChannels(m,n)) / 8;
            fprintf('Configuration requires << %d >> shelves for Node_%d-to-Node_%d\n',...
            ceil(numberOfShelves(m,n)),m,n);
            totalNumberOfShelves = totalNumberOfShelves + ceil(numberOfShelves(m,n));
```

```
        end;        end;     end
      fprintf('Total of << %d >> shelves required for a Mesh Configuration of %d Sites\n',...
        ceil(totalNumberOfShelves), numberOfSites);
      end
   otherwise fprintf('This example is for 7 sites only. Other cases can easily be implemented\n')
   end;end
```

advaData.dat

```
1 1529.55
2 1530.33
3 1531.12
4 1531.90
5 1532.68
6 1533.47
7 1534.25
8 1535.04
9 1535.82
10 1536.61
11 1537.40
12 1538.19
13 1538.98
14 1539.77
15 1540.56
16 1541.35
17 1542.14
18 1542.94
19 1543.73
20 1544.53
21 1545.32
22 1546.12
23 1546.92
24 1547.72
25 1548.51
26 1549.32
27 1550.12
28 1550.92
29 1551.72
30 1552.52
31 1553.33
32 1554.13
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