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Wavelength assignment in all-optical networks for mesh topologies

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WAVELENGTH ASSIGNMENT IN ALL-OPTICAL NETWORKS FOR MESH TOPOLOGIES

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Table of Contents

List of Tables

List of Figures

Abstract

All-Optical Networks employing Dense Wavelength Division Multiplexing (DWDM) are believed to be the next generation networks that can meet the ever-increasing demand for bandwidth of the end users. This thesis presents some new heuristics for wavelength assignment and converter placement in mesh topologies. Our heuristics try to assign the wavelengths in an efficient manner that results in very low blocking probability. We propose novel static and dynamic assignment schemes that outperform the assignments reported in the literature even when converters are used.

The proposed on-line scheme called "*Round-Robin*" assignment outperforms previously proposed strategies such as first-fit and random assignment schemes. The performance improvement obtained with the proposed static assignments is very significant when compared with the dynamic schemes. We designed and developed a simulator in the C language that supports the 2D mesh topology with DWDM. We ran extensive simulations and compared our heuristics with those reported in the literature. We have examined converter placement in mesh topologies and proposed that placing converters at the center yields better results than uniform placement when dimension order routing is employed. We introduced a new concept called "*wavelength assignment with second trial*" that results in extremely low blocking probabilities when compared to schemes based on a single trial. Our proposed schemes are simple to implement and do not add to the cost. Thus we conclude that wavelength assignment plays more significant role in affecting the blocking probability than wavelength converters. We further conclude that static schemes without converters could easily outperform dynamic schemes thus resulting in great savings.

Chapter 1

Introduction

Optical Networks employing Wavelength Division Multiplexing (WDM) are believed to be the next generation networks that can meet the ever-increasing demand for bandwidth of the end users. To support applications that require high bandwidth, low delay and low error rate we must employ networks that can meet the requirements. While the optical fiber provides us with links that have the required properties, network bandwidth is limited by the processing speed of the nodes. The reason is that the processing at the nodes must be done electronically. This means that the optical signal on the fiber must be converted into an electronic signal, processed at low electronic speeds and then converted back to optical signals for transmission over and optical fiber. Apart from slowing the network down, the electro-optic conversion needed to facilitate electronic processing is also expensive. The obvious solution to this problem is to build networks in which the signals are processed in the optical domain. Such networks are called *all-optical networks.*

Demand for higher Bandwidth: Today, the Internet backbones are being built at a very fast pace. The rate of growth in data traffic is 10 times that of voice traffic per year [7]. It is assumed that voice traffic grows at the rate of 13 percent annually whereas data traffic grows at the rate of 7 to 20 percent monthly. Figure 1.1 compares the growth of voice and data traffic over the years [32].

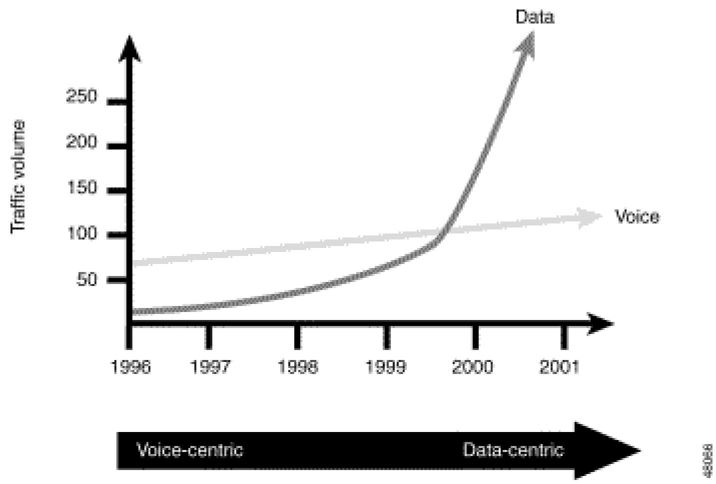


Figure 1-1: Comparison of Voice and Data Traffic.

Leading service providers report bandwidths doubling on their backbones about every six to nine months. Not only is the amount of data traffic increasing at a high rate but also the nature of the traffic itself is becoming complex. Traffic carried on a backbone can originate as circuit based (TDM voice and fax), packet based (IP), or cell based (ATM and Frame Relay). Further, there is an increasing proportion of delay sensitive data, such as voice over IP (VOIP) and streaming video [2] [34].

Evolution of DWDM: Until the late 1980s, optical fiber communications was mainly confined to transmitting a single optical channel. Because fiber attenuation was involved, this channel required periodic regeneration, which included detection, electronic processing, and optical retransmission. Such regeneration caused a high-speed optoelectronic bottleneck and could handle only a single wavelength. In the early 90's optical amplifiers were developed [7], which enabled us to accomplish high-speed repeater-less single-channel transmission. Several different independent wavelengths can be transmitted simultaneously down a fiber to fully utilize this enormous fiber bandwidth. WDM is the advanced technology that enables the transmission of multiple wavelengths over a single fiber. WDM has emerged as a promising technique for opening the Terahertz transmission bandwidth in optical networks. In WDM transmission, different data channels are modulated into the optical fiber with a unique wavelength each [1]. Thus each data channel can be used to carry data independently with its own independent rate without any interference from other channels. Moreover, the overall bandwidth supported by the optical fiber is the sum of all the bandwidth supported by the individual data channels.

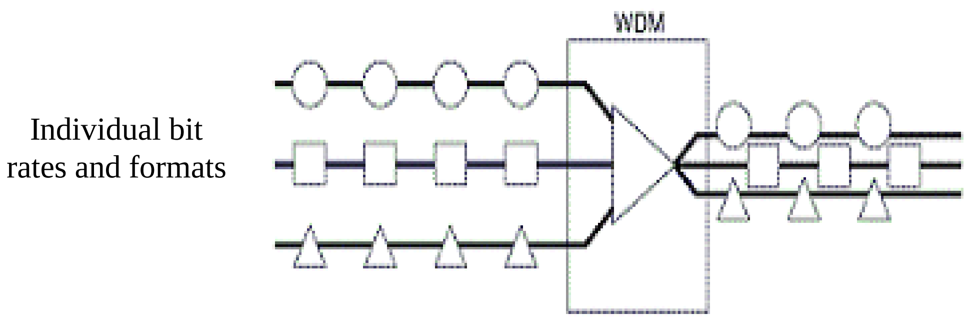


Figure 1-2: WDM in Optical Networks.

WDM technology is being extensively deployed on point-to-point links within transport networks in the United States. However, WDM promises advantages for switching and routing as well as for transmission [2]. Optical cross-connects are currently being developed which can switch an all wavelength from an input fiber to an output fiber so that large bandwidth circuits can be routed through the network [1]. High-speed, fixed-bandwidth, end-to-end connections called lightpaths can then be established between different nodes. Wavelength-routed optical core networks are expected to evolve from the existing separate WDM transmission systems to form optical layers in future transport networks. These optical layers will provide switching, routing, and restoration on a per-wavelength basis.

1.1 Technologies in the Metropolitan Market

There have been a number of technologies for transport and encapsulation of data in the metropolitan network. The main purpose of these networks is to support various older and new types of traffic and rates. Following are some of the technologies used in metropolitan area networks (MANs).

1.1.1 SONET

In 1986, the SONET (synchronous optical network) standard was introduced to synchronize public communications networks and to tie them together via a high-speed fiber-optical links [34]. SONET defines interface standards at the physical layer of the OSI seven-layer model. SONET defines a set of framing standards that determine how bytes are transmitted across links. The standard defines a hierarchy of interface rates that allow data streams at different rates to be multiplexed. SONET establishes Optical Carrier (OC) levels from 51.8 Mbps (about the same as a T-3 line) to 40 Gbps. With the implementation of SONET communication carriers throughout the world can interconnect their existing digital carrier and fiber optic systems.

SONET offers enormous bandwidth based on multiples of the base rate (OC-1) of a 51.84-Mbps or one T-3 link. SONET/SDH has been the foundation for MANs over the last decade serving as the fundamental transport layer for both TDM-based circuit switched network and most overlay data networks. SONET/SDH is fairly expensive to implement. It also has capacity scaling limitations. OC-768 (40 GHz) is supposed to be the practical limit of SONET/SDH.

1.1.2 ATM

Asynchronous transfer mode (ATM) is a switching technology that uses small, fixed-size cells. ATM is a *connection-oriented* technology. ATM runs on top of highly scalable physical layer protocols such as Fiber Channel and the wide area SONET. It is asynchronous because cells are transmitted through a network on an "as needed" basis and not merely transmitted during specific time intervals. ATM cells are small (53 bytes) compared to variable-length LAN packets. The information in the header and the payload are always in the same place which makes the handling of the cells very simple. Moreover, ATM cells need not be buffered because of their fixed length.

ATM can encapsulate different protocols and traffic types into a common format that can be transmitted over a SONET infrastructure. Advancements in Internet Protocol (IP), combined with the scaling capacity of gigabit and multigigabit routers makes it possible to opt for an IP-based network in the data networking world which has the data traffic as the primary component and the voice traffic as the secondary component. Even then ATM remains strong in the metropolitan area that accommodates higher speed line interfaces and provides managed virtual circuit services while offering traffic management capabilities.

1.1.3 Gigabit Ethernet

The Ethernet protocol is the world's most popular LAN protocol [34]. Of all current networking protocols, Ethernet has, by far, the highest number of installed ports and provides the greatest cost performance relative to Token Ring, Fiber Distributed Data Interface (FDDI), and ATM for desktop connectivity. Fast Ethernet, which increased

Ethernet speed from 10 to 100 megabits per second (Mbps), provided a simple, cost-effective option for backbone and server connectivity.

Gigabit Ethernet builds on top of the Ethernet protocol, but increases speed tenfold over Fast Ethernet to 1000 Mbps, or 1 gigabit per second (Gbps). This protocol, which was standardized in June 1998, promises to be a dominant player in high-speed local area network backbones and server connectivity. Since Gigabit Ethernet significantly leverages on Ethernet, customers will be able to leverage their existing knowledge base to manage and maintain gigabit networks.

Gigabit Ethernet (GE) 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) guarantees or fault tolerance on its own.

1.1.4 FDDI

The Fiber Distributed Data Interface (FDDI) specifies a 100-Mbps token passing, dual-ring LAN using fiber-optic cable. FDDI is frequently used as high-speed backbone technology because of its support for high bandwidth and greater distances than copper. FDDI uses dual-ring architecture with traffic on each ring flowing in opposite directions (called counter-rotating). The dual rings consist of a primary and a secondary ring. During normal operation, the primary ring is used for data transmission, and the secondary ring remains idle. The primary purpose of the dual rings is to provide superior reliability and robustness. FDDI uses optical fiber as the primary transmission medium, but it also can run over copper cabling.

FDDI has been replaced by more advanced technologies at this time. Although FDDI is capable of scaling to the metropolitan area, it is also a shared media technology with a relatively low capacity by current standards. This limitation, along with falling availability of FDDI interfaces on network equipment, is causing FDDI to be replaced by Gigabit Ethernet, or ATM.

1.2 Migration from Ring to Mesh

The spread of optical networks from long haul to metropolitan rings and now to customer premise locations is creating an ocean of bandwidth for voice and data communications. At the same time, there has been a phenomenal growth in demand for bandwidth due to increased use of the Internet. To meet growing bandwidth demand, established carriers have built their optical networks with Synchronous Optical Network/ Synchronous Digital Hierarchy (SONET/SDH) ring architectures in North America and other locations around the world. But as we enter the next generation network era, these SONET rings will not be able to provide the required bandwidth [32].

Recent advances in optical technology have resulted in an exponential increase in traffic-carrying capacity of optical equipment. From just 16 wavelengths in 1996, DWDM technology has progressed so rapidly that equipment capable of supporting several hundreds of wavelengths is on the horizon [2]. This, coupled with advances in fiber cable technology, creates a bandwidth tidal wave, crashing on the shores of carrier core networks. The rapid growth of the Internet, on the other hand, together with newer applications and services such as leased lambdas, data mirroring and backup, video-based applications, e-commerce, and other high bit rate services make it imperative that this bandwidth be quickly and effectively harnessed.

The current and future applications will require that this vast bandwidth be rapidly provisioned and that flexible and efficient quality of service (QoS) mechanisms be developed. Moreover, the exponential growth in Internet traffic and increasingly unpredictable demand patterns make the need for scalable network architecture a high priority. SONET ring architectures that suited us well for the European networks, where most of the bandwidth was dedicated to voice, now lay siege on the carrier’s ability to unleash the power of dynamic, flexible, just-in-time bandwidth provisioning.

Consequently some carriers are being forced to look for other topologies. In growing numbers, many carriers are finding a solution in optical mesh design. According to a recent forecast, the market for OXC's (Optical Cross Connects), on which mesh networks are built, is slated to jump to $1.8 billion by 2003 [7].

While rings are well understood in the context of optical networks, much less is broadly known about the mesh. Mesh networks, built on new-world optical cross connects, exploit a combination of IP and SONET based mechanisms to provide dynamic provisioning and fast deterministic shared protection [13].

The benefits of mesh topologies for optical networks fall into five categories [2]. We list these categories and then provide a brief description of each.

- Migration, Scaling
- Deployment Speed
- Capacity Utilization
- Network Restoration
- Operating Costs

Migration and Scaling: The ring can be an inflexible architecture. The typical SONET OC-192 Bi-directional Line Switch Ring (BLSR) ring, for instance, is unable to transport OC-192 Internet backbone trunks [35]. While an increasing number of router vendors are offering OC-192 interfaces, carriers are unable to place the OC-192 circuits on their existing ADM based rings. Thus, the highest available bandwidth is never made available to the client layer elements, and the carriers have to wait for the next generation technology to be available to support BLSR rings. This can present problems as networks migrate to Internet architectures to meet the exploding demand in IP traffic.

Mesh topologies, on the other hand, provide services at the highest line rate, and can work seamlessly with IP routers. They enable routers to dynamically request and release bandwidth for relief on congested routes.

Deployment Speed: The rapid growth of Internet traffic is also increasing the need for long haul capacity at a fast pace. With the Internet, you are as likely to be checking a site that is hosted half way across the world, as one that is hosted locally. In a ring-based network, a typical long haul circuit has to be interconnected through many rings using expensive and inefficient back-to-back tributaries. This requires the availability of bandwidth simultaneously on all rings in order to provision the long haul circuit. In reality, however, the bandwidth may not be available in all rings, and the carrier has to wait till the next build-out for the circuit to be provisioned. In the meantime, the available bandwidth is reserved on the other rings. The end result is a very slow provisioning process typically measured in months. Carriers are forced to waste working capacity on their rings, and are unable to respond quickly to rapid shifts in demand. Clearly, this is not the "bandwidth-on-demand" capability that newer Internet applications require.

Utilizing dynamic mechanisms that are inherent in the IP protocol, mesh architecture enables point and click bandwidth solutions. This capability becomes increasingly important for two reasons:

1) As bandwidth prices decline rapidly, carriers need other means to differentiate themselves; and

2) With unpredictable demand patterns that are getting tougher to forecast, carriers need to be able to configure bandwidth on demand in order to prevent severe congestion in parts of their network.

Capacity Utilization: For fully protected traffic, rings are unable to achieve 50 percent capacity utilization. Capacity may be available only in certain portions of a ring, but not over the entire ring, thus forcing the carrier to provision an entirely new wavelength, while unable to exploit the unused portions of the ring. Thus, entire working capacity cannot be utilized to carry traffic. However, carriers are still forced to dedicate protection bandwidth for non-traffic bearing capacity as well. Mesh architectures, on the other hand, can offer utilization rates of 70 percent or more. The Mesh also provides intelligent and flexible protection sharing [2].

The BLSR ring protocol was specified with an additional capability: extra traffic that was meant to improve the bandwidth utilization of rings. Extra traffic was specified to use the dedicated protection bandwidth available in the ring, and was preempted in the event of a failure anywhere on the ring. However, with no network database capability to support provisioning for end-to-end extra traffic circuits, preemptable traffic service is a no-show in ring networks. With end-to-end dynamic provisioning support, mesh networks on the other hand provide a unique capability to exploit preemptable traffic. For instance, a router requesting temporary bandwidth for congestion relief may provision a preemptable circuit on demand.

Network Restoration: Restoration plays an important role in the performance of the network. It is the ability of the network to withstand failures. The mesh architecture also supports Quality of Service (QoS) features that make more sense for the mixed voice, data and Internet traffic that characterizes today's transmission needs. Circuits can be provisioned while taking into account restoration priorities, and restoration times. This flexibility avoids the one-size-fits-all approach taken by ring-based networks. The mesh also allows the carrier to provide restoration times comparable to those of stacked rings for voice traffic.

Operating Costs: With rapidly falling prices for bandwidth, ring-based architectures are fast reaching a point where the cost of building a network exceeds the revenue they generate. Operational savings through optical mesh topology can be as high as 60 percent compared to ring structures. A ring network, with its dedicated backup bandwidth, uses between two and four times the number of line cards of a mesh network of similar capacity (depending on the degree of connectivity of the nodes, and the demand patterns).

1.3 Problem Formulation and Layout of the Thesis

Previous work on All Optical Networks (AONs) in the metropolitan area was mostly done on Ring topologies [25] [8] [10] [13]. Much is still to be studied when it comes to the mesh topologies. Moreover, most of the research was confined to limiting the number of wavelength converters and to choosing optimal converter placement for a fixed number of converters. Wavelength assignment schemes were not studied in detail.

Traditional wavelength assignment schemes were mostly on-line (or dynamic) in nature [14] [19] [20]. Off-line (or static) assignment schemes have not been studied in any depth. Our work is focused on mesh topologies for AONs. This thesis presents and studies the performance of some novel off-line and on-line wavelength assignment schemes. The schemes exhibit very low blocking probabilities compared to the traditional assignment techniques. Moreover, the results show that our techniques are scalable with network traffic and size.

The remainder of the thesis is organized as follows: Chapter 2 provides some details on optical networking, and the role fiber plays in optical networking. It also provides some background on DWDM systems and their enabling components. Chapter 3 discusses the routing and wavelength assignment problem. Different assignment schemes are discussed. Chapter 4 presents our new assignment schemes, studies their performance, and compares their results with the previously known schemes. Finally, Chapter 5 summarizes the thesis and provides the scope for further study.

Chapter 2

Background

This chapter considers the reason that makes optical networks so popular, and the advantages a medium such as fiber offers. We also give some details on DWDM systems, the enabling DWDM components, and optical cross connect architectures.

With advances in DWDM, bandwidth has become more abundant and economical on long-haul transport networks enabling new high-speed Internet access services and broadband networking applications [6]. The pace of bandwidth growth will continue to escalate as more bandwidth hungry applications come on line. The promise of a transport infrastructure capable of meeting the burgeoning bandwidth demands well into the 21st century, wherein wavelengths replace time slots as the medium for providing high bandwidth services across the network, is indeed tantalizing.

2.1 Optical Networking

Optical networks are high-capacity telecommunications networks based on optical technologies and components that provide routing, grooming and restoration at the wavelength level [24]. In an AON, data is carried in the optical form from the source to the destination with no optical-to-electrical conversions. Optical internetworking, as defined by the Optical Internetworking Forum (OIF), is a data-optimized network infrastructure in which switches and routers have integrated optical interfaces and are directly connected by fiber or optical interfaces such as dense wavelength-division multiplexers (DWDMs). In the past, optical signals could carry information only for a limited distance before the signal degraded to the point that it had to be converted to electrical form to be regenerated. The process was expensive because it involved complex processing both at the optical and electrical layers. New technologies such as optical amplifiers and dense wavelength division multiplexers have reduced the need for electrical regeneration, saving long-distance carriers millions of dollars [2].

Given analog engineering constraints, and considering the current state of the art in all-optical processing technology, the notion of global or even national all-optical networks is not practically attainable [11]. In particular, opto-electronic conversion may be required in optical network elements to prevent the accumulation of transmission impairments – impairments that result from such factors as fiber chromatic dispersion and non-linearities, cascading of non-ideal flat-gain amplifiers, optical signal cross talk, and transmission spectrum narrowing from cascaded non-flat filters [16].

2.2 Drive for Optical Networks

Many factors are driving the need for optical networks. The following are some of the important factors that support the migration to optical networks [2].

Fiber Capacity: The first implementation of what has emerged as the optical network began on routes that were fiber limited. As the demand for more speed and bandwidth grew, service providers needed more capacity between two sites, but higher bit rates or fiber were not available. The only options in these situations were to install more fiber, (which is an expensive and labor-intensive task), or increase the rate of time division multiplexing (TDM) signals on the same fiber, which has a practical limit for speed. With WDM many virtual fibers can be created on a single physical fiber. By transmitting each signal at a different wavelength (frequency), network providers could send many signals on one fiber just as though they were each traveling on its own fiber [21], thus increasing the capacity by the number of wavelengths sent without having to add more fiber to the existing one.

Restoration Capability: A network consists of many layers, and each layer usually has its own protection mechanisms built in, independent of the other layers. There are two reasons for this. First, because each layer is assumed to work with a variety of other layers above and below it. Second, each layer is usually developed and standardized by a separate group of people [29]. As network planners use more network elements to increase fiber capacity, a fiber cut can have massive implications. In current electrical architectures, each network element performs its own restoration. For a WDM system with many channels on a single fiber, a fiber cut would initiate multiple failures, causing many independent systems to fail. By performing restoration in the optical layer rather than the electrical layer, optical networks can perform protection switching faster and more economically. For example instead of each SONET link running over a WDM link taking care of the restoration by itself, a simple switch system connecting two diversely routed fibers in a single WDM system can take care of the restoration. Additionally, the optical layer can provide restoration in networks that currently do not have a protection scheme.

Reduced Cost: With the development of Erbium Doped Fiber Amplifiers (EDFAs) the amplifying cost is tremendously decreased as it eliminates the process of O-E-O conversion at regular intervals. In an Optical Network with Add-Drop Multiplexers (ADMs), only the required channels are added and dropped while the other channels do not go through any conversion. Only those wavelengths that add or drop traffic at a site need corresponding electrical node conversion. Other channels can simply pass through optically, this provides tremendous cost savings in equipment and network management [29]. In addition, performing space and wavelength routing of traffic avoids the high cost of electronic cross-connects, and simplifies network management.

Wavelength Services: One of the great revenue-producing aspects of optical networks is the ability to resell bandwidth rather than fiber. By maximizing capacity available on a fiber, service providers can improve revenue by selling wavelengths, regardless of the data rate required. To customers, this service provides the same bandwidth as a dedicated fiber.

2.3 Fiber Potential

The following are some of the important advantages of fiber optic cable over copper that make fiber much more suitable for high speed communications [33]:

- **Speed:** Fiber optic networks operate at high speeds - into the Terabits
- **Bandwidth:** large carrying capacity.
- **Distance:** Signals can be transmitted further without needing to be "refreshed" or strengthened.
- **Resistance:** Greater resistance to electromagnetic noise such as radios, motors or other nearby cables.
- **Maintenance:** Fiber optic cables cost much less to maintain.

Fiber optic cable functions as a “light guide,” guiding the light introduced at one end of the cable through to the other end. The light source can either be a light-emitting diode (LED) or a laser. The light source is pulsed on and off, and a light-sensitive receiver on the other end of the cable converts the pulses back into the digital ones and zeros of the original signals.

Even laser light shining through a fiber optic cable is subject to loss of strength, primarily through dispersion and scattering of the light, within the cable itself. The faster the laser pulses, the greater the risk of dispersion. Light strengtheners, called repeaters, may be necessary to refresh the signal in certain applications. Some 10 billion digital bits can be transmitted per second along an optical fiber link in a commercial network, enough to carry tens of thousands of telephone calls [30]. Hair-thin fibers consist of two concentric layers of high-purity silica glass, the core and the cladding, which are enclosed by a protective sheath. Light rays modulated into digital pulses with a laser or a light-emitting diode move along the core without penetrating the cladding. The light stays confined to the core because the cladding has a lower refractive index – a measure of its ability to bend light. Refinements in optical fibers, along with the development of new lasers and diodes, may one day allow commercial fiber-optical networks to carry trillions of bits of data per second [30].

There are three types of fiber optic cable: single mode, multimode and plastic optical fiber (POF).

- **Single Mode cable**: It is a single stand of glass fiber with a core diameter of 8.3 to 10 microns that supports one mode of transmission. Single-mode fiber offers a higher transmission rate and up to 50 times more distance than multimode fiber, but it also costs more. Single-mode fiber has a much smaller core than multimode. The small core and single lightwave virtually eliminate any distortion that could result from overlapping light pulses, providing the least signal attenuation and the highest transmission speeds of any cable type. Single-mode optical fiber is an optical fiber in which only the lowest order bound mode can propagate, at the wavelength of interest typically.

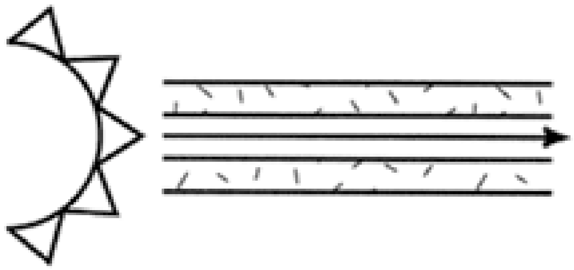


Figure 2-1: Single Mode Fiber: Single path through fiber.

- **Multimode cable**: This type of cable has a core diameter in the 50-to-100 micron range (the most common size is 62.5). Multimode fiber offers high bandwidth at high speeds over medium distances. Light waves are dispersed into numerous paths, or modes, as they travel through the cable's core typically with wavelength of 850 or 1300nm

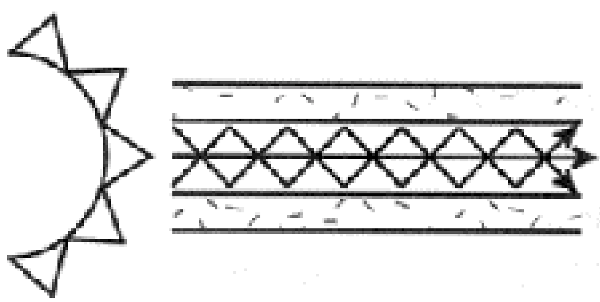


Figure 2-2: Multimode fiber: Multiple paths through the fiber.

- **POF:** It is a newer plastic-based cable that promises performance similar to glass cable on very short runs, but at a lower cost.

While fiber optic cable itself is cheaper than an equivalent length of copper cable, fiber optic cable connectors and the equipment needed to install them are more expensive than their copper counterparts [30].

2.4 Dense Wavelength Division Multiplexing

Dense Wavelength Division Multiplexing (DWDM) is a fiber-optic transmission technique. It involves the process of multiplexing many different wavelength signals onto a single fiber. So each fiber has a set of parallel optical channels each using slightly different light wavelengths. Because incoming signals are never terminated in the optical layer, the interface can be bit-rate and format independent, allowing the service provider to integrate DWDM technology easily with existing equipment in the network while gaining access to the untapped capacity in the embedded fiber. A key feature of DWDM is that discrete wavelengths form an orthogonal set of carriers, which can be separated, routed, and switched without interfering with each other, as long as the total light intensity is kept sufficiently low [4].

It is the use of wavelength and its processing in passive network elements, which distinguishes optical networks, in general, from other network technologies [4]. It is also the latest technology to expand fiber’s potential. It lays the groundwork for true optical networking and gives carriers a path to reach their terabit desires.

Each signal carried can be at a different rate (OC-3/12/24, etc.) and in a different format (SONET, ATM, data, etc.). For example, a DWDM network with a mix of SONET signals operating at OC-48 (2.5 Gbps) and OC-192 (10 Gbps) over a DWDM infrastructure can achieve capacities of over 40 Gbps. A system with DWDM can achieve all this gracefully while maintaining the same degree of system performance, reliability, and robustness as current transport systems or even surpassing them. Future DWDM terminals will handle up to 80 wavelengths of OC-48, a total of 200 Gbps, or up to 40 wavelengths of OC-192, a total of 400 Gbps – which is enough capacity to transmit 90,000 volumes of an encyclopedia in one second.

Consider a highway analogy [30] where one fiber can be thought of as a multilane highway. Traditional TDM systems use a single lane of this highway and increase capacity by moving faster on this single lane. In optical networking, utilizing DWDM is analogous to accessing the unused lanes on the highway (increasing the number of wavelengths on the embedded fiber base). Thus we are able to gain access to an incredible amount of untapped capacity in the fiber.

When dense wavelength division multiplexing first came onto the scene, it was an obvious choice for fiber-constrained long-haul carriers. The economic justification for long-haul DWDM is simple: Optical amplifiers replace multiple SONET regenerators, reducing network costs by a factor of 10 or more.

2.5 DWDM Components

All DWDM systems consist of the following components, optical transmitters (lasers), optical multiplexers (mux) and demultiplexers (demux), optical receivers, optical add/drop multiplexers (OADM) and optical amplifiers. Figure 2.1 shows the basic concept of a DWDM system with an amplifier [7].

2.5.1 Optical Transmitters and Transponders

A fiber optic transmitter is a hybrid device. It converts electrical signals into optical signals and launches the optical signals into an optical fiber [19]. Light emitted by an optical source is launched, or coupled, into an optical fiber for transmission.

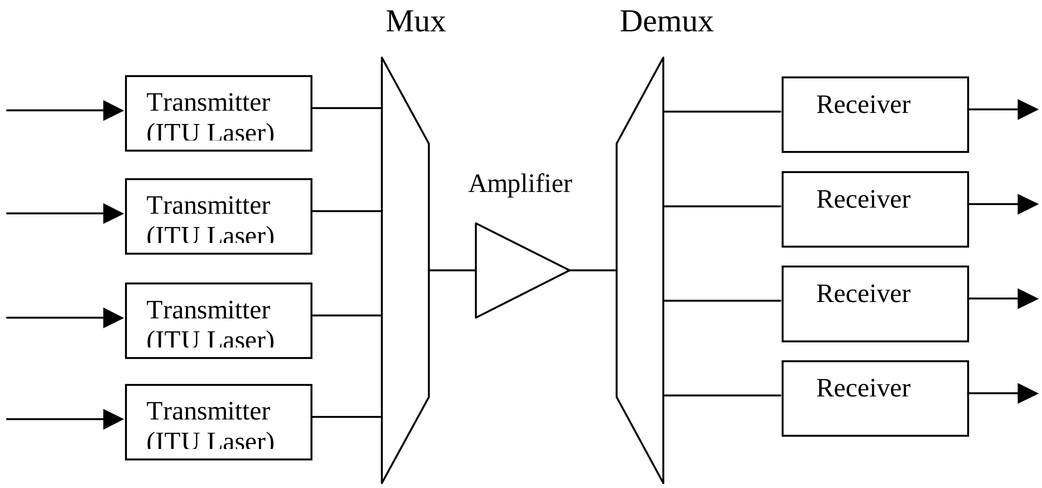


Figure 2-3: DWDM System.

Semiconductor optical sources suitable for fiber optic systems range from inexpensive light-emitting diodes (LEDs) to more expensive semiconductor lasers. Semiconductor LEDs and laser diodes (LDs) are the principal light sources used in fiber optics.

The development of efficient semiconductor optical sources, along with low-loss optical fibers, led to substantial improvements in fiber optic communications [29]. Semiconductor optical sources should have the following physical characteristics and performance properties necessary for successful implementations of fiber optic systems.

- Be compatible in size to low-loss optical fibers by having a small light-emitting area capable of launching light into fiber.
- Launch sufficient optical power into the optical fiber to overcome fiber attenuation and connection losses allowing for signal detection at the receiver.
- Emit light at wavelengths that minimize optical fiber loss and dispersion. Optical sources should have a narrow spectral width to minimize dispersion.
- Maintain stable operation in changing environmental conditions (such as temperature)

- Allow for direct modulation of optical output power.
- Cost less and be more reliable than electrical devices, permitting fiber optic communication systems to compete with conventional systems

Fiber optic communication systems operate in the 850-nm, the 1300-nm, and the 1550-nm wavelength windows. Semiconductor sources are designed to operate at wavelengths that minimize optical fiber absorption and to maximize system bandwidth [2]. By designing an optical source to operate at specific wavelengths, absorption from impurities in the optical fiber, such as hydroxyl ions (OH^-), can be minimized. Maximizing system bandwidth involves designing optical fibers and sources that minimize chromatic and intermodal dispersion at the intended operational wavelength.

The optical transmitters for DWDM systems are high resolution, precision narrow-band lasers. These lasers allow close channel spacing, which increases the number of wavelengths that can be used in the 1500 nm band while minimizing the effects of signal impairments such as dispersion. The optical transmitter minimizes power loss to allow for long transmission distances and a high level of signal integrity. These lasers can use optical amplifiers to boost signal strength for extended distances and to eliminate the electronic-amplifier needed to regenerate individual optical signals. Most laser systems are designed to work with wavelengths that follow the ITU-T, which enables simplified interoperability and easier component selection.

A component of some DWDM systems is the transponder, which converts broadband optical signals to specific wavelengths using optical-to-electrical-to-optical (O-E-O) conversion. Transponders or wavelength converters are optional devices that provide the conversion of one optical wavelength (in other words, 1310 nm or 1550 nm) to a precision narrow-band wavelength. This conversion enables devices that are not equipped with precision narrowband lasers to be multiplexed onto a single fiber, such as routers, ATM switches, or other multiplexers.

2.5.2 Optical Amplifiers

Optical amplifiers boost optical signals in the optical domain to minimize the effects of power loss and attenuation that result from sending light pulses over optical fiber. Optical amplifier technology is the key to enabling the high speed, high-volume transmission of DWDM to take place. Optical amplifier technology was the key to the commercial success of long-haul DWDM systems. However, because of the shorter distances found in metropolitan and regional networks, optical amplifiers are not always deployed in these networks.

Before the advent of optical amplifiers, each signal had to be regenerated electronically. When regenerating an optical signal electronically, the signal must first be converted to an electrical signal, amplified, and then converted back to an optical signal before being retransmitted. Electronic regeneration requires a separate regenerator for each wavelength on each fiber. However, a single optical amplifier can amplify all of the wavelengths on one fiber.

The most common type of optical amplifier is the erbium doped fiber amplifier (EDFA). Conventional EDFAs operate in the 1530 to 1560 nm range. The element Erbium boosts the power of wavelengths and eliminates the need for regeneration. Optical pump lasers are used to transfer high levels of energy to the special fiber, energizing the Erbium ions, which boosts the optical signals that are passing through. Instead of multiple electronic regenerators, which required that the optical signals be converted to electrical signals then back again to optical ones, the EDFA directly amplifies the optical signals. Hence the composite optical signals can travel up to 600 kms without regeneration and up to 120 kms between amplifiers in a commercially available terrestrial DWDM system.

2.5.3 Optical Multiplexers and Demultiplexers

Optical multiplexers combine signals from different wavelengths onto a single optical fiber. Optical demultiplexers separate the combined signals into their component wavelengths at the receiving end. DWDM multiplexers are typically passive devices which means they do not require electrical input. These passive multiplexers behave like high-precision prisms to separate the individual colors of the DWDM signal.

2.5.4 Optical Detector and Fiber Optic Receivers

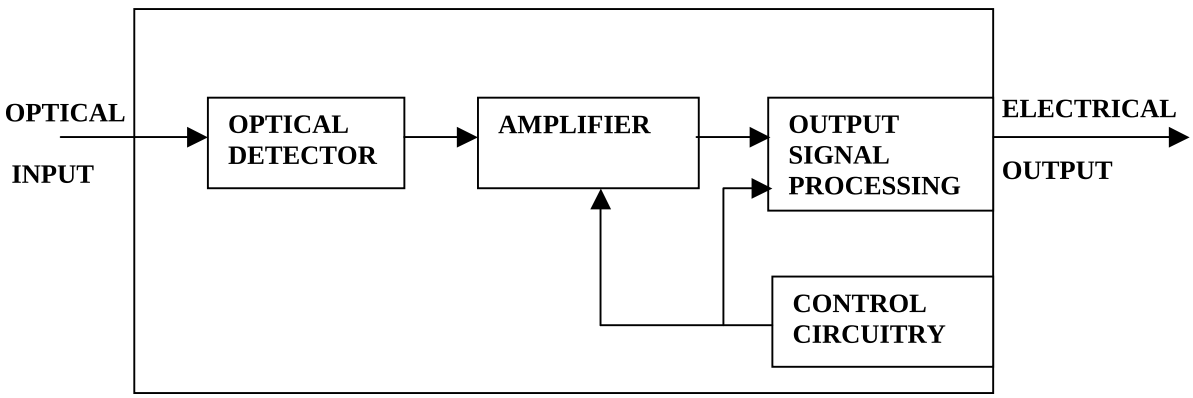


Figure 2-4: Block diagram of a fiber optic receiver.

A ***fiber optic receiver*** is an electro-optic device that accepts optical signals from an optical fiber and converts them into electrical signals. A typical fiber optic receiver consists of an optical detector, a low-noise amplifier, and other circuitry used to produce the output electrical signal. The optical detector converts the incoming optical signal into an electrical signal. The amplifier then amplifies the electrical signal to a level suitable for further signal processing. The type of other circuitry contained within the receiver depends on the type of modulation used and the receiver's electrical output requirements.

A ***transducer*** is a device that converts input energy of one form into output energy of another. An ***optical detector*** is a transducer that converts an optical signal into an electrical signal. It does this by generating an electrical current proportional to the intensity of incident optical radiation.

The following are some of the specific performance and compatibility requirements optical detectors should meet [29]:

- Be compatible in size to low-loss optical fibers to allow for efficient coupling and easy packaging.
- Have a high sensitivity at the operating wavelength of the optical source.
- Have a sufficiently short response time (sufficiently wide bandwidth) to handle the system's data rate.
- Contribute low amounts of noise to the system.
- Maintain stable operation in changing environmental conditions, such as temperature.

The principal optical detectors used in fiber optic systems include semiconductor positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes (APDs). Semiconductor photodiodes generate a current when they absorb photons (light).

2.5.5 Add-Drop Multiplexers

Optical Add-Drop Multiplexers (OADMs) are the key network elements in WDM networks for the broadband Internet era. The function of the ADM is to drop some of the data channels at a node and add other channels in place of the dropped ones. The remaining channels pass through without any modification. The dropped wavelength is replaced with another wavelength without any delay.

2.6 Wavelength Conversion

A wavelength converter is a device capable of switching data from an input port on one wavelength (λ_1) to an output port on another wavelength (λ_2) [11]. Wavelength converters are very useful in reducing the blocking probability of the network. If wavelength converters are included in the cross-connects in WDM networks, connections can be established between the source and destination even when the same wavelength is not available on all the links in the path. Wavelength converters help to eliminate the *wavelength-continuity constraint.* The following are some of the characteristics an ideal wavelength converter should possess [19].

- Transparency to bit rates and signal formats.
- Fast setup time of output wavelength.
- Conversion to both shorter and longer wavelengths.
- Moderate input power levels.
- Insensitivity to input signal.
- Simple implementation.

For example, in Figure 2.5 a lightpath is established between Node 1 and Node 2 on wavelength λ_1 and another lightpath is established between Node 2 and Node 3 on wavelength $\lambda_{2.}$ Now if a request arrives at Node 1 destined to Node 3, the request cannot be accepted because of the *wavelength-continuity constraint.* But if we have a wavelength converter placed at Node 2 that can convert wavelength λ_1 to $\lambda_{2,}$ then the request can be successfully honored. Clearly wavelength converters can help in improving the performance when free wavelengths are available on links, and a common wavelength is not available.

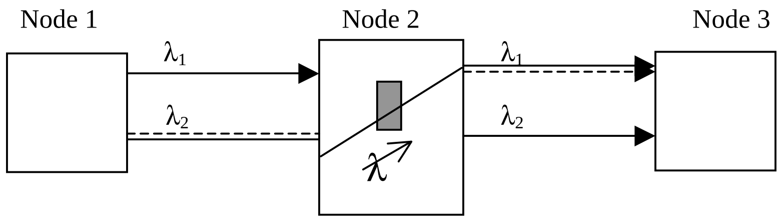


Figure 2-5: Figure showing the use of wavelength converter.

Wavelength converters can be divided into two types based on the amount of conversion possible. A full-wavelength converter is one that can convert an input wavelength into any of the outgoing wavelengths [6] [10] [17]. A limited-wavelength converter is one that can convert an input wavelength only to a subset of the out going wavelengths. A network that has full-wavelength converters at all the nodes will perform well with respect to minimizing the blocking probability. However, this is difficult to implement in practice because of the cost factor and also due to technological limitations [6]. Hence a network in which few nodes are equipped with full or limited wavelength conversion capability is more practical. Such network is referred to as sparse wavelength conversion network [7] [16]. Thus the problem of choosing the appropriate nodes to place the converters in the network becomes significant. This problem is referred to as the converter placement problem [17].

Wavelength conversion implementation techniques can be broadly classified into two types:

- **Opto-electronic wavelength conversion:** In this method [2], the optical signal to be converted is first converted into the electronic domain using a photo detector. The electronic bit stream is stored in a buffer. The electronic signal is then used to drive the input of a tunable laser tuned to the desired wavelength of the output. This method is not suitable for higher bit rates. Data rates of up to 10 Gbps have been demonstrated with this method. Consumption of more power and complex procedure are some of the other drawbacks of this method when compared to other methods. Moreover, the process of opto-electronic (O-E) conversion adversely affects transparency.

- **All-optical wavelength conversion:** In this method, the optical signal is in the optical domain through out the conversion process. All-optical methods can be further classified into the following categories and sub-categories.

  (a) Wavelength conversion using coherent effects: These methods are based on wave-mixing effects. Wave mixing arises from a nonlinear optical response of a medium when more than one wave is present. It results in the generation of another wave whose intensity is proportional to the product of the interacting wave intensities. Wave mixing preserves phase and amplitude information, offering strict transparency. It is also the only approach that allows simultaneous conversion of a set of multiple input wavelengths to another set of multiple output wavelengths and could potentially accommodate signals with bit rates exceeding 100 Gbps [28]. The techniques used in this category are as follows:

  - Four wave mixing (FWM): Four wave mixing is a third-order non-linearity based scheme used in silica fibers, it causes three optical waves of frequencies f_a, f_b and f_c $(a \neq b,c)$ to interact in a multichannel WDM system to generate fourth wave of frequency given by

$$f_{abc} = f_a + f_b - fc$$

This technique provides modulation-format independence and high bit rate capabilities. However, the conversion efficiency from pump energy to signal energy of this technique is not very high and decreases swiftly with increasing conversion span (shift between pump and output signal wavelengths).

- Difference frequency generation (DFG): DFG is a consequence of a second-order non-linear interaction of a medium with two optical waves: a pump wave and a signal wave [28]. This technique offers a full range of transparency without adding excess noise to the signal and spectrum inversion capabilities, but it suffers from low efficiency. The main difficulties in implementing this technique lie in the phase matching of interacting waves and in fabrication of a low-loss waveguide for high conversion efficiency.

(b) Wavelength conversion using cross modulation: These techniques utilize active semiconductor devices such as semiconductor optical amplifiers (SOAs) and lasers. These techniques belong to a class known as optical-gating wavelength conversion [19].

- Semiconductor Optical amplifiers (SOAs) in XGM and XPM mode: The principle behind using an SOA in the cross gain modulation (XGM) is summarized as follows. The intensity-modulated input signal modulates the gain in the SOA due to gain saturation. A continuous wave (CW) signal at the desired output wavelength (λ_c) is modulated by the gain variation so that it carries the same information as the original input signal. The input signal and the CW signal can be launched either co or counter directional into the SOA. The XGM scheme produces a wavelength-converted signal that is inverted compared to the input signal. While the XGM scheme is simple to realize and offers penalty-free conversion at 10 Gbps, it suffers from inversion of the converted bit stream and extinction ratio degradation for an input signal “up converted” to a signal of equal or longer wavelength.

- Semiconductor lasers: Using single-mode semiconductor lasers, the lasing-mode intensity of the medium is modulated by input signal light through gain saturation. The output signal obtained is inverted compared to the input signal. This gain suppression mechanism has been employed in a distributed Bragg reflector (DBR) laser to convert signals at 10Gbps.

2.7 Optical Cross-Connect

Optical Cross-connects (OXC’s) are used to route wavelengths between input and output ports, while adding and dropping the local traffic. The main function of the OXC is to dynamically reconfigure the network at the wavelength level for restoration or to accommodate changes in bandwidth demand. OXC systems are expected to be the cornerstone of the photonic layer providing carriers more dynamic and flexible options in building network topologies with enhanced survivability. OXC’s can be classified into two categories, optical core cross-connect and electrical core cross-connect. In electrical cross-connect the switching function is done electronically. The optical signals after entering the OXC will go through O/E interface and then switching is done in the electrical domain. With this technique higher bit rates cannot be achieved as data is converted to electronic form. As a consequence, cross connects with an optical core have been proposed.

OXC's can be divided into the following classes [2]:

- the fiber switch cross-connect (FXC)
- the wavelength selective cross-connect (WSXC)
- the wavelength interchanging cross-connect (WIXC)

A fiber switch cross-connect switches all of the wavelength channels on one input fiber to an output fiber, in effect acting as an automated fiber patch panel. FXC are less complex, and thus expected to be less costly, than a wavelength selective or wavelength interchanging cross-connect. In parts of the network where protection against fiber cuts is the main concern, FXCs could be a viable solution. They may also make the best use of current proven optical technologies. While FXCs can provide simple provisioning and restoration capabilities, they may not offer the flexibility required to promote new end-to-end wavelength generating services [19].

A wavelength selective cross-connect can switch a subset of the wavelength channels from an input fiber to an output fiber. Functionally, they therefore require demultiplexing (in the frequency spectral domain) of an incoming wavelength multiplex into its individual constituting wavelengths. This cross-connect type offers much more flexibility than an FXC, allowing the provisioning of wavelength services, which in turn can support video distribution, distance learning, or a host of other services. A WSXC also offers better flexibility for service restoration; wavelength channels can be protected individually using mesh, ring or a hybrid protection scheme [2].

A wavelength interchanging cross-connect is a WSXC with the added capability to translate or change the frequency (or wavelength) of the channel from one frequency to another. This feature reduces the probability of not being able to route a wavelength from an input fiber to an output fiber because of wavelength contention. WIXC offers the most flexibility for restoration and provisioning of services. The WIXC may not be very cost-effective since some circuits may not always need wavelength conversions. One effective method is to share wavelength converters. Two methods have been proposed in [1] depending on how the wavelength converters are shared.

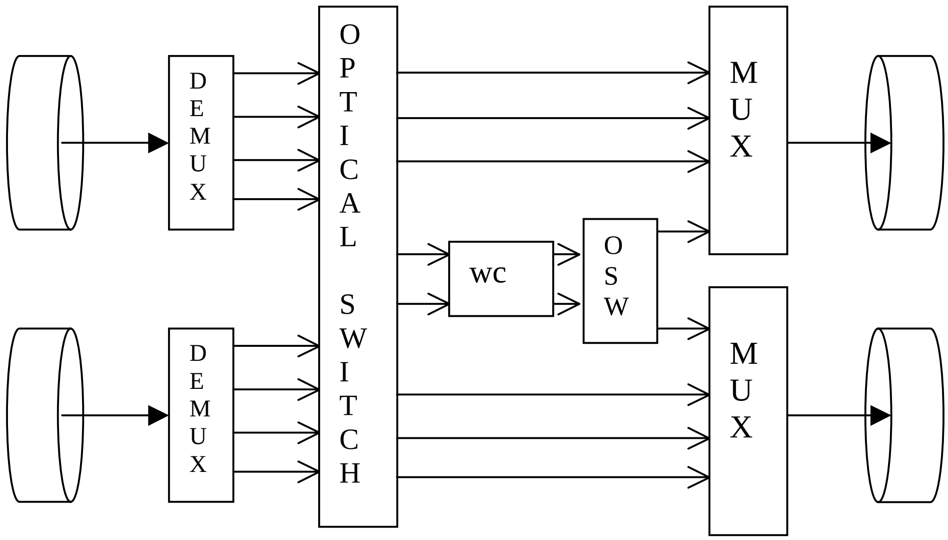


Figure 2-6: Share-per-node wavelength-convertible switch architecture.

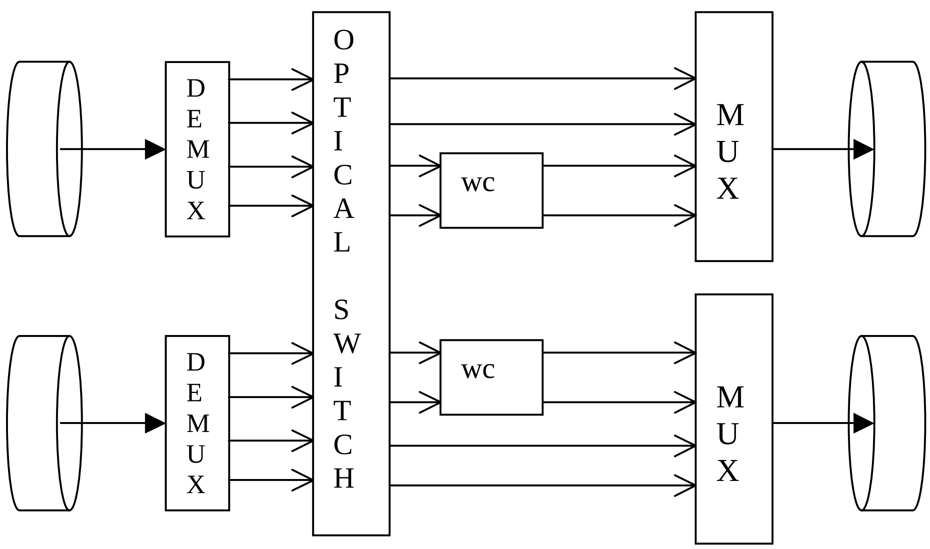


Figure 2-7: Share-per-link wavelength-convertible switch architecture.

In the share-per-node architecture of Figure 2.6, all the converters at the switching node are collected in a converter bank, which can be accessed by all the incoming circuits of that switching node. In the share-per-link architecture of Figure 2.7, each outgoing link owns a dedicated converter, which can only be accessed by those circuits going on that particular outbound link. In the share-per-node architecture, the wavelength converter bank has only a limited set of converters.

Chapter 3

Routing and Wavelength Assignment

A lightpath is a path taken by the signal from the source to the destination in optical form through intermediate links. The wavelength occupied from the source to the destination depends on the availability of the wavelengths at the intermediate links. In a network with no wavelength converters, the lightpath must use the same wavelength from the source to the destination. This is called the *wavelength-continuity constraint* [2] [11] [16] in wavelength-routed networks. The routing and wavelength assignment (RWA) problem deals with routing and assigning wavelengths at every hop in the path [9] [13]. This chapter reviews issues in the literature dealing with the problem of routing and wavelength assignment and with converter placement in all-optical networks.

3.1 Wavelength Routing

Whenever a call arrives at a Wavelength Router (WR), it will run a predefined algorithm and selects the outgoing port and a wavelength. The selection of the wavelength plays an important role in the performance of the algorithm and also on the overall blocking probability. Hence a WR has to find the route for the lightpath request and has to assign a wavelength that minimizes the blocking probability. This function is of fundamental importance in the design of all-optical networks.

RWA schemes can be classified into two categories; static (off-line) or dynamic (on-line) [19]. In a static RWA scheme, all the routes and wavelengths for the lightpaths to be set up are fixed initially. Whenever a lightpath request arrives, the RWA scheme assigns the pre-allocated route and wavelength for that request. Hence the routing procedure doesn't change with time. Moreover, it is not complex to implement, as it does not run any algorithm for every request. It simply assigns the specified route. Dimension order routing technique is an example of static routing for regular topologies [2]. In this technique during routing the call a dimension is completely exhausted before going to the next dimension. XY routing in 2D mesh is an example of dimension order routing for regular topologies. The objective in this approach is to maximize the total throughput in the network, i.e., the total number of lightpaths that can be established simultaneously in the network. Several heuristic approaches have been proposed for solving the static RWA problem in a network without wavelength conversion [9].

In a wavelength-routed optical network, lightpath requests arrive following a particular arrival process and the holding time for these requests also follows a particular process. A dynamic RWA algorithm uses the current state of the network to determine the route for a given lightpath request. The route chosen to establish a connection reflects the current utilization of links in the network, and a connection is blocked if there is no available route to carry it [31]. One of the challenges involved in designing wavelength-routed networks with dynamic traffic demands is to develop efficient algorithms and protocols for establishing lightpaths that minimize the blocking probability in the network. The RWA problem is divided into two parts; selecting a route with fewer links and assigning a suitable wavelength that will minimize the blocking probability. In some cases it might be necessary to have global knowledge of the network when implementing certain dynamic RWA schemes [24]. Adaptive routing approaches come under dynamic RWA schemes.

3.2 Wavelength Assignment Strategies

Wavelength Assignment is the main factor that affects the blocking probability and thereby the performance of the network. Proper assignment of wavelengths can lead to reduced or no use of wavelength converters which can significantly reduce the cost. As stated above, wavelength assignment can be broadly classified into two categories, static (off-line) and dynamic (on-line) assignment [14] [22]. In a static assignment scheme the same wavelength is assigned, if available, for every lightpath request generated at a node or else the request is blocked. In dynamic assignment the node at which the request is generated uses a particular algorithm that selects a particular free wavelength at that node, if available, and then assigns it to that request and routes it, otherwise the request is blocked. Most of the assignment strategies available in the literature are dynamic in nature. The algorithm for every assignment scheme maintains a list of used and free wavelengths at each node. Whenever a call is generated the node selects a wavelength from the set of free wavelengths and assigns it to that call. Some of the proposed wavelength-assignment algorithms are as follows:

- Random wavelength assignment: In this strategy, the node maintains a list of free wavelengths at every instant. Whenever a call is generated the node randomly chooses a wavelength λ_j from the set of free wavelengths and assigns that wavelength to that call [20]. The set of free wavelengths is updated by removing λ_j from the free list. When the call is completed, then wavelength λ_j is removed from the list of used wavelengths and is added again to the set of free wavelengths. In this manner the set of free wavelengths is updated every time a call is answered or when the holding time for the answered call is over. The random assignment distributes the traffic randomly so that wavelength utilization is balanced. Selecting a wavelength randomly makes contention for the wavelength low thereby resulting in lower blocking rate.

- First-fit wavelength assignment: This strategy is implemented by predefining an order on the wavelengths. The list of used and free wavelengths is maintained. The assignment scheme always chooses the lowest indexed wavelength λ_f from the list of free wavelengths and assigns it to the request [4]. When the call is completed the wavelength λ_f is added back to the free wavelength set. The disadvantage of this approach is that the lower indexed wavelengths are much more heavily used compared to others; the higher indexed wavelengths are hardly used. Hence for certain wavelengths the utilization is very low. Further, an increase in the number of wavelengths per fiber does not result in improvement in performance as the highest numbered wavelengths are rarely used. Since all the nodes in the network use the lower numbered wavelengths, contention for these wavelengths increases which results in higher blocking probability.
- Most-used wavelength assignment: In this strategy, the free wavelength that is used on the greatest number of fibers in the network is assigned to the request. If several available wavelengths share the same maximum usage, the wavelength with a specific index, for example the lowest index, is chosen.
- Least-used wavelength assignment: It is similar to the most-used wavelength strategy, but in this strategy the least used wavelength in the network is assigned. This technique is also called Spread scheme assignment [20]. The main purpose

of this approach is to achieve a near-uniform distribution of the load over the wavelength set.

Of the above strategies, random and first-fit techniques are the most practical, as these are simple to implement. Unlike Most used and Least used they do not require global knowledge of the network. They simply depend on the state of the node at that instant and choose the wavelength from the set of free wavelengths at that output link. As they are unaware of the state of the network, the assignment strategy will not yield optimum results. Comparatively, random assignment works better than first-fit assignment as it can choose any of the free wavelengths. This results in less contention for the same wavelength by different nodes at any instant of time.

In order to implement most-used and least-used assignment approaches, each node should have the knowledge of the entire network. The performance of these assignment strategies depends on how accurately the nodes have knowledge of the network. As the state of the network changes rapidly, it is very difficult to have exact knowledge of the network at all times and this may affect the wavelength assignment. Moreover the nodes exchange the state of the network with the neighbors after every fixed interval and these messages may consume network bandwidth to a considerable extent thereby reducing the available bandwidth for data communications. Moreover these algorithms require additional storage and are complex to implement [8].

Wavelength assignment is often compared with the Graph-coloring problem [16]. Given a graph, assigning colors to the paths, so as to we minimize the number of colors used gives the graph-coloring problem. The following method describes the graph-coloring approach. Construct a Graph G = (V, E), so that a node in the graph represents each lightpath. There is an undirected edge between two nodes in graph G if the corresponding lightpaths pass through a common physical fiber link. Now color the nodes of the graph G such that no two adjacent nodes have the same color. This problem is NP-complete [17]. Also the minimum number of colors needed to color a graph G, (which is known as the chromatic number) is difficult to determine. If we are given a fixed number of colors then we do have efficient *sequential graph-coloring* algorithms, which are optimal for allocation of the given number of colors. In a *sequential graph-coloring* approach, nodes are sequentially added to the portion of the graph already colored, and new colorings are determined to include each newly adjoined vertex. At each step, the total number of colors necessary is kept to a minimum [16].

3.3 Virtual Path Establishment

A virtual path is nothing but the path taken by the light from the source to the destination [8]. Whenever a call is generated at a node, the node uses the routing and wavelength assignment algorithm to find the outgoing link and wavelength to the destination. It assigns the selected wavelength to that call and routes it to the next node on the path. At each intermediate node of the route, the wavelength that the lightpath arrived on is checked for availability for the next hop. If it is available that wavelength is assigned. If that wavelength is not available, and the node has a wavelength converter the node may be able to convert to another wavelength and route the lightpath. If there is no converter or if there is no available (free) wavelength on the outgoing link the call is blocked. This approach is followed at every intermediate node in the route. The path that is established is called a virtual path. It is worth pointing out that path establishment follows a circuit switching scheme. The path is established fully before any data is transmitted, typically a probe or a header.

The physical path consists of all the links that form the route from the source to the destination, but the virtual path may consist of the same or different wavelengths from the source to the destination. Two requests from the same source to the same destination could have the same physical path but could have different virtual paths. Figure 3.1 shows the formation of a light path. Here two calls are generated at node 1 and the virtual path for each generated call is shown. For the first call, node 1 assigns wavelength λ_1 and routes it to node 2. Node 2 is assumed to have a converter. But λ_1 is unavailable to assign it to the first call. Hence it converts the wavelength to λ_2 and routes it to node 3. Node 3 assigns λ_2 as it is available and routes it to the destination. In this way virtual path1 is established. Similarly if another call is generated at node 2 at another instant, then following the routing and wavelength assignment algorithm virtual path2 is established.

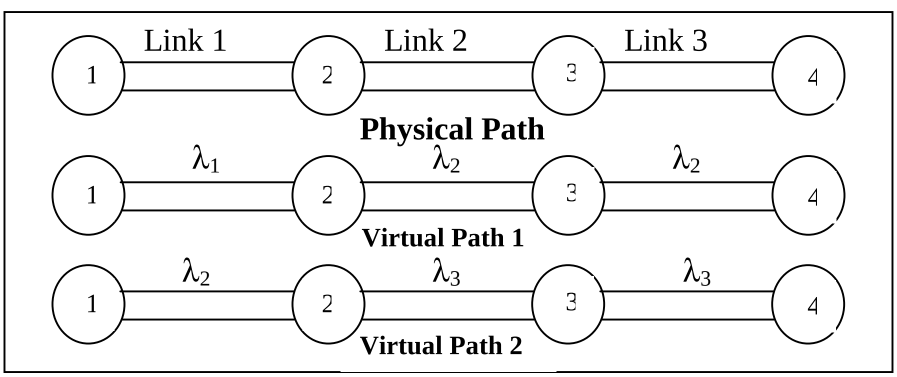


Figure 3-1: Physical and Virtual Paths.

It is shown that though the physical path is same between the source and destination for different calls, the virtual paths established are different. The total number of virtual paths (the upper bound) that can be established from the source to the destination depends on the number of wavelengths per fiber. The actual number of established virtual paths depends on the call arrival rate, among other things. Wavelength converters help in establishing larger number of virtual paths for a given set of requests thus minimizing the overall blocking probability.

The problem of converter placement was defined as an integer-linear programming (ILP) problem [3]. The problem is defined as follows. Let the maximum offered traffic (the number of sessions) for all node pairs (s,d) be λ_{sd}. Also let M_{sd} be the actual number of sessions established between *s* and *d*. The problem is to determine the converter locations so that $\Sigma_{s,d} M_{sd}$ is maximized subject to the wavelength continuity constraint on segments between successive converters and traffic demand constraints, i.e., $M_{sd} \leq \lambda_{sd}$. This problem is shown to be NP-complete for arbitrary topologies and rings.

Barry and Humblet [15] modeled the blocking probability with and without wavelength converters for simple traffic models. They have shown that the blocking probability with and without wavelength converters increase with the number of hops. The effect is much more dramatic in networks without wavelength converters since the number of calls a given call shares a link with tends to increase with the number of hops. They demonstrated that minimizing the network diameter and employing minimum hop routing would reduce the blocking probability.

In [17] optimal converter placement solutions for the bus and ring topologies were proposed for both uniform and non-uniform traffic. It was shown that considerable gains in blocking performance could be obtained when optimal placement was used compared to the case of random placement. It was observed that uniform placement gives a modest performance improvement over random placement. Uniformly spaced converters produced optimal performance when the link loads were uncorrelated and uniform. Dynamic programming for the optimal placement of converters was proposed for non-uniform traffic.

In [2], a wavelength converter placement heuristic was presented which places wavelength converters at nodes with highest average output link congestion. While the heuristic gives almost optimal results for the NSFNET network, it does not give near-optimal results for the simple case of a ring topology with uniform traffic. In [16] it is proved that optimal placement to reduce blocking probability is obtained when the segments on the path have equal blocking probabilities. However, optimal placement was not always obtained since it was not always possible to divide the path into segments with equal blocking probabilities.

In [10] the concept of sparse wavelength conversion was introduced and an analytical model of modest complexity was suggested. It was shown that the usefulness of wavelength converters depends on the connectivity of the network. When the connectivity is low, as in the ring, converters are not very useful because of the high load correlation. When the connectivity is high, such as in the hypercube or a densely connected random topology, converters are not very beneficial because of small hop-lengths, despite low load correlation and significant traffic mixing. A mesh-torus network with a degree of connectivity between those of the ring and the hypercube offers great advantages when wavelength converters are present. It was also shown that wavelength converters are more effective when the number of wavelengths is larger and when the load is lower. The improvement in the performance with respect to the converter density (number of converters to the total number of nodes) was also studied [10]. It was shown that performance improves rapidly as the conversion density increases from zero, but the rate of improvement typically decreases with increasing conversion density.

In [6] the problem of limited wavelength translation in wavelength routed, all optical WDM mesh networks was examined. They demonstrated that limited wavelength translation of fairly small degree is sufficient to obtain benefits comparable to those obtained by full wavelength translation. They proved that the efficiency of the network depends on the extent of translation and not on the total number of wavelengths per fiber. Network performance improves as the extent of translation increases, but the rate of improvement typically decreases with the increase in extent of translation.

Chapter 4

New Wavelength Allocation Strategies and Simulation Results

Previous work has shown that wavelength converters can help in decreasing the blocking probability considerably. However, taking the cost factor into consideration the improvement obtained is not necessarily satisfactory. It is observed that the blocking probability depends more on wavelength assignment than on the number of converters or converter placement. We hypothesize that having an effective wavelength assignment technique can outperform networks with wavelength converters while reducing the cost. This thesis attempts to support the hypothesis and to improve on existing approaches for the RWA problem. We introduce and prove the effectiveness of novel and simple off-line and on-line assignment strategies that have very low blocking probabilities.

4.1 Our Approach

As was explained earlier, that the spread of optical networks from long haul to metropolitan rings and now to customer premises locations has created the demand for effective topologies and assignment techniques. In the literature it has been shown that ring topology had many drawbacks [6]. Mesh topologies are becoming the most popular topologies in metropolitan networks [7]. Most networking operators are migrating from ring to mesh topology. As we stated earlier a few of the reasons for such migration are the ease of scaling, network restoration and operating costs. Our work focuses on 2D mesh networks. We propose off-line and on-line assignment techniques for the mesh topologies. We show through extensive simulations that our proposed approaches perform very well and in most cases outperform existing schemes. It is also shown that the proposed approaches work well not only for mesh topologies but for ring networks also. As explained our approaches try to make use of the available wavelengths in such a way that the contention for the same wavelength are reduced.

In order to show that our approaches work well we had to rely on extensive simulations. We were not able to access a good simulator that takes care of our proposed approaches with the required parameters. Therefore, we designed and developed a simulator in the C language to implement our proposed approaches. We ran extensive simulations with different parameters to obtain comprehensive results. We also simulated the existing schemes under the same set of assumptions so as to report fair comparisons.

4.1.1 Dynamic Assignment

The blocking probability depends on how well the available wavelengths are utilized. The First-fit approach tries to use to first free wavelength thus using the last numbered wavelengths rarely. As will be shown this causes more blocking and affects the performance adversely. The random assignment approach is good with respect to utilization but the lack of definite approach may not be useful in all cases and may become a drawback in some cases.

We propose a new on-line (dynamic) wavelength assignment for the mesh topologies called ***Round-Robin*** assignment. Under this strategy, the wavelengths are indexed and the assignment algorithm starts by assigning the first numbered wavelength for the first requested lightpath at that node. When a subsequent request arrives, the node chooses the next numbered wavelength and so on. This process continues in a round-robin manner. The first wavelength is reached again after all the wavelengths in the available set have been assigned. In this way each wavelength is used for wavelength assignment at some point. Hence we try to utilize the available wavelengths at all the nodes in the network to the maximum extent possible so as to minimize the blocking probability. We report the simulation results for our new approach as well as existing ones in section 4.2.

4.1.2 Static Assignment

Not much work has been done on static assignment strategies. In static assignment each node will be assigned a specific wavelength. Whenever a request is generated at a node, it assigns the specified wavelength to that request. For every lightpath request that is generated at any time at a given node, that node will use the same specified wavelength. A possible assignment scheme for an 8*8 mesh is shown in Figure 4-1. Here it is assumed that there are an equal numbers of wavelengths per fiber that is also equal to the number of nodes in each dimension. In this scheme each node is assigned to use the wavelength whose index equals the column number of the node. If we assume dimension (order XY) routing, then it can be seen from the figure that during routing no call can blocked in the row. Blocking occurs only on the columns. In general off-line schemes must be based on some logic that attempts to minimize the possibility of blocking. Figure 4-2 shows a possible assignment scheme for 8*8 mesh with 16 wavelengths.

In this context we take some recently proposed static assignment schemes [33] and evaluate their performance. We consider schemes with different number of wavelengths that produce good results with respect to blocking probability. The main aspect lies in trying to reduce the contentions for the same wavelength by different nodes in the network. Simulation results for off-line assignments will be reported in section 4.2.

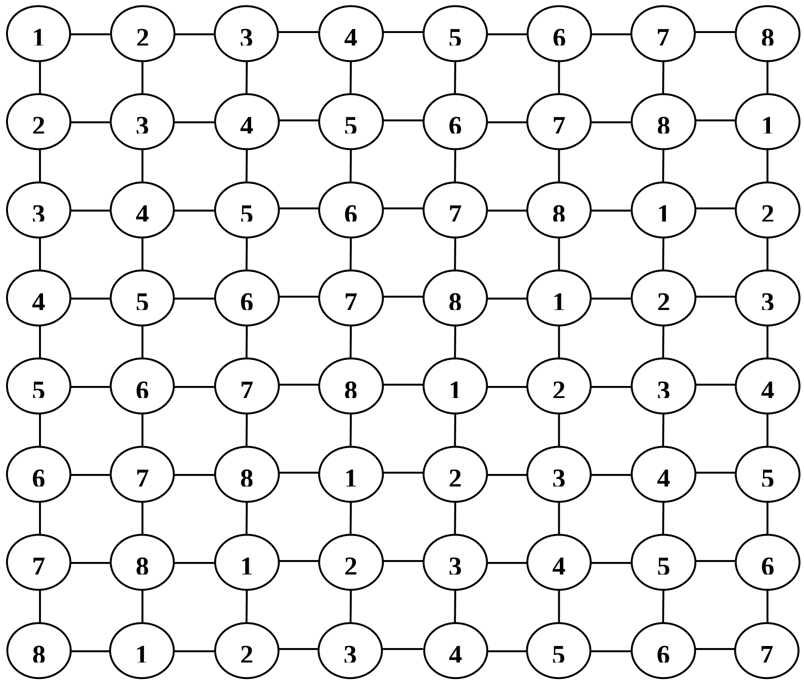


Figure 4-1: A possible static assignment in 2D mesh with 8 wavelengths.

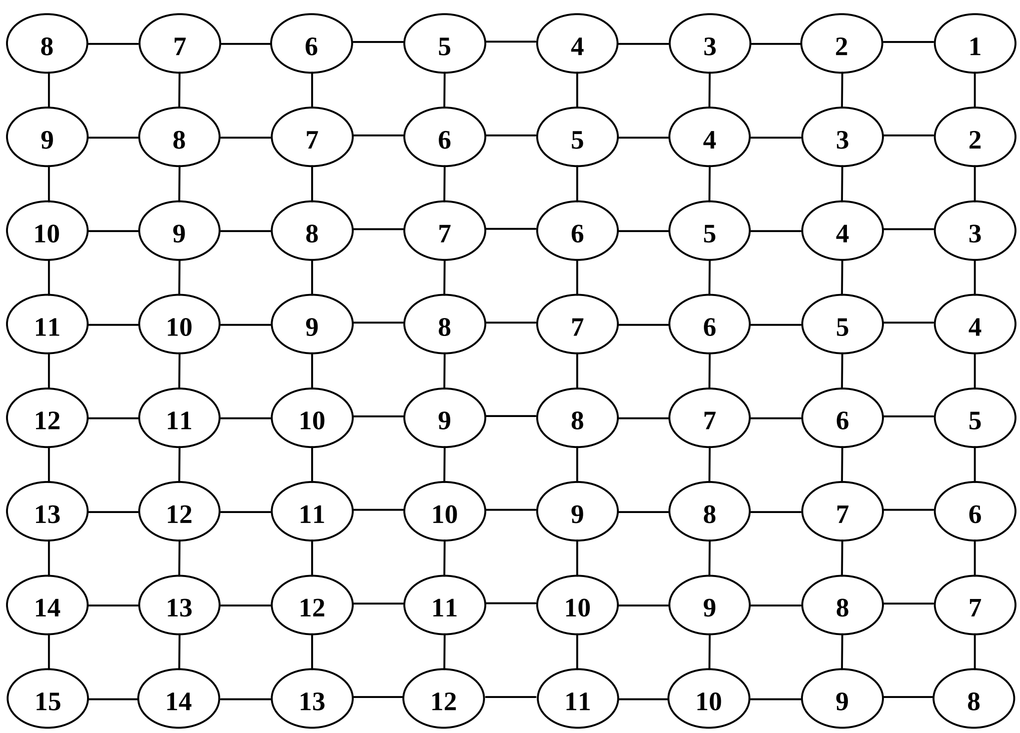


Figure 4-2: A possible static assignments in 2D mesh topology with 16 wavelengths.

4.1.3 Converter Placement

Wavelength converters tend to reduce the blocking probability in the network. One extreme is placing a full wavelength converter at every node in the network so as to reduce the blocking probability to zero. But this is not a practical solution as it ignores the cost factor. Wavelength converters are expensive and noise prone. So we are likely to use fewer converters. Hence the problem of optimal converter placement comes into picture. As reported in chapter 2, many heuristics have been proposed in the literature to reduce the blocking probability. Uniform and random placement of converters may work well with arbitrary topologies, but with respect to the mesh these placement techniques do not yield optimal results.

In mesh using XY routing larger traffic is concentrated at the center. Thus placing converters at the boundaries for instance do not yield good results. Hence for the mesh we propose placement strategies that place converters near or at the center of the mesh. We ran extensive simulations with a fixed number of converters with converters placed in different ways. We show through simulations that best results are obtained when the converters are placed at the center compared to uniform or random placements.

4.2 Results

In this section we present the results obtained for our proposed approaches. We compare the results with the approaches presented in the literature and show that our approaches perform better. We ran extensive simulations for the same set of parameters for different approaches in order to compare their results. First we compare the on-line assignment strategies varying the parameters for the mesh and the traffic. Then we present the results obtained for some off-line assignment strategies. Further, we compare the on-line assignments with the proposed off-line assignments. Wavelength converter placement is also studied for mesh topology for both on-line and off-line assignment strategies with the different converter placements. Our converter placements are then compared with the traditional uniform placement.

4.2.1 Simulator Setup

No heuristics could be validated until they are supported by practical results. In order to demonstrate that our approaches perform better than those reported in the literature and to investigate the performance of the new off-line assignments we must resort to simulations. Not able to find a suitable simulator that could support our proposed heuristics, we designed and developed a simulator to implement wavelength assignment and wavelength converter placement in all-optical networks for mesh topologies. The simulator was developed in the C language. The simulator accepts input parameters such as the dimension of the mesh, number of wavelengths per fiber, lightpath requests are generated dynamically. All of the requests that arrive at the nodes are not answered successfully. Some of the calls will be blocked because of the unavailability of a free wavelength on a link from the source to the destination. The ratio of the total number of calls blocked to the total number of calls that arrived at all the nodes in the network is defined as the blocking probability. The output of the simulator is the blocking rate for the specified parameters. As observed in the literature [1] [19] [20] the lightpath requests arrive at the nodes following Poisson arrivals. The length of the call (holding time) is assumed to be an exponentially distributed random variable with unit mean. The arrival rate for the requests can be varied from 0 to 1. The requests with the given arrival rate and holding time can be generated for the required time period which is taken in seconds.

All these parameters can be initialized before running the simulations to obtain results for a given selection of parameters. Extensive simulations are then carried out for every combination of parameters of interest and the obtained results are tabulated. The simulator assumes that the source and the destination of the arrived request must be available (or free) in order to establish the lightpath for that request. If either is busy then that request is not counted in calculating the blocking probability. The blocking probability is then calculated as the ratio of the total number of requests blocked to the total number of requests that arrived at all the nodes in the network.

4.2.2 Dynamic (on-line) Assignment Strategies

As stated in the previous sections with dynamic assignment, whenever a lightpath request arrives at a node, the node executes a routing and wavelength assignment algorithm that selects a wavelength for the next hop and routes the call using that wavelength. Random wavelength assignment and first-fit assignment techniques are the most important among the previously proposed techniques. The drawback of the first-fit assignment technique is that the wavelengths are not utilized uniformly as it tries to use the lowest indexed wavelengths always leaving the highest indexed wavelengths unused most of the times. The Random assignment technique suffers from the lack of a definite approach for wavelength assignment and that may not yield good results in some cases. We propose a new assignment approach called ***Round-Robin*** assignment. In this assignment, the wavelengths are indexed. The assignment algorithm starts with assigning the first indexed wavelength for the first requested lightpath at that node. With every subsequent request, the node chooses the next numbered wavelength and so on. This process continues in a round-robin manner and the first wavelength is reached again after all the wavelengths in the available set have been assigned. In this manner all the wavelengths are utilized equally. As we will show, this helps in reducing the blocking probability considerably. Figure 4.3 compares the results for the three assignment approaches. The simulations are executed for an 8*8 mesh with the arrival rates ranging from 0.25 to 0.75. Eight wavelengths per fiber are assumed.

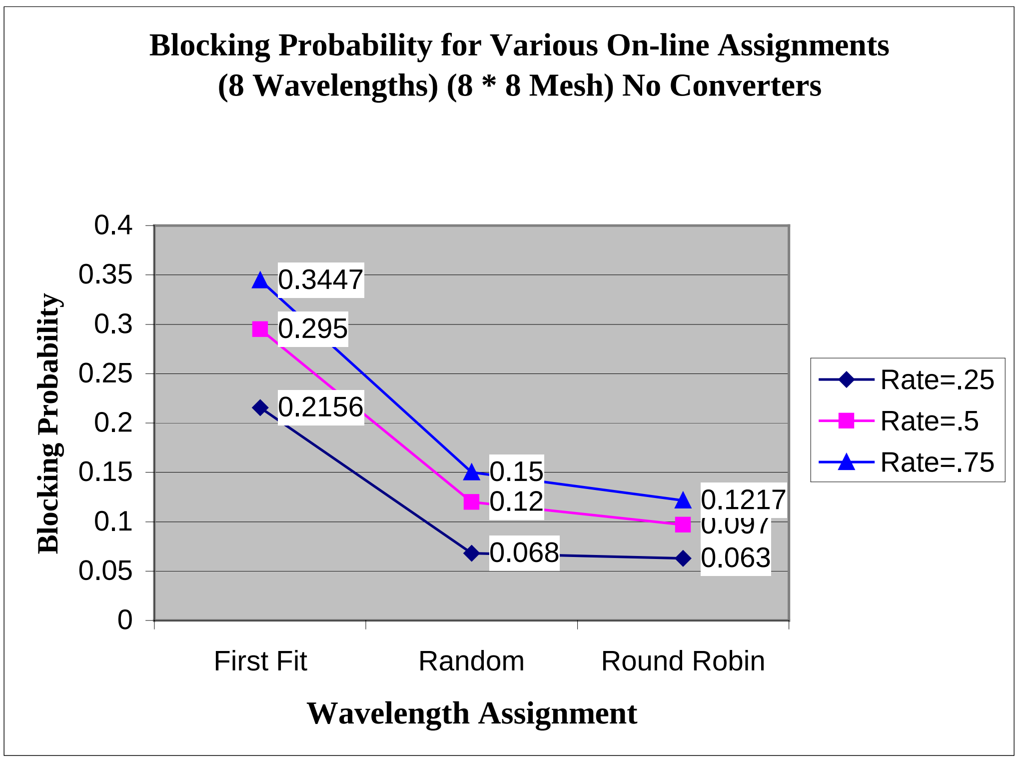


Figure 4-3: Blocking Probability for on-line assignments.

From the figure it is clear that First-Fit assignment performs poorly when compared to the other assignment techniques. The Random assignment scheme performs better than First-Fit as it tries to utilize the wavelengths in a better manner. But it can be seen that Round-Robin assignment performs better than the others for different arrival rates. The improvement over Random assignment ranges from 8% to 18% depending on the arrival rate. 65% to 75% improvement is obtained over first-fit assignment. It can also be observed that initially the blocking probabilities are lower when the arrival rate is lower. The blocking probabilities increase as the arrival rate is increased. When the arrival rate is lower, requests at the nodes are fewer and hence contention for the same wavelength is less. As the arrival rates increase the number of requests increases and contention for the wavelengths becomes higher and blocking probability increases.

4.2.2.1 Changing the Number of Wavelengths

Figure 4.4 compares the blocking probabilities for the mentioned assignment techniques for different number of wavelengths and arrival rates. As the numbers of wavelengths is increased the nodes will have more wavelengths available for assignment. Hence they can accept more requests thus reducing the blocking probability.

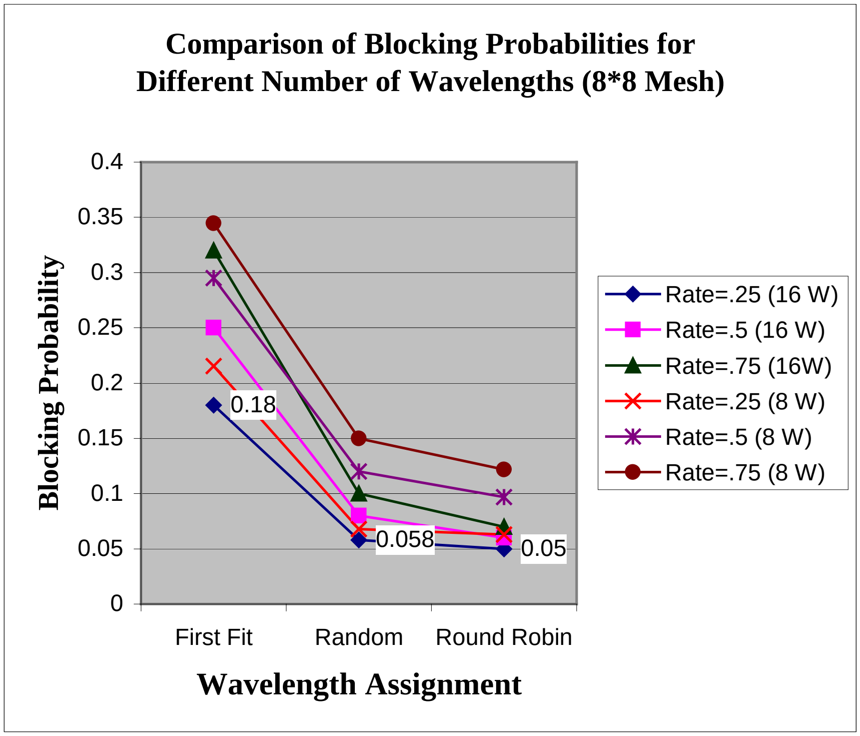


Figure 4-4: Blocking Probability for Different Number of Wavelengths.

It is observed that the increase in blocking probability for higher arrival rates is very less for round-robin assignment. 20% to 40% improvement is obtained using 16 wavelengths with round-robin over 8 wavelengths. Even with 16 wavelengths round-robin performs better than random assignment. We observed a 15% to 30% improvement over random assignment for different arrival rates.

4.2.2.2 Changing the Mesh Size

Figure 4.5 compares the results for different mesh sizes. As mesh size is increased the average distance between source and destination is increased. An increase in average distance implies an increase in the number of links a particular wavelength is held during lightpath establishment. Also as network size increases number of requests also increases. All these can result in higher blocking probability as the network size increases for a fixed number of wavelengths. Figure 4.5 conforms to the above logic.

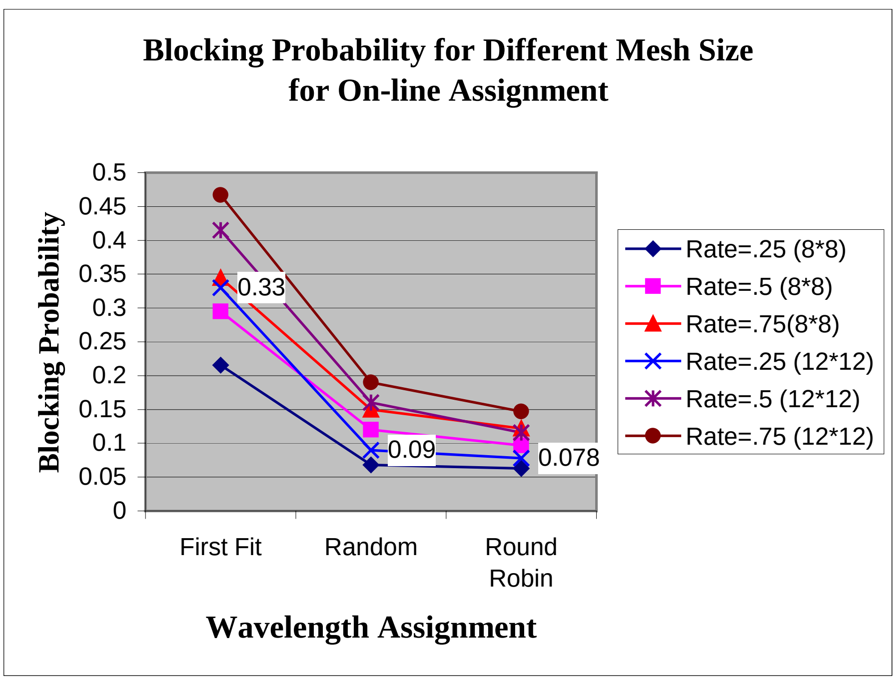


Figure 4-5: Blocking Probability for Different Mesh Dimensions.

It can be seen for instance that as the size is increased from 8*8 to 12*12, the blocking probability is increased by 20% with round-robin; Whereas the increase is 30% with random assignment and 42% with first-fit scheme.

4.2.3 Results for Static (Off-line) Assignment Schemes

Dynamic assignments are more complex to implement compared to static assignments. It has been hypothesized [43] that the blocking probability can be further reduced by proper static assignment of wavelengths. In static assignment each node will be assigned a preferred wavelength to use to establish the lightpath requests sourced at that node. For every lightpath request that is generated at any time at a given node, that node will always use the same specified wavelength. Hence wavelength assignment becomes simpler. Figure 4.1 shows a static assignment with n wavelengths for an n*n mesh. Figure 4.2 shows a 2n assignment.

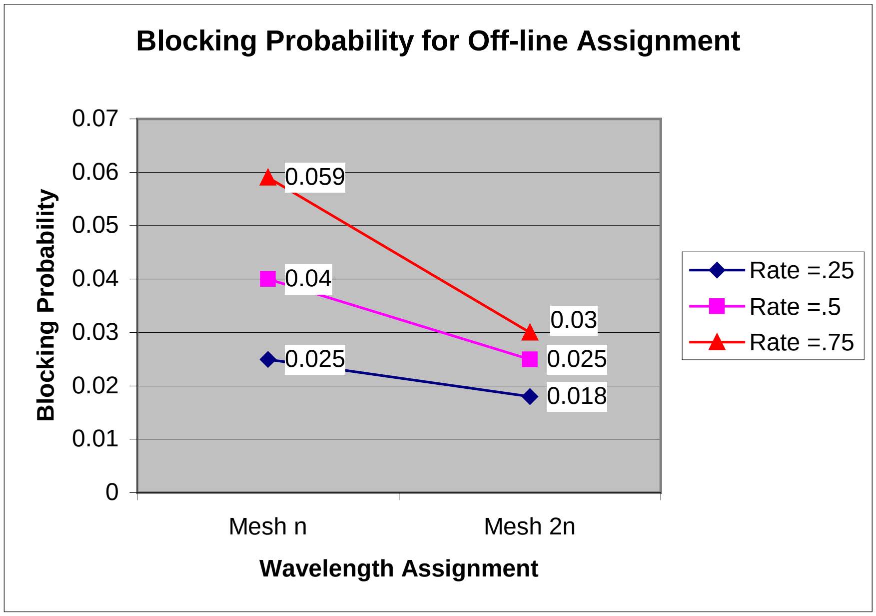


Figure 4-6: Static (off-line) Wavelength Assignment.

Figure 4.6 shows the results for two off-line strategies with 8 (Mesh n) and 16 (Mesh 2n) wavelengths for different arrival rates for an 8*8 mesh. It is observed that as the number of wavelengths is increased the blocking probability reduces further because of the availability of larger number of wavelengths thus reducing the contention for the same wavelength. But as the arrival rate is increased the number of requests increases thereby increasing the blocking probability. As can be seen the increase in blocking probability (as the arrival rate increases) is smaller for 16 wavelengths compared to 8 wavelengths. We observed 30% to 50% reduction in blocking probability with 16 wavelengths compared to 8 wavelengths.

4.2.4 Comparison of Dynamic and Static Assignment Strategies

As discussed earlier the blocking probability depends on the successful utilization of the available wavelengths. On-line assignments are more complex than off-line assignments. Off-line assignments should be done by careful selection of the wavelengths so as to minimize contention for the same wavelength as much as possible. Improvement in performance of on-line assignments is not considerable even when we increase the number of wavelengths. On the other hand, off-line assignments work much better as the number of wavelengths is increased.

Figure 4.7 compares the on-line and off-line assignment strategies for an 8*8 mesh with 8 wavelengths. It can be observed that the off-line assignment performs better than the on-line assignments for the same set of parameters. The wavelength assignment for the off-line scheme used is as shown in Figure 4.1. In the shown scheme, each node in the same row is assigned a wavelength with an index different from the rest of the nodes in the row. This wavelength is used to route a call to the next hop. This assignment does not cause any blocking along the row. Blocking may occur only along the columns. This may explain why the blocking probability for off-line schemes is very low when compared to the on-line schemes. We noted 50% to 60% reduction in blocking probability using off-line scheme with 8 wavelengths compared to the best on-line (round-robin) scheme.

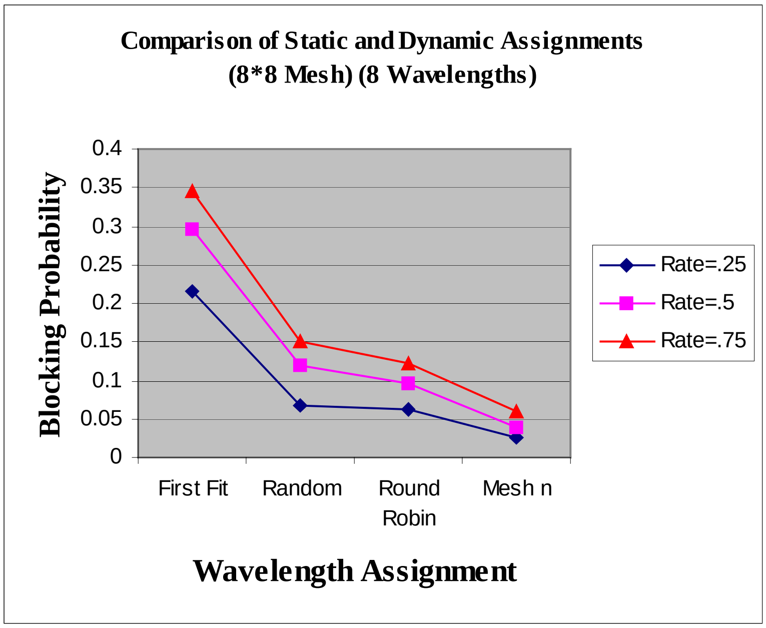


Figure 4-7: Comparison of static and dynamic wavelength assignments (8 Wavelengths).

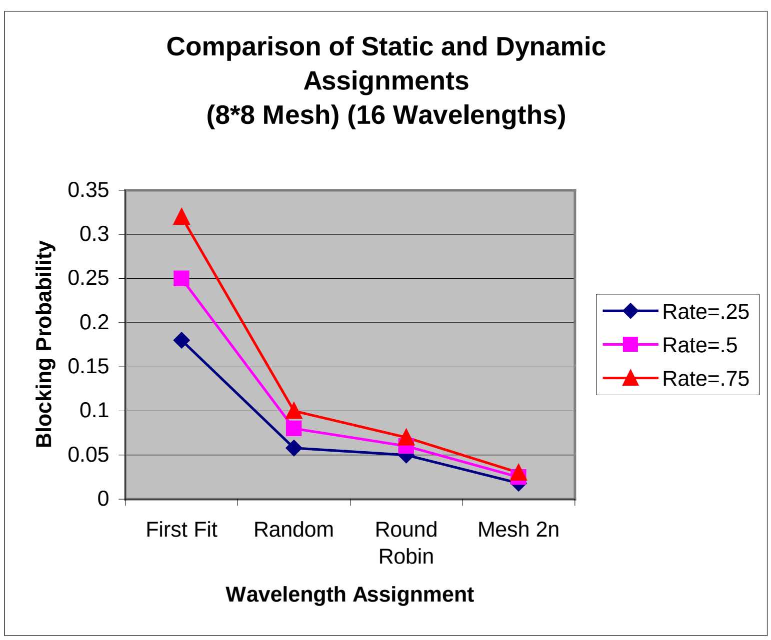


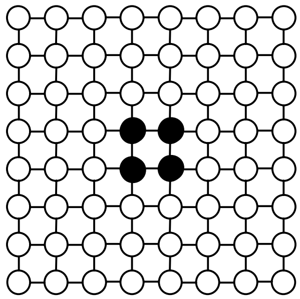
Figure 4-8: Comparison of static and dynamic wavelength assignments (16 Wavelengths).

Even as the arrival rate is increased the increase in blocking probability is less for off-line schemes when compared to the on-line schemes. Figure 4.8 compares the strategies for 8*8 mesh with 16 wavelengths. Notice that the blocking probability is very low with 16 wavelengths for off-line assignment. It almost remains constant even at higher arrival rates. Availability of more wavelengths in off-line schemes reduces the contention for the same wavelength. This results in very low blocking probability. With 16 wavelengths 55%-65% performance improvement is obtained using off-line scheme when compared to round-robin assignment.

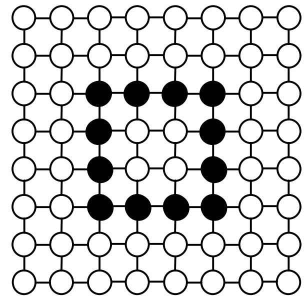
4.2.5 Wavelength Converter Placement

Wavelength converters can help in overcoming the *wavelength-continuity constraint* thereby decreasing the overall blocking probability. Hence, in general, networks with wavelength converters can perform better than the networks without them. Wavelength converters are costly and hence having them at all the nodes in the network is not feasible. This makes the problem of optimal converter placement for a given number of converters significant. According to the heuristics reported in the literature [9] [17] [18] placing the converters at the nodes where maximum traffic mixing takes place may be a better option. In mesh most of the traffic is concentrated at the center. Hence we propose to investigate placement of the converters at or near the center of the mesh.

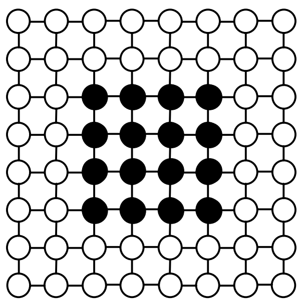
Figure 4.9 shows the different converter placements in a 2d mesh. Figure 4.9.a shows the converter placement with 4 converters placed at the center of the mesh. Figure 4.9.b and 4.9.c show similar placements at the center with 12 and 16 converters. Uniform converter placement with 21 converters is shown in Figure 4.9.d. Simulations are run for the specified converter placements for off-line and on-line approaches.



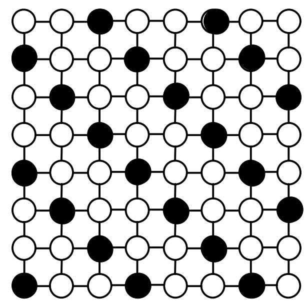
a) Placement with 4 Converters



b) Placement with 12 Converters



c) Placement with 16 Converters



d) Uniform Placement with 21 Converters

Figure 4-9: Different converter placements in 8*8 mesh.

Figure 4.10 compares the blocking probability for the off-line and on-line assignments with and without converters as placed in Figure 4.9. As expected the blocking probability is lower when converters are used. When XY routing is used, traffic is more concentrated at the center. Placing converters at the center gives better results than with uniform placement for the mesh. It can be observed from Figure 4.10 that even with converters, off-line assignments work better than on-line assignments. It is also observed that even with converters, the improvement obtained is not significant when we take cost into consideration. Hence it can be concluded that assignment strategies affect the blocking probabilities more than the number of converters. Choosing a good assignment strategy rather than going for converters can be more favorable especially when the cost is taken into consideration.

As shown in Figure 4.10 the values on the x-axis represent the number of converters used in an 8*8 mesh. The value 0 on the x-axis corresponds to the blocking probability obtained for different assignments when no converters are used. The value 4 corresponds to the case when 4 converters are placed as shown in Figure 4.9.a. Similarly the values 12 and 16 correspond to the converter placement in Figure 4.9.b and 4.9.c, respectively. The 16u corresponds to placing the converters uniformly in the 2D mesh. The 21u corresponds to uniform placement with 21 converters as shown in Figure 4.9.d. The difference in blocking probabilities using the same number of converters can be observed for the values of 16 and 16u.

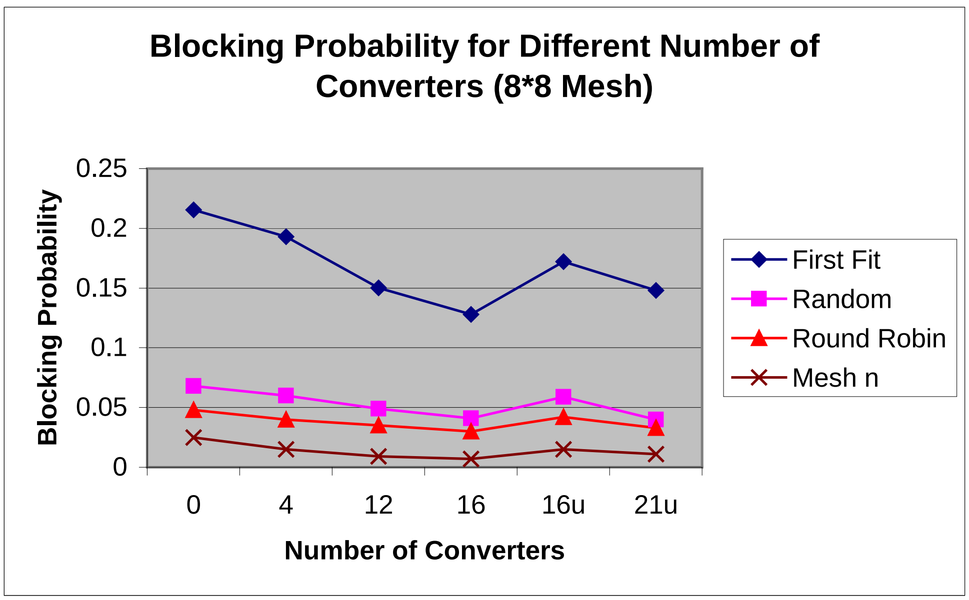


Figure 4-10: Blocking Probability with Different Number of Converters.

It shows that uniform placement does not yield better results in 2D mesh with XY routing. Even using 21 converters with uniform placement does not give better results when compared to placing 16 converters at the center. On an average 15%-40% improvement is observed using converters with on-line schemes. Whereas, 40%-70% improvement is obtained with converters for off-line schemes. Thus, clearly with XY routing in 2D mesh, placing converters at the center gives better results. This supports the hypothesis that converters are better utilized when placed at nodes with high traffic.

4.2.6 Blocking Probability with Second Trial

Blocking occurs when the requested wavelength is not available on all the links that form the route. Even though we try to assign the wavelengths carefully, the wavelength utilization would still be less. There will be many free wavelengths even when a call is blocked. There may be chances of the call being able to go through if it is routed again but with another wavelength. We propose a new concept of attempting to route the blocked call a second time on another wavelength. The assignment algorithm for this approach works as follows. First the lightpath request is routed with the initially assigned wavelength. If that request is blocked with that wavelength, then the same request is routed with another pre-selected wavelength.

This new approach can also be simulated with on-line and off-line strategies. Results show that the blocking probability is very much reduced when the call is re-routed using the second trial. The blocking probability with the second trial is calculated as the ratio of the total number of lightpath requests blocked after second trial to the total requests generated at all the nodes in the network.

4.2.6.1 Blocking Probability for On-line Assignment with Second Trial

As mentioned attempting to route the first blocked call with another wavelength can reduce the blocking probability. All the on-line assignments described in the previous sections can be implemented using the second trial approach also. In the First-Fit assignment when a call is blocked for the first trial, the next available wavelength is used to route the lightpath for the second trial. For the Random assignment, the routing algorithm randomly selects another wavelength from the available set of wavelengths and assigns this wavelength to establish the lightpath. In case of Round-Robin assignment, the next indexed wavelength is used to route the lightpath for the second time. In this way lightpaths are routed for the second time in case of failure in the first attempt.

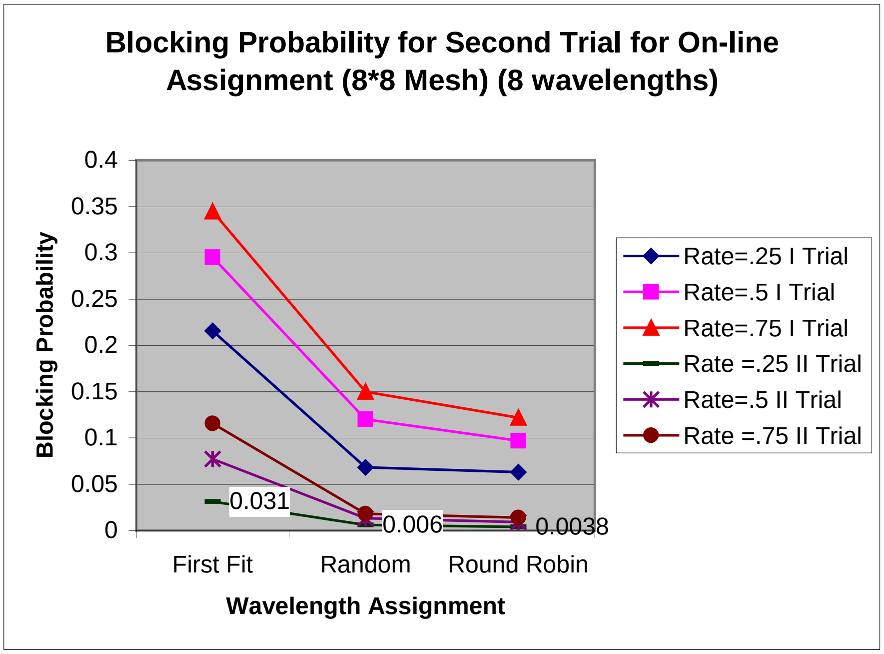


Figure 4-11: Blocking Probability for Second Trial with on-line Assignments.

Extensive simulations were run for different traffic arrival rates and the obtained results are compared in Figure 4.11. As stated, the blocking probability after the second trial is reduced considerably for all the assignments. However, Round-Robin assignment still works better even here. Also with the second trial the blocking probability is nearly constant for different traffic arrival rates for the Round-Robin assignment. The average percentage reduction in blocking probability with the second trial is about 70%-85%. The improvement with round-robin scheme is around 87%, with random it is about 80% and it is around 60% with first-fit assignment.

4.2.6.2 Blocking Probability for Off-line Assignment with Second Trial

Similar to the on-line assignment, the second trial approach can be used with off-line strategies as well. For an 8*8 mesh with 8 wavelengths the procedure is as follows. For the first time, the source uses the index number of the source to assign to the lightpath for routing. If this request is blocked then the source uses the index number of the destination to establish the lightpath. Similar assignment can be established using 16 wavelengths. Simulations were run for the mesh with 8 (mesh n) and 16 (mesh2n) wavelengths for the off-line assignments for the same set of parameters and the results are shown Figure 4.12.

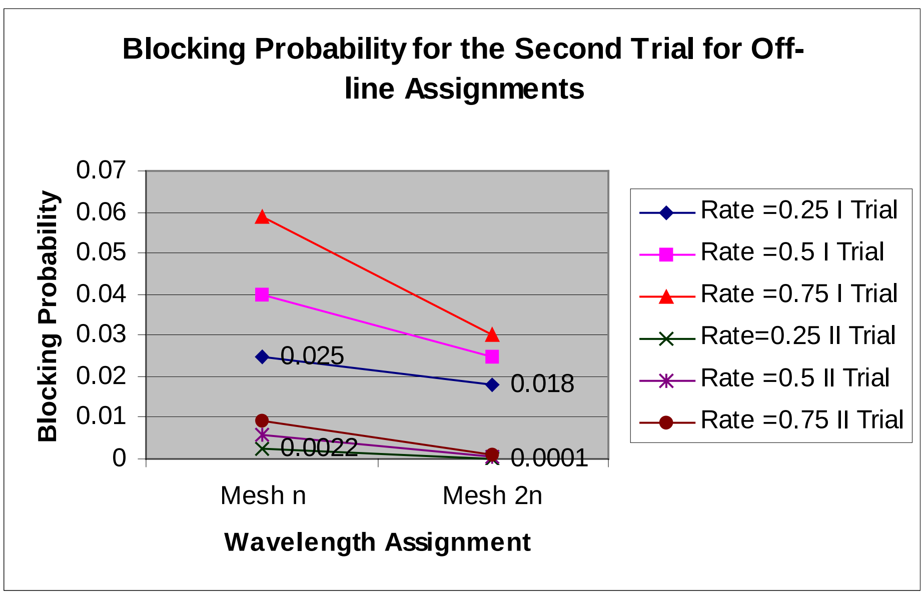


Figure 4-12: Blocking Probability for Second Trial with off-line Assignments.

It can be seen that the blocking probability with two trials is extremely low when compared to the case of one trial. Blocking probability with 16 wavelengths is extremely low and is very much constant for all the arrival rates. The improvement obtained with the off-line assignments using second trial is more than the improvements with on-line assignments because of effective wavelength utilization of the former schemes. On an average 90% reduction in blocking probability is observed with second trial using 8 wavelengths. With 16 wavelengths the improvement is about 98%.

4.2.6.3. Comparison of on-line and off-line Assignments with Second Trial

The results for the on-line and off-line assignment's blocking probability with the second trail are compared in Figure 4.13. Even here it can be seen that off-line assignment performs better than the on-line assignments.

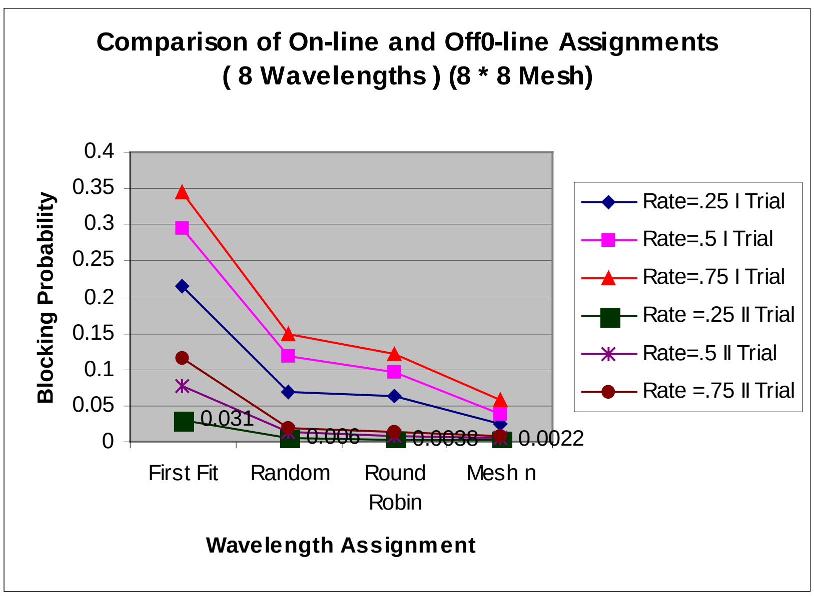


Figure 4-13: Comparison of on-line and off-line Assignments with second trials.

The blocking probability for the off-line assignment is almost constant with the second trial irrespective of the arrival rates. Attempting to route for the second time with proper selection of another wavelength proves to be beneficial in reducing the blocking probability. Table 4-1 shows the percentage reduction in blocking probability obtained using the second trail approach with 8 wavelengths for an 8*8 mesh. It is observed that blocking probability is reduced by close to 90% for all assignments. Table 4-2 shows the reduction in blocking probability with 16 wavelengths.

Table 4-1: Percentage Reduction in Blocking Probability with 8 wavelengths.

Assignment	Blocking Probability with First Trial	Blocking Probability with Second Trial	% Reduction in Blocking Probability
First Fit	0.2156	0.031	85.62
Random	0.068	0.006	91.18
Round Robin	0.063	0.0038	93.97
Mesh n	0.025	0.0022	91.20

Table 4-2: Percentage Reduction in Blocking Probability with 16 wavelengths.

Assignment	Blocking Probability with First Trial	Blocking Probability with Second Trial	% Reduction in Blocking Probability
First Fit	0.18	0.021	88.33
Random	0.058	0.004	93.14
Round Robin	0.05	0.002	96.00
Mesh 2n	0.018	0.0001	99.44

Chapter 5

Conclusion and Future Scope

All-Optical Networks are supposed to be the networks that satisfy the insatiable demand for bandwidth in future networking applications. Wavelength Assignment plays an important role in All-Optical Networks. Wavelength converters may also improve network performance allowing more efficient use of network resources. Proper assignment of wavelengths in the network reduces the blocking probability thus increasing the bandwidth of the network.

In this thesis we have studied wavelength assignment and optimal wavelength converter placement in 2D mesh networks. We have shown that wavelength assignment is the main factor affecting the blocking probability in regular networks. We have shown through extensive simulations that assigning wavelengths in an efficient manner can yield better results than those obtained by utilizing converters. We proposed novel on-line and off-line assignment strategies that outperformed on-line strategies previously reported in the literature. The proposed on-line assignment called "***Round-Robin***" assignment has very low blocking probability when compared to first-fit and random assignments. Performance improvement of around 20% is obtained when compared with random assignment. When compared with first-fit assignment the improvement is more than 70%. We have also shown that round-robin assignment scales well with the network size and traffic.

Not much previous work was done on off-line assignments. We proposed two possible off-line strategies. The proposed off-line strategies outperformed all existing on-line strategies. The performance improvement obtained is very significant. Moreover, the proposed on-line and off-line schemes are simple and easy to implement. They need not have any knowledge of the network status. They just depend on the status at the individual nodes. Off-line schemes work better than on-line schemes even with a smaller number of wavelengths. On an average 65%-75% performance improvement is obtained using off-line schemes when compared with on-line schemes. In the proposed off-line schemes wavelengths are assigned in a manner such that contention for the same wavelength is reduced thereby decreasing the blocking probability.

Wavelength converters help in eliminating the *wavelength-continuity* constraint. They also help in utilizing the network resources in a better manner. But due to cost in consideration it is not practical to use converters at all the nodes in the network. Hence the problem of optimal converter placement arises. In a 2D mesh with dimension order routing most of the traffic is concentrated at the center. Hence placing converters at the center may provide better results. Through extensive simulations we have shown that placing converters at the center of the mesh yields better results than uniform placement using the same number of wavelengths. The improvement can be as high as 40% with on-line schemes and 70% with off-line schemes.

Wavelength converters do help in reducing the blocking probability. But we have shown that wavelength assignment plays a more significant role in affecting the blocking probability than converters. Thus we conclude that proper assignment of wavelengths yields much better results than utilization of converters alone. Moreover, the proposed schemes are simple and do not add to the cost. They are certainly less costly to implement than converters. Off-line assignments are much simpler than other schemes, yet they produce significant improvements in blocking probability.

We also introduced the new concept of second trial. If a call is blocked then we try again right away using another wavelength. Since a call is blocked due to unavailability of a certain wavelength, routing the call with another wavelength for the second time can reduce the blocking probability considerably. As expected, our results show that blocking probability with the second trial is much smaller than that obtained with the first trial alone. The performance improvement with the second trial is as high as 90%-95% when compared to the first trial alone. Moreover, the second trial option can be implemented with both the on-line and off-line strategies. This shows the significance of the second trial concept. Again our simulation results show that off-line assignments perform better than on-line assignments even with second trial approach.

Our study has concentrated on regular mesh networks. Irregular topologies were not dealt in this thesis. Further research on wavelength assignment in irregular topologies should be conducted. Other topologies like hypercube, torus can also be investigated. All the simulation sessions that were generated were unicast based. Further study can be conducted with broadcasting and multicasting communications where many-to-many and one-to-many sessions run at the same time.

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