STATISTICALLY PREDICTIVE OPTIMAL ROUTING AND WAVELENGTH ASSIGNMENT IN ALL-OPTICAL NETWORKS

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ABSTRACT

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Network management and fault management are important issues in all-optical wide area networks. In this thesis, we consider the minimization of the effect of router and link failures on network performance by assigning to lightpath requests the most reliable route and wavelength(s) on that route. Hence, number of lightpaths affected by failures is minimized. For this purpose, we propose a statistically predictive routing and wavelength assignment algorithm. The objective of our algorithm is to minimize the probability of lightpath reconfiguration due to failures without deteriorating blocking probability performance. The parameters used in routing decisions are the network state at the time of routing and operational statistics collected from the network. Simulation results show that our algorithm achieves better reconfiguration probability and comparable blocking probability performance compared to the adaptive RWA algorithms that do not take failures into account.

Keywords: All Optical Networks, Routing and Wavelength Assignment, Statistically Predictive Optimal Routing.

ÖZ

TÜMÜYLE OPTİK AĞLARDA İSTATİSTİKSEL ÖNGÖRÜYE DAYALI ENİYİ YÖNLENDİRME VE DALGA BOYU ATAMA

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Tümüyle optik geniş alan ağlarında ağ yönetimi ve bozukluk yönetimi önemli konulardır. Bu tezde yönlendirici bozulmalarının ve optik bağ kırılmalarının ağ başarımı üzerindeki etkisinin, ışıkyollarına en güvenilir yol ve dalga boyu atanması yöntemiyle enküçültülmesi konusu ele alınmaktadır. Geliştirilen yeniden düzenleme olasılığını enazaltan yönlendirme algoritması sayesinde bozulmalardan etkilenen ışıkyolu sayısı azaltılmaktadır. Yönlendirme sırasındaki ağ durumunun ve ağ çalışması sırasında toplanan istatistiklerinin kullanımıyla bozukluk nedeniyle ışıkyolu yeniden yönlendirme olasılığının ve tıkanma olasılığının ortaklaşa enküçültülmesi algoritmanın amaç işlevi olarak seçildi. Yapılan benzetimlerden elde edilen sonuçlar, önerilen algoritmanın bozulmaları dikkate almayan diğer uyarlamalı yönlendirme ve dalga boyu atama algoritmalarıyla karşılaştırıldığında daha iyi yeniden düzenleme ve benzer tıkanma başarımına sahip olduğunu gösterdi.

Anahtar Kelimeler: Tümüyle Optik Ağlar, Yönlendirme ve Dalga Boyu Atama, İstatistiksel Öngörüye Dayalı Eniyi Yönlendirme.

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LIST OF ABBREVIATIONS AND ACRONYMS

APON	:	ATM Based Passive Optical Network
ATM	:	Asynchronous Transfer Mode
AUR	:	Adaptive Unconstrained Routing
BSN	:	Broadcast and Select Network
CDM	:	Code Division Multiplexing
FPLC	:	Fixed Path Least Congestion (Routing)
FR	:	Fixed Receiver
FT	:	Fixed Transmitter
HRWA	:	Heuristic Routing and Wavelength Assignment
ILP	:	Integer Linear Program
IP	:	Internet Protocol
LCP	:	Least Congested Path (Routing)
LLR	:	Least Loaded Routing
LR	:	Link Restoration
LSP	:	Label Switched Path
LSR	:	Label Switching Router
MCgR	:	Minimum Congestion Routing
MCvR	:	Minimum Conversion Routing
MPλS	:	Multi Protocol Lambda Switching
MPLS	:	Multi Protocol Label Switching
MRPR	:	Minimum Reconfiguration Probability Routing
MTV_WR	:	Move To Vacant Wavelength Retuning
OBS	:	Optical Burst Switching
ONU	:	Optical Network User

OTDM : Optical Time Division Multiplexing
OXC : Optical Cross Connect
p.d.f. : Probability Distribution Function
PON : Passive Optical Network
PR : Path Restoration
PRd : Path Restoration with Link Disjoint Route
QoS : Quality of Service
r.v. : Random Variable
RWA : Routing and Wavelength Assignment
SDH : Synchronous Digital Hierarchy
SDR : State Dependent Routing
SONET : Synchronous Optical Network
SPN : Share Per Node
SP-RWA : Shortest Path Routing and Wavelength Assignment
TE : Traffic Engineering
TR : Tunable Receiver
TT : Tunable Transmitter
WDM : Wavelength Division Multiplexing
WGR : Wavelength Grating Router
WI : Wavelength Interchanging
WRN : Wavelength Routing Network
WS : Wavelength Selective

CHAPTER 1

INTRODUCTION

In the last decade, Internet has become an integral part of our lives. In an always-on world, Internet is constantly available; ready to instantly deliver information that is custom tailored to the recipients' precise needs and wants. This technological transformation also pervades most sectors in the society. Today, e-government, e-business, e-banking, e-commerce, etc. are topics of interest. In addition to widespread use of Internet, the content of information transferred is also changing. Image and multimedia based content replacing text-based content. Moreover, security and robustness gain importance as more mission critical applications emerge. Therefore, data traffic carried by the networks is increasing at incredible rates and quality-of-service requirements are more pronounced in every passing day. Many studies have revealed 100% increase in every six months in overall data traffic, and it is widely believed that this increase will not slow down in the near future. For many years to come, the major enabler for this growth is expected to be the optical communication. Without optical communication technology, it would be hard to envisage today's networks. Today, optical fibers are the primary choice in long-distance and high-speed communications due to their low cost, simplicity of use, high reliability, large bandwidth (30THz in low loss region), low attenuation (0.2db/km), and low error rate (up to 10^{-9}).

1.1. All-Optical Networking

The continuity of the progress in networked world mainly depends on provision of much more bandwidth, improved reliability and reduction of costs in backbone and access networks. Therefore, the capacity of existing networks should be expanded to meet the increasing demand and, in parallel, costs should be reduced. The traditional way to achieve this expansion is to increase bit rates or laying more fibers into the network. However, such an approach is neither economical and nor practicable due to several reasons. Although it is possible to expand the capacity of a network by introducing more fibers, it is not possible to reduce costs since it requires extra amplifiers on the spans and large and complex switches at the edges. On the other hand, increasing the rate of communication equipment at the edges increases the cost and more importantly suffers from electronic bottleneck (i.e., rate of electronics can not be increased beyond some value). Therefore, alternative approaches should be employed to exploit vast bandwidth available in optical fibers.

There are many techniques based on enabling concurrency among multiple transmissions to make use of large bandwidth available in optical fibers. Efficiency of such methods highly depends on cost effective applicability to optical communication. Recent improvements in optical device technologies and introduction of new fibers and all-optical wideband amplifiers make possible the construction of networks totally made up of glass material. Therefore, concurrent transmissions can effectively be transferred to their destinations in optical domain without requiring complex electronic switches and re-generators in between. Such networks are called *all-optical* networks. Functional simplicity and inherent robustness are the major advantages of all-optical networks [1]. In such networks, concurrency can be supplied through time slots (OTDM-optical time division multiplexing), wave shape (CDM-code division multiplexing) or wavelength (WDM-wavelength division multiplexing) [2].

In *optical time division multiplexing* (OTDM) [3], many low speed channels, each transmitted in the form of ultra-short pulses, are time interleaved to form a single high-speed channel. By this way, the information carrying capacity of the network can be improved to 100 Gigabits/sec or higher without experiencing electronics bottleneck. In order to avoid interference between the channels, transmitters should be capable of generating ultra-short pulses, which are perfectly synchronized to desired channel (time slot), and receivers should have a perfect synchronization to desired channel (time slot).

In *code division multiplexing* (CDM) [4], each channel is assigned to a unique code sequence (very short pulse sequence), which is used to encode the low speed data. The channels are combined and transmitted in a single fiber without interfering with each other. This is possible since the code sequence of each channel is chosen such that its cross-correlation between the other channels' code sequences is small, and the spectrum of the code sequence is much larger than the signal bandwidth. Therefore, it is possible to have an aggregate network capacity beyond the speed limits of electronics. Like OTDM, CDM requires short pulse technology, and synchronization to one chip time for detection.

In WDM [5], the available optical spectrum is carved up into some number of smaller capacity channels (Figure 1). The users can transmit into and receive from these channels at peak electronic rates, and channels at different wavelengths can be used simultaneously by many users. Hence, the aggregate network capacity can reach the number of channels times the rate of each channel.

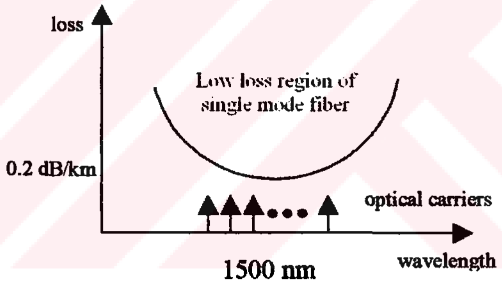


Figure 1 Wavelength Division Multiplexing

WDM is the favorite choice against OTDM, and CDM. This is due to the complex hardware requirements, and synchronization requirements of OTDM and CDM (synchronization within one time slot time and one pulse time respectively). OTDM and CDM are viewed as a long-term network solution, since they rely on a different and immature technology whereas it is possible to realize WDM systems using components that are already available commercially. Moreover, WDM has an inherent property of *transparency*. Since there is no electronic processing involved in the network, channels called *lightpaths* act like transparent pipes between the end nodes. Once a lightpath established between the end-nodes, the communicating parties have freedom to choose the bit rate, signaling and framing conventions, etc.

Transparency makes it possible to support various data formats, and services simultaneously on the same network. In addition to this great flexibility, transparency protects the investments against future developments. Once deployed, WDM networks will support the variety of future protocols and bit rates without making any changes in the network.

The commonly used architectural forms for WDM networks are *WDM Link*, *Passive Optical Network* (PON), *Broadcast and Select Network* (BSN), and *Wavelength Routing Network* (WRN). Today, most of the long haul communication networks make use of WDM links between electronic switches. However, in the near future, it is expected that PONs will become the major choice for access networks and transport network infrastructure will be replaced by WRNs to form an *optical transport network*.

At present, ATM and/or SONET/SDH are used to interface IP networks to optical networks causing complex multi layer architectures such as IP/ATM/WDM, IP/SONET-SDH/WDM, IP/ATM/SONET-SDH/WDM. However, these multi-layer architectures will probably converge to IP over WDM by eliminating intermediate layers for simplicity, ease of maintenance, and cost effectiveness purposes. This evaluation necessitates services supplied by some upper layer protocols such as network control and management, fault management, provision of quality of service (QoS), traffic engineering, etc. to be provided by this two layer architecture. Today, there is a growing need to devise QoS models in order to handle applications that require strict performance requirements. QoS and reliability of services must be engineered and guaranteed for next generation networks. Therefore, together with traffic engineering, a differentiated services model that aggregates the traffic belonging to the same QoS classes into coarser grained flows, which can directly be mapped into lightpaths, is required. Such a differentiated service can be defined by a set of parameters, which can specify some lightpath characteristics such as delay, average error rate, bandwidth, and jitter or are based on functional capabilities such as monitoring, protection, and security.

1.2. Scope, Objective and Contributions of This Study

We consider WRNs having a mesh structure consisting of links having one or more fibers and wavelength routers capable of selectively routing wavelength channels at the input ports to output ports in the optical domain. The main network control problem in these networks is the provision of connections called lightpaths between the users of the network. If a lightpath spans multiple links, it should be assigned to the same wavelength on all links along its route. If wavelength converters are available in the routers, this constraint can be relaxed. To establish a lightpath, a route should be found between the source and destination routers and suitable wavelength(s) along this route should be assigned. This process is called *routing and wavelength assignment* (RWA).

There are mainly two types of RWA algorithms: static and dynamic. In static RWA, all lightpath requests are known initially. Therefore it is possible to find an optimum solution for static RWA for some objective function such as maximization of carried traffic, minimization of resources required to satisfy a given demand, etc. The main assumption in static algorithms is that the traffic volume between users of network is static or remains constant for a long time period and the network is re-configured only to reflect changes in the long-term traffic demand. Although static demand has been a reasonable assumption for voice intensive communications up to now, it is likely that it will not hold for data communication intensive networks with rapidly changing traffic demands in the future. Therefore, *dynamic* RWA algorithms, which support request arrivals and lightpath terminations at random times, are proposed. In dynamic RWA, lightpath requests arrive at random times and remains in the network for a random amount of time.

The most commonly used performance criteria for dynamic RWA algorithms are throughput and blocking probability. Dynamic RWA algorithms can be classified as *fixed* or *adaptive*. In fixed RWA algorithms, a predefined set of routes/wavelengths is searched in a predefined order to accommodate the request. The main advantage of these algorithms is their simplicity. However, since usually one or more minimum hop routes are used and fixed order search without taking into account congestion on the links is carried out, it is not possible to reduce blocking probability with such algorithms. On the other hand, adaptive RWA algorithms make use of the network state information at the time of routing to find the optimum path for the request. Therefore, potential blockings in the future can be minimized.

In this thesis, we propose a statistically predictive dynamic RWA algorithm called *minimum reconfiguration probability routing* (MRPR) for WRNs. In WRNs, a multitude of high-speed channels are accommodated by a single fiber and wavelength routers are responsible for switching of even more channels. Consequently, a single fiber or router failure leads to large revenue losses. There are many proposals that try to protect lightpaths against failures or restore the lightpaths broken by the failures using reserved spare capacity. These proposals mainly deal with the *reconfiguration* of lightpaths broken due a failure. However, with MRPR, we claim that, it is possible to minimize the effect of failures if links/routers/etc. used in the network have different reliability characteristics. Therefore, by choosing as much reliable routers/links as possible in the RWA process, it is possible to minimize the probability of service disruption due to a failure; equivalently, it is possible to minimize the mean number of lightpaths broken due to a failure. However, considering only reliability characteristics may cause lightpaths to be routed on longer routes and blocking performance may be deteriorated. For this reason, MRPR algorithm is based on the joint optimization of the probability of reconfiguration due to router/link failures and probability of blocking for the future requests.

The objective of this study is to enable minimization of the effects of potential router and link failures without disturbing the network's blocking performance. For this purpose, lightpath arrival/holding time and failure arrival statistics to the links and routers collected from the network, as well as the network state information at the time of request arrival, are used in routing decisions. That is, the behavior of the network is predicted by the current state information and the operational statistics of the past to assign the most reliable path to the lightpath requests.

The contributions of this work can be summarized as:

1. The concept of statistical prediction is proposed for RWA in WRNs and an algorithm based on this idea is developed;
2. Reconfiguration probability is defined as an objective function and corresponding prediction expressions for *probability of reconfiguration due to failure* and *probability of reconfiguration due to blocking in the future* are derived;

3. Different types of WRNs are considered. In the routing decisions, channel costs and converter costs are related to having a blocked call in the future. Therefore, a more realistic cost assignment, which takes care of network state and lightpath arrival statistics, is done to minimize blocking probability for each particular network type;
4. Since all the cost functions make use of local information, proposed algorithm can easily be adapted for distributed operation;
5. A general purpose WRN simulator is developed for performance evaluation.

1.3. Dissertation Outline

In Chapter 2, a literature review on WDM all-optical networking is presented. Several WDM network architectures are investigated and several issues including network design and control are discussed. In Chapter 3, minimum reconfiguration probability routing algorithm for statistically predictive optimal RWA in WRNs is introduced. Three different types of WRNs in which MRPR is applied are introduced. For each network type, associated cost functions are derived and RWA process is presented. In Chapter 4, the performance of MRPR algorithm is evaluated by simulations and compared with the performances of other adaptive RWA algorithms. Finally, in Chapter 5, some concluding remarks and possible directions for future work are presented.

CHAPTER 2

ALL-OPTICAL NETWORKS

There are four most commonly used architectural forms for WDM all-optical networks such as *WDM link*, *passive optical network*, *broadcast and select network*, and *wavelength routing network* [6]. In the following sections, these networks are introduced and survey of relevant literature is presented. In parallel with the scope of this dissertation, the emphasis will be on the wavelength routing networks and routing and wavelength assignment process in these networks.

2.1. WDM Link

Although, WDM link is not a network in the usual sense, it represents the first step towards all-optical networking. In early days of optical networking, separate optical fibers were used to carry different signals on a point-to-point link or when the demand exceeded the capacity of existing fibers, more fibers were laid between the end points. However, by the introduction of WDM it has become possible to accommodate multiple signals in a single fiber at different wavelengths. A typical WDM link consists of a set of lasers tuned to distinct wavelengths, an optical multiplexer which typically made up of a piece of glass called grating, all-optical wide band amplifiers which amplify the signals at different wavelengths all together to cope with attenuation on long spans, an optical demultiplexer to separate signals on different wavelengths, and a set of receivers. WDM links offer a very cost effective alternative to laying more fibers to expand the capacity of existing fiber plant especially for long distance communication [7]. The other factors that make WDM links very popular are the maturity of technology and simplicity of integration with legacy equipment.

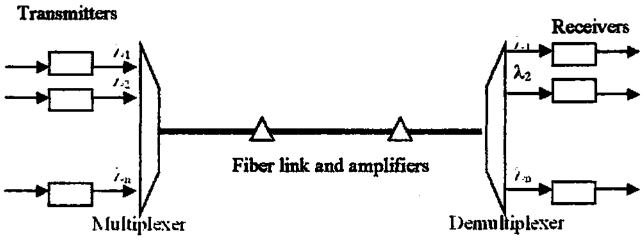


Figure 2 A Typical WDM Link

2.2. Passive Optical Networks

Passive optical networks (PON) are based on a similar approach used in cable modem systems for cable TV networks and are mainly used by regional communication providers. In PONs, broadcast and multiplexing functions are carried out passively in the optical domain. A multiple star or tree-like structure that enables bi-directional communication between a central office (or server) and multiple customers (ONUs) with centralized routing and control at the central office is employed.

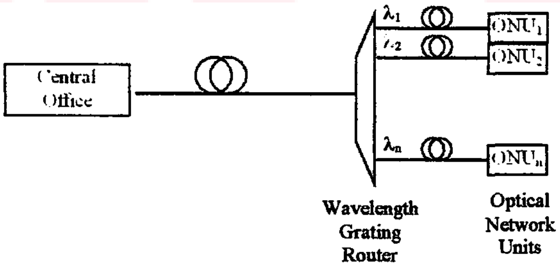


Figure 3 Passive Optical Network (PON)

Recently, *ATM based passive optical network*s (APON) have been standardized and their commercial deployment has started. The WDM upgrade of these single wavelength PONs is on the way [8]. There are two possible ways to implement WDM PONs [9]:

1. Use of tunable transmitters/receivers at the customer side to allow reconfiguration of the network upon change on demand, and
2. Assigning a set of wavelengths to a group of ONUs and using fixed transmitters/receivers at the customer side.

In Figure 3, a simplified view of a WDM PON based on second approach is presented. In [9], detailed discussion of WDM PONs, and experimental prototypes can also be found.

2.3. Broadcast and Select Networks

Broadcast and select networks (BSN) offer an optical equivalent of radio systems. The network infrastructure is totally made up of glass material, which acts as a propagation medium that broadcasts individual transmissions to whole network. In BSNs, each end-node has one or more transmitters and/or receivers. Signals are transmitted on distinct wavelengths to the network, and the network combines these signals and distributes the aggregate signal to the receivers (Figure 4). Star is the most popular physical topology in which end-nodes connected by a pair of fibers to a passive star coupler [10], which evenly distributes optical power at the input ports to the output ports. Instead of star, the physical topology can also be bus [11] or ring [9]. However, these are less efficient in distributing optical power compared to star topology.

In a BSN, tunability characteristics of transmitters and/or receivers determine how the connections can be setup and determine feasible connections between the end-nodes. According to tunability, there are four possible organizations: *fixed transmitter/fixed receiver* (FT-FR) [12], *fixed transmitter/tunable receiver* (FT-TR)[13], *tunable transmitter/fixed receiver* (TT-FR) [14], and *tunable transmitter/tunable receiver* (TT-TR) [15]. Among these choices TT-TR is the most flexible one and FT-FR offers the cheapest solution. On the other hand, FT-TR organization enables broadcast and multicast communications and in TT-FR systems there is no need to inform receiving side before transmission. According to how communication is carried out, BSN networks can be classified into two types: single hop BSN and multi hop BSN.

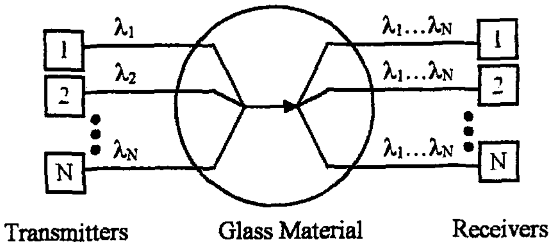
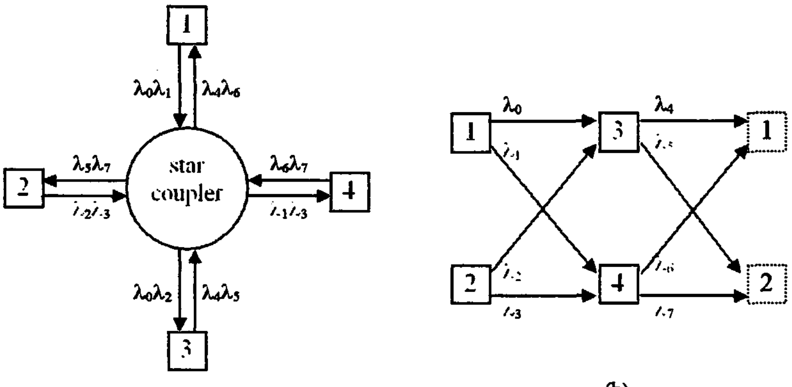


Figure 4 Broadcast and Select Network (BSN)

In single hop BSNs [16], communication is carried out directly in the optical domain between the end-nodes. That is, every end-node should be capable of reaching any other end-node, and end-nodes should be tuned to the same wavelength to communicate with each other. Therefore, wavelength agile tunable transmitters/receivers or an array of fixed transmitters/receivers are required for efficient use of the network. If tunable transmitters/receivers are not fast enough, circuit switching will be the most suitable choice and a simple polling based medium access protocol can be employed [13]. Packet switching in single hop BSNs requires significant amount of dynamical coordination between the end-nodes. There are several medium access protocols for packet switched single hop BSNs [11], which are mainly based on three different approaches: *Pre-transmission coordination*, *random access*, and *transmission schedules*. The pre-transmission coordination based protocols [16] use one of the wavelength channels as the *control channel* where end-nodes broadcast their channel reservation information before packet transmissions. In random access protocols [17], usually TT-FR organization is preferred because there is no need to inform destination before packet transmission. However, in such networks, some mechanisms are needed to cope with collisions. In protocols using transmission schedules, channels are assigned to the end-nodes in a time division multiplexed (slot length equal to packet length) way to avoid collisions. There are several proposals to create optimal schedules to support unicast, multicast, and broadcast communication [18], for non-uniform traffic demand [19], [20] and to minimize the effect of tuning delay on performance [21].



(a) (b)

Figure 5 A Multi-Hop Network: (a) Physical Structure (b) Logical Structure

Since, tunable transmitters/receivers are very expensive devices and usually they are not fast enough for packet switching, an alternative mechanism based on a fixed channel assignment, which avoids wavelength switching altogether, is used in multi hop BSNs [12]. In multi hop BSNs, a logical topology that determines the actual connectivity between the end-nodes is embedded over the physical topology by properly assigning wavelengths to the fixed tuned transmitters/receivers on the end-nodes (Figure 5). Since there may not be a direct channel between the end-node pairs, packets may need to be forwarded by some intermediate end-nodes to reach their final destinations in multi hop networks. The logical topology employed in a multi-hop network can either be *irregular* or *regular*. It is possible to optimize logical topology for some performance criteria such as maximum throughput or minimum delay resulting in an irregular topology [12] and irregular topologies can perform better under non-uniform traffic patterns. However, they suffer from the routing complexity, which is an important issue in high-speed networks. There are several regular topologies *ShuffleNet*, *De Brujin Graph*, and *Manhattan Street Network* proposed for multi hop networks [22]. Although routing is much simpler, due to their structured connectivity pattern, adding or removing one or more end-nodes from the network is a problem in regular topologies.

Reliability, robustness, and ease of maintenance due to passive nature of the network, and inherent support for broadcasting and multicasting are the most important advantages of the BSNs. However, splitting loss and lack of wavelength reuse limits scalability of BSNs. Therefore, BSN approach is mainly suitable for local and metropolitan area networks and has a limited use on wide area networks.

2.4. Wavelength Routing Networks

Splitting loss and lack of wavelength reuse restrict BSNs from spanning long distances and having large number of end-nodes. Wavelength routing networks (WRN) get around these problems by channeling the transmitted power to a specific route between the source and destination end-nodes (i.e., avoiding broadcasting signals to irrelevant destinations), and reusing the wavelengths in spatially disjoint areas of the network.

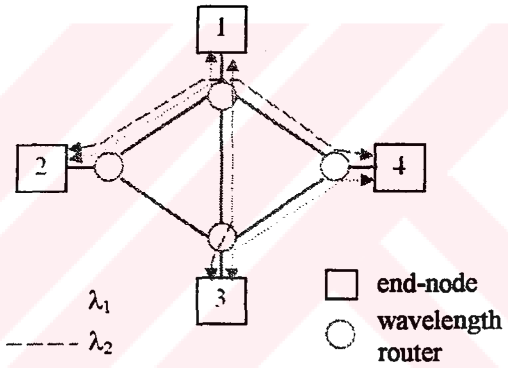
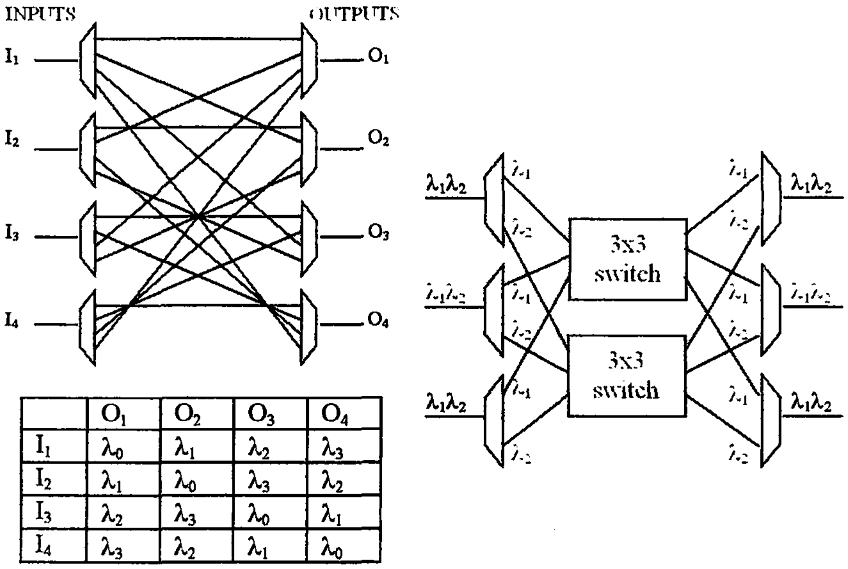


Figure 6 A Wavelength Routing Network

WRNs are composed of one or more wavelength selective elements and fibers connecting them (Figure 6). These wavelength selective elements are totally made up of glass material (i.e., no electro-optical conversions) and they are called *wavelength routers*. Wavelength routers are capable of routing signals at the input fibers to the output fibers individually. The output port of each signal in a wavelength router is determined by the input port (fiber) it arrives to and its wavelength. The signals routed to the same output port should be on the different wavelengths to avoid mixing of different signals.

In WRNs, each wavelength router is connected to one or more wavelength routers to constitute a physical topology. In this topology, end-to-end connections between the end-nodes are established on wavelength channels through one or more wavelength routers and links. If the wavelength routers are supposed to be ideal, the connections between the end-nodes do not experience any splitting loss and electro-optical conversion. Therefore, such an end-to-end connection behaves like a high-speed transparent pipe between the end-nodes, which is called a *lightpath*. If two lightpaths do not share a fiber on their routes, they can be assigned to the same wavelength. Therefore, spatial reuse of wavelengths can be achieved in wavelength routing networks. For example, in Figure 6, lightpaths between the end-nodes *1-3* and *2-4* (similarly *1-2* and *3-4*) are assigned to the same wavelength.

According to the routing matrix they have, there are four major types of wavelength router architectures: *Fiber Cross-Connects*, *Add-Drop Multiplexers*, *Static Wavelength Routers*, and *Reconfigurable Wavelength Routers* [10]. Actually, a fiber cross-connect is not a wavelength router because it does not distinguish between different wavelengths. However, as the number of lightpaths increase, many of the lightpaths will follow the same route through a wavelength router. Therefore fiber cross-connects can be used with other wavelength selective routers, to build a cost effective network [23]. In add-drop multiplexers, one or more signals on different wavelengths at the input port are routed to drop port. The remaining signals and new signals (at the same wavelength of the dropped signals) at add port are combined and routed to the output port. Add-drop multiplexers are widely used in networks with ring or bus topologies (e.g. [24]). Static wavelength routers can be realized by using a stage of demultiplexers followed by a stage of multiplexers whose inputs are hardwired to the outputs of demultiplexers (Figure 7.a). Alternatively, it is possible to implement a static router as an integrated device such as wavelength grating router (WGR), which can easily be fabricated at a low cost. In addition to their low cost and high reliability due to their passive nature, WGRs offer many other advantages and they have a potential use in WRNs [25]. Reconfigurable wavelength routers are usually composed of wavelength demultiplexers followed by optical cross-connects and wavelength multiplexers (Figure 7.b), and their routing matrix can be changed dynamically during network operation. They are very flexible devices and widely used in WRNs.



	O_1	O_2	O_3	O_4
I_1	λ_0	λ_1	λ_2	λ_3
I_2	λ_1	λ_0	λ_3	λ_2
I_3	λ_2	λ_3	λ_0	λ_1
I_4	λ_3	λ_2	λ_1	λ_0

(a) (b)

Figure 7 (a) A 4x4 static and (b) a 3x3 reconfigurable wavelength routers

The main network control problem in WRNs is the provision of lightpaths between the end-nodes. The lightpaths in a WRN usually span multiple links. According to whether wavelength conversion is available or not in the routers, lightpaths may be assigned to different wavelengths or assigned to the same wavelength on different links along its route, respectively. In this process, it should be ensured that lightpaths sharing some fibers should be on different wavelengths. Therefore, to establish a lightpath, a route should be found between the source and destination routers and suitable wavelengths along this route should be assigned. This process is called *routing and wavelength assignment* (RWA). If all lightpath requests are known initially, the RWA problem is called *static RWA*. The mostly used objective of static RWA algorithms is the maximization of carried traffic. On the other hand, if lightpath requests arrive at random times and remain in the network for random period of times, RWA should be performed per request basis. Such algorithms are called *dynamic RWA* algorithms, and most commonly used performance criterion for these algorithms is the blocking probability which can be defined as the chance that a lightpath request is rejected due to insufficient free capacity to establish a lightpath between the source and destination routers.

Availability of wavelength conversion is also an important issue in the operation of RWA algorithms and network performance. In the following subsections several types of WRNs, possible use of wavelength converters, and RWA methods are investigated.

2.4.1. Wavelength Selective and Wavelength Interchanging Networks

In wavelength routing networks, the lightpaths should be assigned to the same wavelength along their route. This is called the *wavelength continuity constraint* and such networks are called *wavelength selective* (WS) networks. In WS networks, having at least one idle wavelength channel on all fibers along a route may not be sufficient to establish a lightpath on that route because wavelength continuity constraint should also be satisfied. That is, at least one idle channel on a common wavelength should also exist on all links of the route. For example, in Figure 8, although there are idle channels on *Link 1* and *Link 2*, it is not possible establish a lightpath between *Node 1* and *Node 3*, since there is no common wavelength channel available on both links.

The wavelength continuity constraint can be avoided by employing wavelength converters in the wavelength routers. Wavelength converter devices are used to transfer a signal from a wavelength channel to a different wavelength channel. There are two types of wavelength conversion techniques: *optoelectronic conversion* and *all-optical conversion*. In optoelectronic conversion [26], the optical signal is first converted to an electrical signal and then reproduced by a laser tuned to the desired wavelength [26]. This method is quite complex and consumes much more power compared to all-optical alternatives and more importantly transparency is lost. On the other hand, in all-optical wavelength conversion [27] the signal is converted to the desired wavelength in optical domain thus transparency is preserved.

Networks, which employ wavelength converters, are called *wavelength interchanging networks* (WI networks) and are equivalent to traditional circuit switched networks. In circuit switched networks, a free capacity (channel) on all the links along a route between two end-nodes is sufficient to establish a circuit. Similarly, in WI networks, having an idle channel (possibly at different wavelengths) along a route will be sufficient to establish a lightpath on that route. Hence, WI networks achieve better performance compared to WS networks especially under dynamic demand [28].

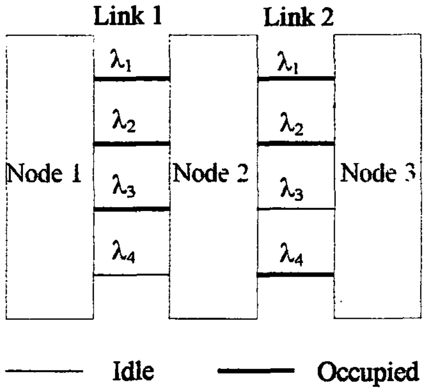


Figure 8 Blocking in Wavelength Routing Networks

The performance gain offered by the use of wavelength converters is assessed in many studies. Blocking probability with and without wavelength converters increase with number of hops *H*, and amount of increase is much higher in WS networks. Therefore, wavelength conversion gain is large in networks with large diameters. However, the interference length, L, (= expected number of links shared by two lightpaths which share some link) is also an important parameter in blocking probability. Networks with large interference lengths have smaller blocking probabilities than the networks with small L, and performance improvement by using wavelength converters decreases with large L. It has been shown in [29] that effective path length (i.e., *H/L*) is an important factor in performance improvement achieved by wavelength converters. In Figure 9, gain in fiber utilization that is achieved by using wavelength converters is plotted for a 20-hop path with blocking probability of 10^{-3}, and interference lengths of L=1,2,4. As it can be seen from the figure, gain is proportional to effective path length.

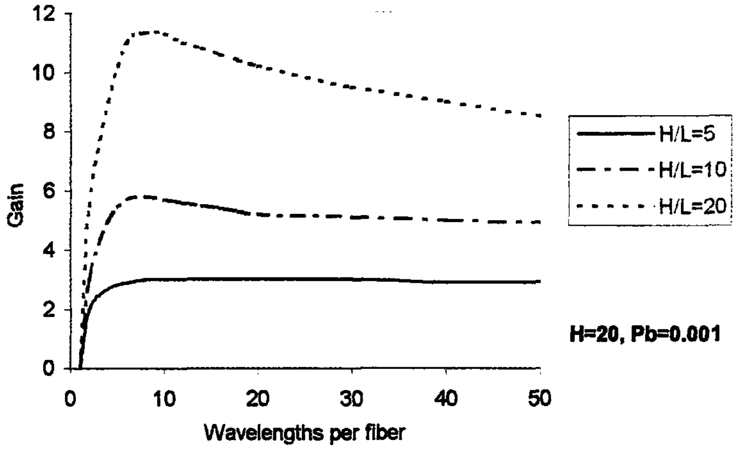


Figure 9 Effect of interference length on the gain [29]

In [30], the performances of non-blocking centralized switch, mesh-torus network, and ring network are evaluated using analytical models and simulations. It has been shown that, wavelength converters can significantly improve the performance in large mesh-torus networks, and performance gain obtained in centralized switch and ring topologies are modest. This is because effective path length in mesh topologies is much higher than centralized switch and ring topologies.

In addition to improved performance, wavelength converters can offer many other advantages in WRNs. For example, it may be hard to find a common wavelength for longer (in hops) paths to setup a lightpath as stated previously. Therefore, wavelength converters can improve the fairness (i.e., approximately equal chance of setting up short and long lightpaths) by resolving wavelength conflicts in longer paths. In addition, if the end-nodes equipped with fixed tuned transmitters and receivers, wavelength converters can make possible setting up connections between the end-nodes, which have no transmitters and receivers tuned to a common wavelength. Wavelength converters can also improve the fiber utilization if different numbers of wavelengths are available on fibers. It is also possible to use wavelength converters at the interfaces of the sub-networks (smaller partitions of whole network) to simplify the management of the whole network [31], especially if each sub-network has different operators.

2.4.2. Limited Conversion WI Networks

In WI networks, it is possible to support full wavelength conversion in all nodes resulting in a network equivalent to circuit switched networks. A possible re-configurable wavelength router of this type is shown in Figure 10. In this router, each wavelength channel on the output links is assigned to a distinct wavelength converter, which is capable of converting the wavelength of input signal to any other wavelength. This organization is called a *dedicated WI router*.

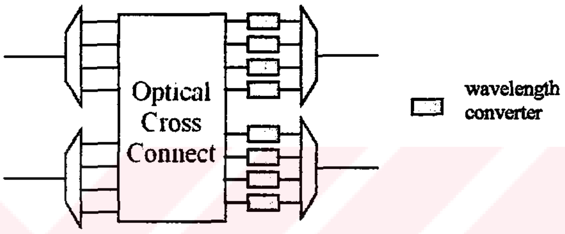


Figure 10 A 2x2 Dedicated WI Router

In WRNs, lightpaths need wavelength conversion rarely to resolve wavelength conflicts. Therefore, many of the wavelength converters in a dedicated WI router will not be used most of the time resulting in a reduced utilization of wavelength converters. Therefore, wavelength converters can be shared in wavelength routers to have a cost-effective network. There are mainly two approaches for sharing wavelength converters in wavelength routers [32]: *share-per-node*, and *share-per-link*.

In the share-per-node WI router (Figure 11.a), each converter can be accessed by any of the signals on the input ports. In this router, the signals at proper wavelengths are directly routed to the multiplexers of the desired output port. However, if there is a wavelength conflict (i.e., two signals at the same wavelength are to be routed to the same output port), only one of the conflicting signals can be directly routed. The remaining signals can be routed through wavelength converters. These signals are first converted to an idle wavelength on the desired output link, and the desired output link is chosen by the second optical cross-connect. The main disadvantage of this method is the need for an extra optical cross-connect.

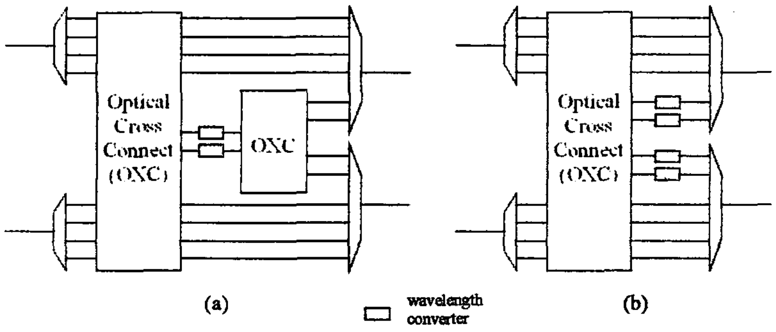


Figure 11 (a) A 2x2 Share Per-Node and (b) A 2x2 Share Per-Link WI Routers

In share-per-link WI routers (Figure 11.b), each output link has its own wavelength converters, which can be accessed by only the signals that will be routed to those output ports. If there is a wavelength conflict, one of the conflicting signals is directly routed and remaining signals are routed through wavelength converters. After conversion they are multiplexed into the output fiber.

Simulation results presented in [32] have shown that using only a limited number of converters in each wavelength router is sufficient to provide good performance in terms of blocking probability and fairness (i.e., short and long lightpaths experience approximately same blocking probability). In Figure 12, blocking probability versus number of converters at heavy, medium, and light input traffic in 21-node, 52-link ARPA-2 network with 16 wavelengths per link is plotted. As stated, blocking probability reduces as the number of converters increases and remains constant after some value. In [33], some algorithms are proposed to allocate limited number of wavelength converters in share-per-node WI networks and it was shown that overall blocking probability and maximum of the blocking probabilities experienced by the source routers can be significantly reduced.

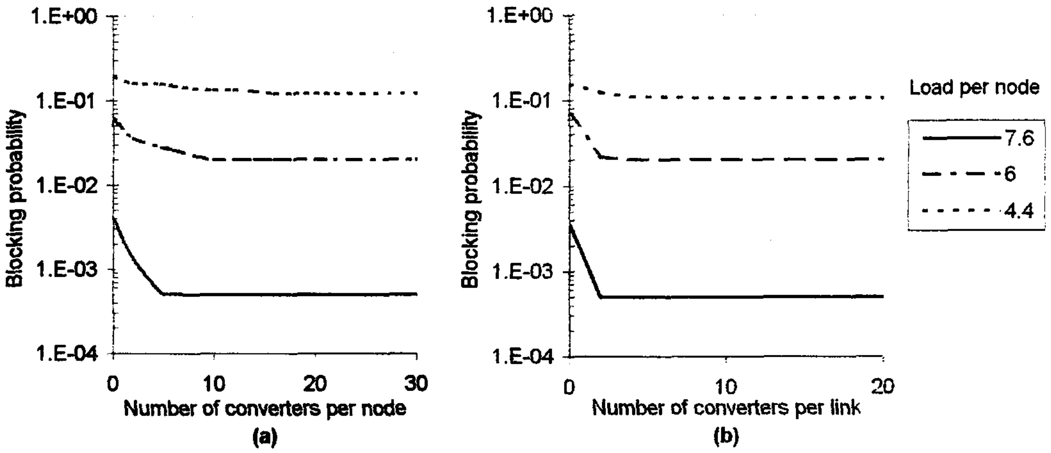


Figure 12 Blocking probability versus number of converters at different traffic loading in (a) the share per node (b) the share per link WI networks [32].

All limited wavelength conversion approaches presented above assume that, every wavelength router in the network has wavelength conversion capability, and wavelength converters are ideal (i.e., any wavelength can be converted to any other wavelength). However, in some networks, *sparse wavelength conversion* is provided or *non-ideal wavelength converters* are employed.

In sparse wavelength conversion approach, wavelength converters are employed only in selected wavelength routers. In most of the cases, a small number of WI routers are sufficient to achieve acceptable performance [28]. It has been shown in [34] that half of the capacity penalty (i.e., increase in cost of the network to satisfy a given demand) that is incurred if wavelength conversion is not used can be removed by equipping only 20% of routers with wavelength converters. Optimal placement of WI routers in a network is also an important issue in sparse WI networks [35].

If non-ideal wavelength converters are used in wavelength routers, any wavelength can be converted to only a small subset of available wavelengths. In most cases, the performance gain achieved by using non-ideal wavelength converters is close to performance gain achieved by using ideal wavelength converters [28]. It has also been shown that significant improvements can be achieved in the blocking probability with limited-range wavelength converters tunable over only one quarter of the whole range [26]. On the other hand, significant improvements in traffic carrying capacity can be obtained by providing very limited wavelength conversion capability [36].

2.4.3. Multi-Fiber Networks

Most of the optical networks deployed so far employ multiple fibers between end-nodes. This is due to the economic advantage of installing bundles of fibers for the purposes of fault tolerance and future network growth.

If *K* fibers employed over between adjacent wavelength routers, and number of wavelength channels is *W*, the capacity of each link will be equal to *KxW* channels. This is functionally equivalent to a single fiber wavelength routing network with *KxW* wavelength channels in each fiber. In general, in multi-fiber networks, wavelength routers serve each fiber separately. That is, if a wavelength router has d neighbors, its uses *W* switches of size *dKxdK*, instead of using *KxW* switches of size dxd. Therefore, for the same capacity, larger switches are required in a multi-fiber network. However, such a *K* fiber *W* wavelength network is functionally equivalent to *KW* wavelength network with partial wavelength conversion of degree *K* wavelengths. That is, multi-fibers are functionally equivalent to using limited range wavelength converters, which can convert a signal to any of the *K* wavelengths among *KW* wavelengths. This is because a signal on a wavelength can be routed to one of the possible *K* fibers to reach the same destination using the same wavelength channel.

The benefits of using multiple fibers in a wavelength routing network have been evaluated in [37]. It has been shown that blocking performance improves dramatically with the use of only two fibers in each link. The throughput of two-fiber network increases by an approximate factor of four with respect to single fiber networks.

In [38], an optical path accommodation design algorithm is proposed to heuristically establish lightpaths in wavelength continuous or WI networks in which multiple fibers employed are between wavelength routers. The objective is to minimize the total number of fiber ports required at each node. Analyses show that difference between the objective functions in wavelength continuous and WI networks decreases as the traffic intensity increases (i.e., as the number of optical fibers required to accommodate lightpaths in a link increases).

2.4.4. Routing and Wavelength Assignment

Routing and wavelength assignment (RWA) [39] is the process of finding routes for the lightpaths through the network and assigning wavelengths to these lightpaths. A similar routing problem arises in circuit switched networks where the connections are routed by selecting a path on which a free circuit available on every link. However, in WRNs, *wavelength continuity* and *distinct wavelength assignment* constraints should also be satisfied in order to establish the lightpath. That is, a lightpath should be assigned to the same wavelength on every link in the path, and lightpaths sharing some links should be assigned to different wavelengths. If wavelength converters are employed in the wavelength routers, wavelength continuity constraint can be relaxed and the RWA problem can be made equivalent to the circuit routing problem in circuit switched networks.

Depending on whether all lightpath requests are known initially and fixed over time or not, RWA algorithms can be classified into two categories such as *static* and *dynamic*. In static RWA, all lightpath requests are assumed to be known initially. Maximization of carried traffic is the most commonly used objective of static RWA algorithms. The main assumption made in static demand is that the traffic volume between users of network is static or remains constant for a long time period and the network is re-configured only to reflect changes in the long-term traffic demand. Although static demand has been a reasonable assumption for voice intensive communications up to now, it is most likely that it will not hold for data communication intensive networks with rapidly changing traffic demands in the future. Therefore, *dynamic* RWA algorithms, which support request arrivals and lightpath terminations at random times, are proposed. Blocking probability and throughput are the most commonly used performance criteria for dynamic RWA algorithms.

2.4.4.1. Static Routing and Wavelength Assignment

In static RWA, all lightpath requests in the network are known initially. Therefore, it is possible to find an optimal RWA by employing some optimization methods. Many integer linear programming (ILP) based methods are proposed for static RWA in WS and WI networks. Generally, these methods are based on multi-commodity flow formulations, and problem size grows much faster than the size of the network. Usually, an ILP based RWA formulation is composed of an objective function and some constraints. Most commonly used objectives are the maximization of carried traffic and minimization of network cost (or resource requirements to satisfy a given demand matrix). Constraints include equations corresponding to traffic demand and topological constraints. That is, traffic demand matrix should be completely or partly satisfied and, in WI networks, the number of lightpaths passing through a link should be smaller than the capacity of that link (=number of fibers on the link * number of wavelengths per fiber). In WS networks, in addition to the capacity constraint, the wavelength continuity and distinct wavelength assignment constraints should also be satisfied.

In [40], two major types of ILP formulations are considered for RWA in both WS and WI networks: *route formulations* and *flow formulations*. In route formulations, all routes between all end-node pairs are enumerated, and how many times a route is used is determined. In flow formulations, the basic decision variables are the flows on the links generated through each end-node pair. In Table 1, route and flow formulations for RWA in WS and WI networks are compared, and computational requirements are expressed in terms of the number of variables and the number of constraints. As it can be seen, the size of the RWA problem in WI networks is independent of the number of wavelengths whereas the RWA problem in WS networks grows with the number of wavelengths. On the other hand, the number of variables is proportional to the number of routes in the route formulations. Therefore, the number of variables increases exponentially with the network size for highly connected networks. Although number of variables is much lower in flow formulations, the number of constraints grows similar as the number of routes in route formulations resulting in the same computational requirements.

Table 1 Problem Size of ILP Formulations [40]

	Route Formulations		Flow Formulations	
	WI Networks	WS Networks	WI Networks	WS Networks
Number of Variables	R	R*W	M*S	M*S*W
Number of constraints	M+S	M*W+S	M+N*S	M*W+ N*S*W+S

where,
R : Number of all possible cycle free routes between all router pairs,
W : Number of wavelengths per fiber,
M : Number of links ,
N : Number of routers,
S : Number of source destination router pairs in the network.

There are also many alternative formulations proposed for RWA in WI and WS networks with different objective functions. In [41], RWA in WI networks is formulated as an integer linear program similar to flow formulation with the objective being the minimization of the flow in each link. This corresponds to the minimization of the number of wavelength channels required in each fiber (i.e., number of wavelengths required) to carry all lightpath requests over a known physical topology. An alternative approach, which tries to minimize the total facility cost for a given physical topology and a given lightpath demand matrix, is proposed in [42] for both WI and WS networks. In these formulations, the facility cost is obtained from transmission, multiplexing, and cross-connection costs. These costs are proportional to fiber length, total number of fibers and total number of optical cross-connects used on fiber links and wavelength routers. In many studies optimal physical topology design is also considered. For example, fiber topology and optical path layer (virtual topology) design problems to minimize the total cost of the network for a given demand matrix is formulated in [43]. Both WI and WS networks are considered and location of wavelength routers, a set of candidate links between these routers, and demand between each end-node pair is given initially.

Since, both route and flow formulations are computationally intensive, some approximate methods are proposed to solve the ILP for large networks. For example, in [41], the routing and wavelength assignment problem is decomposed into a number of sub-problems, which are solved independently. First, the RWA problem is formulated as an ILP based on flow formulations in WI networks. Then, the ILP is pruned by tracking a limited number of alternate breadth-first paths between sd-pairs to reduce problem size. Instead of solving the ILP, the problem is solved as a linear program (LP) and a probabilistic technique (called *randomized rounding*) is applied to LP solution to obtain integer solutions. Once paths for each lightpaths found, *graph-coloring algorithms* are used to assign wavelengths to those lightpaths. It has been shown in [41] that the number of wavelengths required for this approximate solution is asymptotically close to the lower bound obtained through LP solution.

Since, ILP based optimal RWA is computation intensive and the size of the problem grows exponentially with the size of the network, some heuristic approaches are also developed to find a near optimal solution in an acceptable time period.

In [44], a heuristic algorithm is proposed for lightpath allocation in an arbitrarily connected wavelength routing network. Every end-node pair is assigned to a single lightpath through the network and algorithm tries to minimize the number of wavelength channels required in fibers to route this traffic over the given physical topology. First, shortest path routes are determined between each end-node pair and these routes are assigned to lightpath requests. Therefore, total and average transit traffic through the wavelength routers is minimized. Since usually more than one shortest path exists between each end-node pair, it is possible to balance the number of lightpaths among all links by choosing routes properly from these alternatives. Therefore, substitutions of alternative shortest paths are carried out for lightpaths while the number of channels in the most loaded link in the alternative path is lower than the previous one. When there are no substitutions possible, routing of lightpaths are completed, and assignment of wavelengths to these paths takes place. Wavelength assignment is done in such a way that the lightpaths with longer paths are considered first and assigned to smallest index wavelength available through its route. The reason for this longer path first policy is that it is harder to find a free wavelength on more links. It has been shown that this algorithm yields the wavelength requirements that are very close to optimal number of wavelengths required. Moreover, it has been observed that in all analyzed networks number of wavelengths required is equal to the number of lightpaths on the most loaded link(s), implying wavelength converters does not lead to a reduction of wavelength requirements. Instead of using wavelength converters, replacement of heavily loaded links with multiple fibers leads to a reduction on wavelength requirements.

Another heuristic algorithm called *Heuristic Routing and Wavelength Assignment algorithm* (HRWA), which minimizes the required number of wavelengths per fiber, is proposed in [40]. The algorithm starts with searching shortest paths for each sd-pair and selecting the shortest routes that minimize wavelength requirement. Then, number of required wavelengths is decreased by rerouting a number of lightpaths. The next step is repeated until no further improvement is possible. The simulations show that HRWA performs well from the view of calculation time and maximization of the wavelength reuse as compared to ILP solutions.

Two similar heuristic algorithms (that use rerouting of lightpaths to minimize an objective function) for RWA in WS and WI networks are proposed in [38]. In these algorithms, each link is composed of multiple fibers and the algorithms try to minimize optical path cross connect system scale (i.e., the total number of fiber ports required in each node). That is, the objective is the minimization of the average number of fibers handled at the wavelength routers. In some networks this is required for practical (or cost effective) realization of wavelength routers. In WI networks, the lightpaths initially setup so that they are evenly distributed within the network (i.e., every link should have equal number of lightpaths). Then, the links with the most inefficient wavelength utilization (i.e., having a large value of number of lightpaths using link *mod* number of wavelengths in each fiber) are determined. Then, the lightpaths that use maximum number of such links are re-routed. Re-routing iteration is done a certain number of times and algorithm completes. Once the routes are determined the fiber requirements for each link can be determined as $\lceil$number of lightpaths/number of wavelengths$\rceil$. In WS networks, first, routes for lightpaths in corresponding WI network is found. Then, all the lightpaths are divided into minimum number of layers in such a way that any two lightpath in a layer do not share any link. Then layers are assigned to a layer number randomly and wavelengths assigned according to the layer number (i.e., assigned wavelength = Layer number *mod* number of wavelengths). Finally, all these steps for different set of initial routes are repeated some number of times and the assignment with the lowest value of the objective function is selected as routing of lightpaths. The simulations show that RWA in WS networks incur large optical path cross connect system scale than RWA in WI networks. Moreover, the difference increases as the number of wavelengths increases. This is because in WS networks much more wavelengths remain unassigned on the links as the number of wavelengths multiplexed in a single fiber increases.

In [45], a heuristic static RWA algorithm, which tries to minimize the overall network cost, is proposed. WS networks are considered and each fiber is assumed to have a fixed set of wavelengths. Therefore, multiple fibers are used on the links whenever the capacity of the link exceeds number of wavelengths. The algorithm starts by an arbitrary initial assignment for the lightpaths. Then, node pairs greedily attempt to decrease the maximum lightpath metric observed by their connections to obtain a configuration with minimal cumulative metric thereby minimizing the network cost.

2.4.4.2. Dynamic Routing and Wavelength Assignment

Dynamic RWA algorithms can be classified as *fixed* or *adaptive*. In fixed RWA algorithms, a predefined set of routes and wavelengths on those routes are searched in a predefined order to accommodate the request. The main advantage of these algorithms is their simplicity. However, since usually one or more previously defined routes are used and fixed order search without taking into account congestion on links is carried out, it is not possible to further improve blocking performance with such algorithms. On the other hand, adaptive RWA algorithms make use of the network state information at the time of routing to assign the optimal route and wavelength, which minimizes (or maximizes) an objective function. Therefore, risk of blocking for the future lightpath requests is minimized.

In the fixed RWA algorithms, usually minimum hop route between each source-destination router pair is used and a suitable wavelength on this route is searched for a lightpath request. If at least one link on the route does not have an idle channel in WI networks or if a common wavelength that is available on all links cannot be found in WS networks, the request is blocked. In WS networks, wavelength selection among the available wavelengths plays an important role in the performance of the algorithm. In fixed RWA, there are two commonly used methods for wavelength assignment as random and first-fit. In random wavelength assignment, a wavelength is selected randomly among all possible wavelengths. In first-fit wavelength assignment the smallest index wavelength is selected. That is, lightpaths are packed to smallest index wavelengths and largest index wavelengths are reserved to facilitate finding a common wavelength for future requests. Therefore, first-fit wavelength assignment is better than random wavelength assignment. In Figure 13, performances of random and first-fit algorithms obtained by simulations on an 11x11 mesh-torus network are presented. In [46], first-fit and random wavelength assignment methods with fixed shortest path routing are compared through simulations, and an analytical model has been developed for analyzing blocking probability of the first-fit algorithm. It has shown that, first-fit algorithm performs much better than the random algorithm at low loads, and performance difference is marginal at higher loads. This is because, at lower loads, most of the request blockings are caused by wavelength conflicts. Therefore, blocking probability is reduced in first-fit algorithm due to packing of lightpaths in smaller indexed wavelengths. On the other hand, at higher loads, most of the requests are blocked due to insufficient capacity. Therefore, wavelength assignment algorithm has a little effect on the performance at high loads. It has also shown that, first-fit algorithm performs better when the number of fibers per link is small in multi-fiber networks.

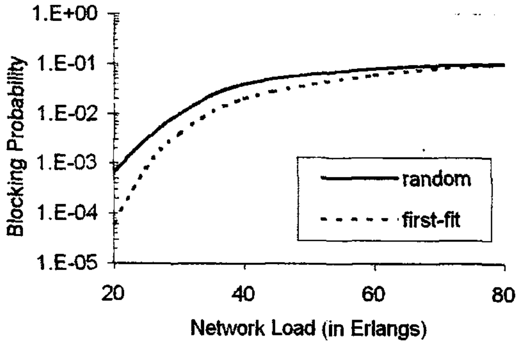


Figure 13 Blocking probability versus load on 11x11 mesh torus WS network when wavelengths per fiber is five [30]

Instead of using a single route, multiple alternate routes can also be used in RWA. SP-RWA proposed in [47] is one of such alternate routing algorithms. In SP-RWA, a set of minimum hop routes between a source destination pair is ordered in some manner and a new lightpath is routed on the first path on which a wavelength is available. In [37], a method for obtaining approximate blocking probabilities for fixed and alternate routing with first-fit wavelength assignment is developed. It has shown that alternate routing with only two alternate paths between each sd-pair results in a large reduction in the blocking probability compared to fixed routing. This is due to fact that there are more wavelength-route alternatives in alternate routing to setup the lightpath. Moreover, performance improvement is more pronounced if the number of wavelength channels in fiber links is large. It has also shown that, blocking performance improves dramatically with the use of multiple fibers in the links. For example in Figure 14, fixed and fixed-alternate (with two alternate routes) routing with first fit wavelength assignment are compared in a randomly generated topology with one and two fibers per link and four wavelengths per fiber.

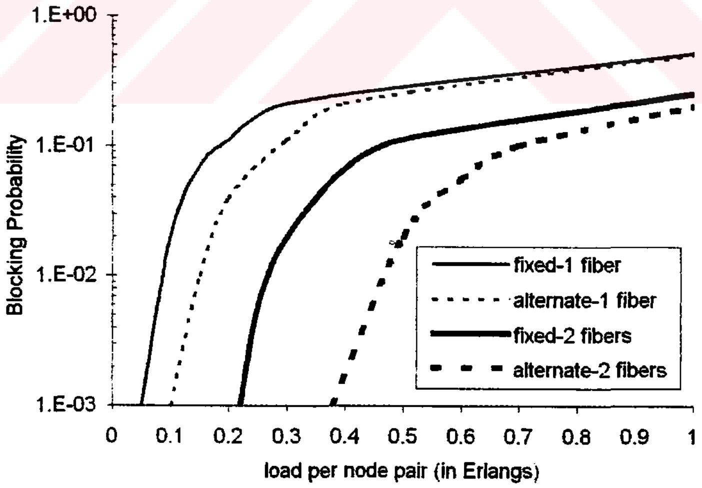


Figure 14 Blocking probability versus load per node pair on a randomly generated WS network [37]

Adaptive RWA algorithms uses network state information to find optimal route and wavelength(s) on that route for a lightpath request. There are mainly three types of adaptive routing algorithms:

1. Fixed routing-adaptive RWA: Every source destination router pair is assigned to a single fixed route, which is usually the minimum hop route between those routers. One of the available wavelengths on this route is selected using wavelength usage information in the network at the time of routing.
2. Alternate routing-adaptive RWA: Each source destination router pair is assigned to a set of paths, which is usually formed by k minimum hop routes between those routers. This route set is searched in adaptive order to accommodate the request.
3. Unconstrained routing-adaptive RWA: All possible routes between the source and the destination router are considered in the routing decision. Usually shortest path routing algorithm with link costs obtained from network state information at the time of routing is employed to search route and wavelength for a lightpath.

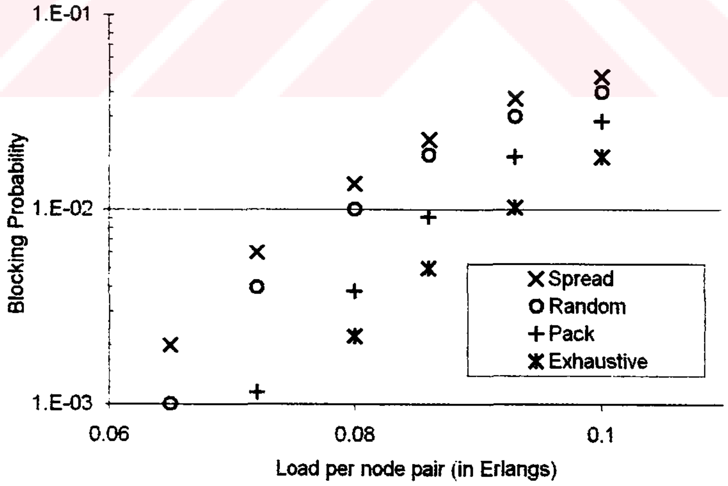


Figure 15 Blocking probability versus load per node pair for the ARPA-2 WS network with eight wavelengths per fiber[37]

In [37], five variations of an adaptive RWA algorithm called AUR with unconstrained routing are proposed. To establish a lightpath, wavelengths are ordered according to the algorithm employed and sequential search over this ordered set is performed to find an available path on the network using a shortest path algorithm. The proposed wavelength search orders are as follows:

1. Pack: Wavelengths are searched in descending order of their utilization. Therefore, utilization of available wavelengths are maximized,
2. Spread: Wavelengths are searched in ascending order of their utilization. Therefore, load is uniformly distributed over the wavelengths,
3. Random: Wavelengths are searched in random order. Therefore, load is uniformly distributed over all route-wavelength pairs.
4. Exhaustive: All wavelengths are searched for the shortest available path,
5. Fixed: Wavelength search order is fixed a priory.

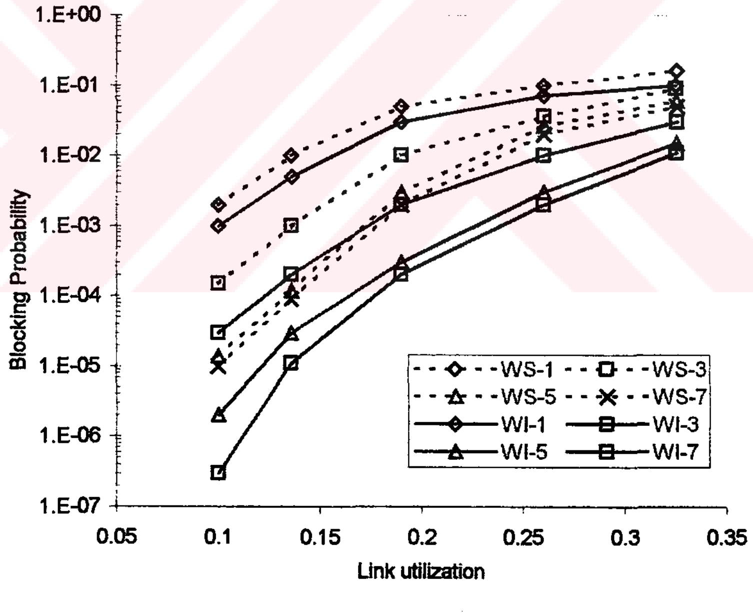


Figure 16 Blocking probability versus link utilization with the LLR algorithm for k=1,3,5,7 on the 30 Node network

Performance evaluation of AUR by simulations has shown that (Figure 15) exhaustive scheme has the best performance regarding to blocking probability. The pack scheme better than the random and the spread schemes and if the number of wavelengths is large, the performance of the pack scheme outperforms the other two schemes by a significant margin. The results also indicate that performance of the first-fit scheme is very close to the pack scheme. This is due to the fact that the first-fit scheme approximates the pack scheme by assigning most lightpaths to wavelengths with smaller indexes.

The *least-loaded routing* (LLR) algorithm proposed in [46] jointly selects the least-loaded route-wavelength pair over the k alternate routes between a source destination router pair. Therefore, the residual capacity over all wavelengths on k shortest routes is maximized. The LLR algorithm chooses the route p and wavelength j pair that achieves

$$\max_{p,j} \min_{l \in p} M_l - A_{lj}$$

where p denote the routes in the alternate route set, j denote the wavelengths, l denote the links, M_l denote the number of fibers on link l, and A_{lj} denote the number of fibers for which wavelength j is utilized on link l. The LLR algorithm can also be adapted to RWA in WI networks by choosing the route p that achieves

$$\max_{p} \min_{l \in p} KM_l - \sum_{j=1}^{K} A_{lj}$$

where K is the number of wavelength channels in each fiber. Simulations results have shown that (Figure 16) in both WS and WI networks, the LLR algorithm achieves much better blocking performance compared to fixed-routing algorithms. Moreover, performance difference in WS and WI networks gets larger as the number of alternate routes increased. This is because the alternate routes may be longer than the shortest route, and probability of a wavelength conflict increases along longer routes.

An alternative approach called *least congested path* (LCP) routing is proposed in [21]. In LCP, the lightpaths are routed on the least congested path and first-fit wavelength assignment is done. In [21], the LCP is compared with the static RWA with ILP formulation. The same set of lightpaths is routed over the same physical topology and lightpaths arrive randomly in dynamic RWA case. It has been shown that the congestion over all links and the number of wavelengths required are very close to each other for dynamic and static RWA. That is, the wavelength requirements for LCP and the optimal routing are close to each other.

In [32], [48], and [49], graph based methods for finding optimal routes and wavelengths for lightpaths using shortest path routing are considered. In such methods, network is represented by an auxiliary graph, which is composed of multiple layers of sub-graphs that correspond to the view of network at particular wavelengths (construction of such a graph can be found in Chapter 3). In the graphs, edges represent the resources used to establish lightpaths and edge costs are obtained from the state of the network (usually resource usage level) at the time of routing. Then, shortest path routing algorithms are used to find optimal route and wavelength(s) on that route. Graph based approaches also facilitate the incorporation converter costs in conjunction with channel costs in routing decisions. Hence, they are widely used in WI networks with limited wavelength conversion.

In many cases, although there is enough capacity available in the network, some of the lightpath requests are blocked due loss of optimality of the routes and wavelengths used by existing lightpaths. Therefore, it may be possible to avoid blocking of a lightpath request by rearranging existing lightpaths in the network. Move-to-vacant wavelength-retuning (MTV_WR) algorithm [50] makes use of this approach to improve the network performance. In MTV_WR, a lightpath is moved to a vacant wavelength on the same path to make room for an already blocked lightpath request. Therefore, blocking probability can be considerably reduced. It has been shown in [50] that, with MTV_WR, call blocking probability can be reduced by an average of 30% with only rerouting average of 1.3 lightpaths in a 21-node test network.

While all the works reviewed so far in this section are all *centrally managed*, that is, they assume that a central controller is present and has access to all necessary information for solving the RWA problem. In [51], two distributed adaptive RWA algorithms namely MCgR and MCvR are proposed. Based on the classical Bellman-Ford algorithm, MCgR and MCvR select the shortest path with minimum congestion and minimum conversion, respectively. It has been shown that both algorithms show significant blocking performance improvement by using small number of wavelength converters.

Lightpath setup delay is also an important issue in RWA algorithms. In [52], fixed-path least-congestion algorithm (FPLC), which selects minimum congestion route among previously defined k alternate routes have been proposed. In FPLC algorithm, source router searches the available number of wavelengths on those routes in parallel by sending needle packets toward the destination router to setup a lightpath. Then, destination selects the route, which has largest number of idle wavelengths to setup the lightpath. To reduce the setup delay, a new method, which uses neighborhood information, is also proposed. In this method, instead of searching all the links on the routes, only the first k links are searched for availability. It was shown that k=2 is generally sufficient to have good performance in a 4x4 mesh-torus network and in the NSFnet T1 backbone network.

2.4.5. Packet Switching

In packet switched networks, each end-node must be able to transmit/receive successive packets to/from different destinations/sources possibly on different wavelengths. To support packet switching in a wavelength routing network, there are two possibilities: each sd-pair is assigned to a separate lightpath for packet communication or packet switching is done at wavelength routers. The first approach may not be practical for large networks due to two reasons. First, the number of wavelengths available imposes a limit on the number of lightpaths that can be setup on a network. Second, each end-node can be the source and sink of only a limited number of lightpaths determined by the number of transmitters and receivers it has. Therefore, logical topologies can be designed to carry the packets in a multi-hop manner efficiently for a given traffic demand and physical topology. On the other hand, optical packet switching suffers from the need for per packet basis fast switching and the difficulties in optical processing (packet headers to determine routes) and optical buffering.

2.4.5.1. Packets on Lightpaths

The simplest way to support packet switching in WRNs is to employ permanent lightpaths between all possible router pairs in the network. In general, traffic demand between the routers are lower than the capacity of lightpaths, moreover, it may not be possible to establish required number of lightpaths due to physical limitations. Therefore, lower rate streams are multiplexed onto the higher capacity lightpaths and possibly follows multiple hops to reach their destination. This operation is referred as logical topology design and routing (embedding in physical topology) problem. In order to design an efficient logical topology, traffic demand between the end-nodes should be determined. The traffic demand can be obtained from the long-term averages of the number of packets communicated between each sd-pair. Once the demand matrix is determined, the problem is to design an optimal logical topology according to some objective function and embed this logical topology onto a given physical topology. The objective functions can be minimization of maximum congestion among all links (therefore traffic matrix can be scaled by a larger factor) [53], maximization of single hop traffic (reduce electronic forwarding) [54], minimization of delay (improve quality of service) etc. The logical topology design and RWA problems can be formulated as integer linear programs. Since, solving ILP problems are computationally hard, some heuristic design algorithms are also employed [53], [54].

2.4.5.2. IP over WDM

Many studies of communication patterns for the future transport networks predict that data traffic will dominate voice communication. Therefore, WRNs should clearly be optimized for data traffic. In particular, the networks should be optimized to carry *internet protocol* (IP) traffic, which seems to remain the major portion of overall data communication in the near future. At present, most of the all-optical networks are formed by WDM links and ATM and/or SONET/SDH are used to interface IP networks. However, in the long run, WRNs will be the single choice for transport networking and those multi-layer networks will converge to IP over WDM by eliminating intermediate layers [55]. There are several issues including lightpath routing with tighter cooperation with IP routing, survivability, framing/monitoring and addressing that should be addressed in IP over WDM integration [56].

The introduction of *multi protocol label switching* (MPLS) as extension to the existing IP architecture has enabled new possibilities in IP over WDM integration. MPLS adds new capabilities to the IP architecture such as *traffic engineering* (TE) and integration of IP routing and optical switching. In MPLS, all the packets in a particular session are sent along a predefined path called *label switched path* (LSP) by giving them the same label when they enter to the network. Each *label switching* *router* (LSR) routes the packets according to their label value and provides a new label to be used in next router to the packets. By using the analogy of labels in MPLS and wavelengths in WRNs, Multi Protocol Lambda Switching (MPλS) is proposed as an extension of MPLS for optical networks [57]. In MPλS, wavelength routers correspond to LSRs, lightpaths correspond to the LSPs and wavelengths of the lightpaths serves as the labels for the packets flowing through the lightpath.

MPλS is a potential enabler for IP over WDM integration. The MPλS based control plane [58] in such architecture will be responsible from resource discovery, state information dissemination and establishment and maintaining lightpaths according to QoS and predicted traffic requirements.

2.4.5.3. Optical Packet Switching and Optical Burst Switching

Today, optical processing technology is far behind electronic processing technology hence it is not possible to develop a packet switch operating entirely in optical domain. Instead, optical switching with electronic header recognition and processing is mainly used for optical packet switching. Several issues should be addressed in design of optical packet switches [59]:

1. Synchronization: In a network of routers, packets can arrive at different times at the input ports of each router. Since the reconfiguration of switches in a router is usually done at discrete times, all packets at the input ports should be aligned before they enter to the router. Therefore, bit level synchronization and fast clock recovery is required for proper packet header recognition and packet delineation.
2. Contention resolution: Usually packets need to be forwarded by multiple intermediate routers to reach their destinations. When, two packets at the same wavelengths are to be routed to the same output port, contention occurs. There are three major types of contention resolution:
    a. Optical buffering: Re-circulating loops and optical delay lines with delays of multiple packet durations are used for delayed forwarding of packets to output ports.
    b. Wavelength conversion: Wavelengths of the contending packets are switched to route toward idle channels on the correct output fiber. By

exploiting wavelength dimension in optical buffers may also considerably reduce the required number of fiber delay lines for the same performance [60], [61].

c. Deflection routing: One of the contending packets are routed to intended destination and others are routed to available output ports causing those packets to follow possibly longer routes to reach their destinations.

3. Packet and header format: Several possibilities exist. Usually, a fixed duration packet, which contains a payload and header, is considered. Payloads are usually processed transparently in optical domain and header is appended to payload or placed in a sub carrier in the same wavelength channel. Although variable length packets can be interesting, much complex hardware is required [62].

There are many router architectures that are proposed for optical packet switching [63], [64], [65]. Each router is composed of the input interface, switching fabric, output interface, and control unit [66]. When a packet arrives at a router, its header is converted to electronic domain at the interface and switches configured by control unit for intended destination. Then payload passes through the switch in optical domain. Finally, payload is combined by (possibly new) header at the output interface.

An alternative approach called *optical burst switching* (OBS) [66] is also proposed as an intermediate step between packet switching and circuit switching. OBS networks are composed of *burst switches* interconnected by WDM links. A burst is composed of multiple packets for the same destination and dynamically assigned to a channel through network. Therefore no optical buffers are required. The control packet associated with a burst is sent (over a separate control channel or signaling network) before the transmission of burst to inform intermediate switches to establish the channel. Therefore burst is conveyed by this temporary channel to its destination. A control and provisioning method based on MPLS is also proposed for OBS for IP over WDM integration [67].

2.4.6. Survivable WRNs

Survivability can be defined as the ability of network to recover lightpaths affected by failures. Since, each fiber and wavelength router accommodates a large amount of traffic in WRNs, the amount of bandwidth lost due to a fiber link or wavelength router failure is much larger than other types of networks. Therefore, survivability is indispensable in wavelength routing networks. Although some upper layer protocols such as IP, ATM, and SONET/SDH have their own protection mechanisms, handling failures in optical layer has many advantages [68]. For example, optical layer protection can efficiently handle certain types of failures such as fiber cuts which causes large number of lightpaths to generate alarms each requiring separate restoration by upper layers.

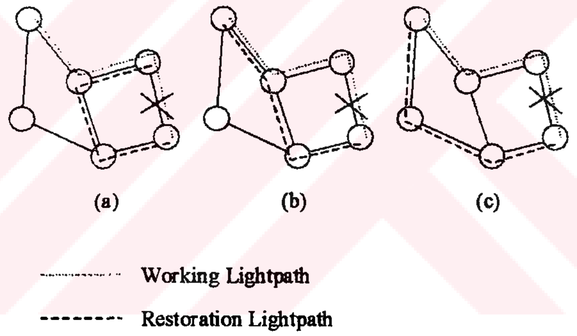


Figure 17 Restoration strategies [43] (a) Link restoration (b) Path restoration (c) Path restoration with link-disjoint route

Fast failure detection, fast restoration, and efficient use of resources are the important issues in survivable networks. Protection against failures requires lots of spare resources in the network. In meshed networks, by sharing spare resources among several restoration lightpaths, it is possible to reduce the amount of required spare capacity compared to ring topologies. There are mainly two protection schemes [69]:

1. Optical multiplex section level fiber protection: Working fibers are backed up by protection fibers. Although this is a fast recovery method, it causes low resource utilization.

2. Optical channel level protection: There are three possible ways (Figure 17):
    a. Link restoration (LR): The lightpaths passing through the failed link are rerouted. LR supplies the fastest failure detection and tries to recover traffic locally at the expense of efficiency (more hops, more bandwidth, more end-to-end delay).
    b. Path restoration (PR): The lightpaths broken are rerouted on a new path between their source and destination routers. PR efficiently uses spare capacity all over the network. However, failure detection times are long.
    c. Path restoration with link-disjoint route (PRd): Working and restoration paths do not use any common link. Therefore, the restoration process can be started immediately after a failure without knowing the exact location of the failure.

Generally, RWA problem for working and restoration lightpaths are jointly solved to have better sharing of resources. There are several proposals [38], [42], [43], [70] that consider logical topology design and physical resource assignment to maintain survivability. In these studies, static routing and wavelength assignment problems are formulated to route a predefined set of lightpath requests and corresponding set of restoration lightpaths for single link failure. In [42], [43], and [70], the routing and spare capacity planning problems are formulated as integer linear programs. Heuristic algorithms are also proposed for this purpose in [38] and [43].

CHAPTER 3

MINIMUM RECONFIGURATION PROBABILITY ROUTING

In WRNs, a multitude of high-speed channels are accommodated by a single fiber and wavelength routers are responsible for switching of even more channels. Consequently, a single failure (i.e., fiber cut or router failure) leads to large revenue losses. Although upper layer protocols such as IP, ATM, and SONET/SDH have some mechanisms to deal with failures, there are many advantages of handling failures in the optical network layer [68]. Moreover, achieving survivability in the optical network layer has an important role in unifying the underlying transport infrastructure. Survivability schemes are mainly based on protection switching and restoration. Protection mechanisms offer fast recovery from the failures by switching from working routes to pre-provisioned protection routes quickly. On the other hand, restoration mechanisms provide better utilization of spare capacity. There are many proposals for optimal or near optimal routing of working and restoration lightpaths in a given physical topology, capacity planning for a given traffic demand and restoration requirement, and fast restoration after failures [38], [43], [42], [70], [71]. Most of such algorithms deal with the fast reconfiguration of lightpaths broken due to a failure by using the previously determined restoration paths. Although restoration times in the order of milliseconds can be achieved, it is not possible to completely eliminate the disruption of lightpaths. In many cases such as voice communication or *best effort* data communication such disruptions can be tolerated. However, even short disruptions may be catastrophic for critical data traffic and compensation of lost packets by retransmits rather complicate the problem by a surge in the congestion of the packet network after recovery.

In this thesis, we propose a dynamic routing and wavelength assignment algorithm called ***minimum reconfiguration probability routing*** (MRPR). Our approach is based on minimization of lightpath reconfiguration probability by using the observed behavior of the network. Therefore, the probability of a lightpath being rerouted in the future due to a failure in the network is minimized. Consequently, both the effect of failures and service disruptions caused by failures are minimized. In order to evaluate the lightpath reconfiguration probabilities, the failure interarrival time statistics (i.e., mean and variance of failure inter-arrival times) for each router and link and lightpath holding time statistics (i.e., mean and variance of lightpath holding times) for each source router are collected. These statistics are used to predict the probability of reconfiguration due to failure in the future on all possible paths, which have enough free capacity to allocate for the request. Then, the path with the minimum reconfiguration probability (i.e., most reliable path) is chosen.

Selecting the most reliable path usually corresponds to selecting the path, which passes through as many reliable routers and reliable links as possible between the source and destination routers. Consequently, the most reliable path may be longer than the others or it may contain much more congested links than the others. This causes increased link congestions for the same traffic demand thereby causes higher blocking probabilities for the future requests. Therefore, to optimize probability of reconfiguration due to failures and blocking probability jointly, we need a measure of blocking probability that is compatible with the failure probabilities. For this purpose, we introduce a second category of reconfigurations: *repacking*. Repacking can be defined as the re-routing of some existing lightpaths currently using fully occupied resources with the purpose of making room for a request blocked due to insufficient free capacity on those resources (links or converters in routers). That is, although there is enough capacity available in the network, some of the lightpath requests are blocked due to loss of optimality of the routes and wavelengths used by existing lightpaths. A similar approach is employed in move-to-vacant wavelength-retuning (MTV_WR) algorithm [50]. In MTV_WR, a lightpath is moved to a vacant wavelength on the same path and the performance results show that blocking probability can be considerably reduced by such a rerouting method.

Probability of lightpath reconfiguration due to repacking can be defined as the probability of blocking of a future request, which can be avoided by re-routing the lightpath. This happens when a future request is blocked due to lack of free capacity in one of the resources used on the path of the lightpath during its lifetime. Actually, in MRPR, no lightpath is re-routed to obtain free space for a blocked request. Instead, the path with the minimum repacking probability is chosen for the lightpaths to minimize the chance of repacking in the future, thereby minimizing the blocking probability for the future requests. To predict the probability of reconfiguration due to repacking for a lightpath, lightpath arrival rate and lightpath holding time statistics are collected on each resource in the network. Then, these statistics are used in conjunction with the present state information (resource usage level at the time of routing) to evaluate the repacking probability for the lightpath on all possible resources. Our approach differs from other dynamic adaptive RWA algorithms in the parameters used in routing decisions. Most of the adaptive RWA algorithms proposed so far make use of present network state to minimize the potential blockings in the network. However, in MRPR, we use the operational statistics as well as the current state information. Therefore, our algorithm can easily adapt to changing load and failure conditions.

After the probability of reconfiguration due to failure, F_i, and the probability of reconfiguration due to repacking, R_i, have been evaluated for a request on each resource i in the network, the most reliable path for the lightpath can be found as:

$$\max_{p \in P_{sd}} \left\{ \prod_{i \in p} (1 - F_i)(1 - R_i) \right\} \qquad (1)$$

where, P_{sd} is the set of all paths between the source and destination routers s and d, a path p is a set containing the resources utilized, and it is assumed that repacking and failure events on each resource are independent events for individual resources. In MRPR, to find the most reliable path, the above problem is converted to a shortest path search problem on an auxiliary graph representing the network being considered (like in [32]). In this graph, each edge represents the resource(s) that are used to establish the lightpaths and edge costs are set to:

$$C = \begin{cases} \infty, & \text{i has failed or is fully occupied,} \\ -\ln(1\text{-}F_i)\text{-}\ln(1\text{-}R_i), & \text{otherwise.} \end{cases} \quad (2)$$

Then, the shortest path in the graph corresponds to the most reliable path in the network. In this study, we consider the search over all possible routes between the source and destination routers. However, our approach can easily be applied to alternate routing where a predefined set of routes between each source destination pair is considered for RWA.

In the following section, three types of WRNs on which MRPR is applied are considered. Then, how the failure and repacking probabilities are evaluated from the present network state and gathered statistics and how auxiliary graphs can be prepared for each network type are discussed. For simplicity, we start with the WI networks and derive corresponding failure and repacking probability functions. Then, we make use of these functions and show how they can be extended, possibly with different parameters, for the other network types.

3.1. Network Models

MRPR is mainly designed for WRNs composed of wavelength routers and links with an arbitrarily connected (mesh) topology. In such networks, each link is composed of one or more fibers with multiple channels on distinct wavelengths, and routers can selectively route each lightpath at an input fiber to any other output fiber. To demonstrate how MRPR approach can be employed in different types of networks for RWA, according to the usage level of wavelength converters in the routers, we consider wavelength selective (WS), wavelength interchanging (WI) and share-per-node wavelength interchanging (SPN) (limited conversion WI networks with share-per-node router architectures) networks as described in Section 2.4. Although MRPR can be employed for both share-per-node and share-per-link architectures, we consider share-per-node configuration since it requires lower number of converters to achieve the same blocking performance.

In these networks, lightpath requests arrive at each router at random times and, if not blocked, they stay on the network for a random amount of time. It is assumed that each router or link may fail at random times, may be repaired in a random amount of time and lightpaths broken due to a failure are re-routed on a new path.

There are two possibilities for restoration path computation: *offline* and *online*. In offline approach restoration paths are determined at the same time with the working paths (or before the failure happens). Therefore, offline approach provides faster recovery from failures compared to online approach in which restoration path is searched after the failure. The recovery issues are out of the scope of this thesis, hence, for simplicity, we consider online restoration. It is also assumed that, *lightpath arrival rate* statistics for each link, *lightpath holding time* statistics on each router and link and *failure interarrival time* statistics for each router and link are collected to be used in RWA decisions.

3.2. MRPR in WI Networks

Since there is a full set of wavelength converters in the routers, RWA problem in WI networks reduces to the circuit routing problem. After the routing problem is solved, wavelengths on the links along the route can be assigned randomly. In order to find the route with minimum reconfiguration probability for a lightpath request, a simple auxiliary graph $G=(N,E)$, where nodes $n \in N$ represent the routers and each directed edge $(i,j) \in E$ represents the link (i,j) from router i to router j, is constructed. Then, cost of each edge (i,j) is set to:

$$C_{ij} = \begin{cases} \infty, & \text{edge can not be used,} \\ -\ln(1-F_{ij})-\ln(1-R_{ij})-\ln(1-F_j), & \text{otherwise.} \end{cases} \tag{3}$$

where,

- F_{ij} is the probability of reconfiguration due to failure on link (i,j),
- R_{ij} is the probability of reconfiguration due to repacking on link (i,j),
- F_j is the probability of reconfiguration due to failure on router j,

for the lightpath to be routed if it is routed through link (i,j) and router j, and

- *'edge can not be used'* means that the link (i,j) or router j has already failed or link (i,j) has no free wavelength channel to allocate.

Then, the minimum cost route will be the most reliable route for the lightpath request. The reconfiguration due to failure and reconfiguration due to repacking probabilities used in (3) are derived in the following subsections.

3.2.1. Reconfiguration Due To Failure

In this subsection we derive the probability of reconfiguration due to failure for a lightpath on a resource (link or router) in terms of mean and variance of failure interarrival times on that resource and mean and variance of holding times for the lightpaths between the source and destination routers. Probability of reconfiguration due to failure, *F*, for a lightpath on a resource is equal to the probability of a failure on that resource during the lifetime of the lightpath. Therefore, if we assume that failure arrival and lightpath termination events are independent and failure arrival process is memoryless (i.e., probability that resource *i* fails in the interval *t+dt* is independent of the time *t*), *F* can be found as:

$$F = \int_{y=0}^{\infty} \left(\int_{x=0}^{y} f(x)dx \right) h(y)dy \tag{4}$$

where,

- *x* is a random variable (r.v.) representing failure interarrival times on the resource,
- *f(x)* is the probability distribution function (p.d.f.) of r.v. *x*,
- *y* is a r.v. representing the lightpath holding times between the source and destination routers, and
- *h(y)* is the p.d.f. of r.v. *y*.

To determine *F*, knowledge of *f(x)* and *h(y)* are required. A straightforward way to evaluate (4) is to approximate *f(x)* and *h(y)* by an appropriate distribution function with mean and variance equal to the corresponding values obtained from the statistics. Lightpath holding times are usually approximated by an exponential distribution function and failure interarrival times are usually approximated by an exponential distribution function or a Weibull distribution function, which may approximate closely the observed phenomena [72]. In particular, if both failure interarrival and lightpath holding times are approximated by exponential distribution functions, F can be found as:

$$F = \int_{y=0}^{\infty} \left[\int_{x=0}^{y} \frac{1}{m_f} e^{-\frac{x}{m_f}} dx \right] \frac{1}{m_h} e^{-\frac{y}{m_h}} dy = \frac{1/m_f}{1/m_f + 1/m_h} = \frac{m_h}{m_h + m_f} \tag{5}$$

where, m_f and m_h are the mean failure interarrival and mean lightpath holding times, respectively.

On the other hand, if we make some assumptions on *f(x)* and *h(y)*, without using distribution functions directly, we can approximate the right hand side of equation (4) in terms of the moments of x and y. First, an upper bound for F can be found by using *Tchebycheff Inequality*, which states:

Tchebycheff Inequality **[73]**: *if x is a r.v. with p.d.f. f(x), mean* m_f *and variance* V_f*, then, for any* $\varepsilon>0$,

$$P\{|x-m_f| \ge \varepsilon\} = \int_{x=-\infty}^{-m_f-\varepsilon} f(x)dx + \int_{x=m_f+\varepsilon}^{\infty} f(x)dx \le \frac{V_f}{\varepsilon^2} \tag{6}$$

■

If we assume that *f(x)* is symmetric around its mean and *h(y)* is negligible for the values larger than mean failure interarrival time (i.e., lightpath durations are much smaller than the mean failure interarrival time), we have:

$$\int_{x=0}^{y} f(x)dx \le \frac{V_f}{2(m_f-y)^2} \tag{7}$$

and, therefore,

$$F_i = \int_{y=0}^{\infty}\left(\int_{x=0}^{y} f(x)dx\right)h(y)dy \le \int_{y=0}^{\infty} \frac{V_f}{2(m_f-y)^2}h(y)dy \tag{8}$$

where, m_f and V_f are the mean and variance of failure interarrival times for the resource, respectively. Hence, we are left with only one unknown, *h(y)*, to evaluate F. However, if we assume that the r.v. y is concentrated near its mean, the right hand side of (8) can be approximated by the following method:

Estimate of the mean of g(x) **[73]**: *If y is a r.v. with p.d.f. h(y), mean* m_h*, and variance* V_h*, then, the mean of the r.v. z=g(y) can be expressed in terms of* m_h *and* V_h *as:*

$$E\{g(y)\} = \int_{-\infty}^{\infty} g(y)h(y)dy \cong g(m_h) + g''(m_h)\frac{V_h}{2} \qquad (9)$$

■

Then, by using (9), we have:

$$F \le \frac{V_f}{2(m_f - m_h)^2} + \frac{3V_f}{(m_f - m_h)^4}\frac{V_h}{2}$$

$$F \le \frac{V_f}{2(m_f - m_h)^2}\left(1 + \frac{3V_h}{(m_f - m_h)^2}\right) \qquad (10)$$

where, m_h and V_h are the mean and variance of the holding times respectively for the lightpaths between the source and destination routers. Finally, in the worst case, F can be found as:

$$F = \min\left\{1,\ \frac{V_f}{2(m_f - m_h)^2}\left(1 + \frac{3V_h}{(m_f - m_h)^2}\right)\right\} \qquad (11)$$

Note that, in above equation, we have assumed that the mean failure interarrival time is larger than the mean lightpath holding time and *min{1,...}* term is used to guarantee that resultant probability value is less than or equal to one.

3.2.2. Reconfiguration Due To Repacking

In this subsection we derive the probability of reconfiguration due to repacking, R, for a lightpath on a link in the network in terms of the number of lightpaths currently passing through the link (present link state) and arrival rate and service time statistics for the lightpaths on the link. To find R, we need to find the probability of having a call blocked due to lack of free capacity on that link during the lifetime of the lightpath. Therefore, we need the transient repacking probabilities on the link under consideration to find the expected value of repacking probability for a lightpath. However, it is very hard to find a function for exact transient repacking probabilities, because, we need to know the arrival and holding time processes for the lightpaths and the present state of the (whole) network. In order to evaluate the approximate repacking probabilities, we have made the following simplifying assumptions:

- The links in the network are independent of each other. That is, lightpath arrivals to each link are independent processes and a lightpath on an *n* link route behaves like *n* independent lightpaths. Link independence assumption is widely used in analysis of circuit switched networks[30],
- Lightpaths arrive at the link under consideration according to a Poisson process with rate λ and lightpath holding times are exponentially distributed with mean $1/\mu$, and
- Repacking events on each link are independent of the repacking events on other links. That is path costs are separable into link costs. Therefore, repacking probability for a lightpath on route *p*, R_p, can be found from individual link repacking probabilities, R_l, as

$$R_p = 1 - \prod_{l \in p} (1 - R_l).$$

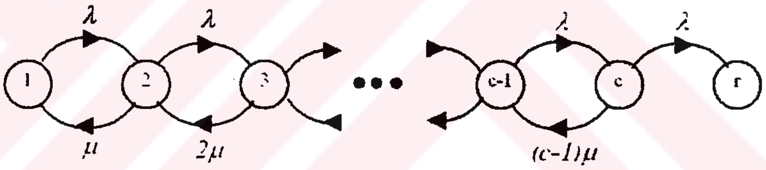


Figure 18 State diagram of the Markov Process constructed to determine R.

With the help of these assumptions, we can find the repacking probability, *R*, for a lightpath request, *lp-0*, on a link with capacity *c* and initially having n_0 lightpaths ($n_0<c$), by modeling the link as a *Markov Process* as in Figure 18. In this process, all states except the one labeled by *r* are the *transient* states which correspond to the number of lightpaths on the link before any repacking is experienced. On the other hand, the state labeled by *r* is the *trapping* state, which represents the repacking occurrence before the termination of *lp-0*.

The differential equations characterizing this Markov Process can be found as [74]:

$$
\begin{aligned}
&p_1'(t) = -\lambda p_1(t) + \mu p_2(t),\\
&p_n'(t) = -(\lambda + (n-1)\mu)p_n(t) + n\mu p_{n+1}(t) + \lambda p_{n-1}(t)\\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad 1 < n < c,\\
&p_c'(t) = -(\lambda + (c-1)\mu)p_c(t) + \lambda p_{c-1}(t),\\
&p_r'(t) = \lambda p_c(t),\\
&p_n(0) = \begin{cases} 1, & n = n_0 + 1, \\ 0, & otherwise. \end{cases} \qquad 1 \le n \le c, \qquad p_r(0) = 0.
\end{aligned}
\tag{12}
$$

where,

- $p_n(t)$ for $n=1,2,\ldots,c$ are the probability of having n lightpaths on the link at time t and no repacking has occurred up to time t,
- $p_r(t)$ is the probability of experiencing a repacking on the link up to time t,
- n_0+1 is the state of the link at time $t=0^+$, if the lightpath request is routed on this link, and
- We assume that *lp-0* remains in the link for $t \geq 0$, or equivalently, at least one lightpath exists in the link for $t \geq 0$. Therefore, the number of lightpaths that may terminate at state n equals $n-1$, hence death rate at state n equals $(n-1)\mu$.

Finally, the probability of repacking on the link until *lp-0* terminates can be found by finding the expected value of $p_r(t)$ as:

$$R_L = \int_0^\infty p_r(t)\mu\, e^{-\mu t} dt \tag{13}$$

Therefore, if we assume that when repacking occurs the lightpath to be re-routed is randomly selected among the lightpaths in the link, we can find the probability of reconfiguration due to repacking for a lightpath as:

$$R = \frac{1}{c}\int_0^\infty p_r(t)\mu\, e^{-\mu t} dt \tag{14}$$

Equation (14) states that, in order to find R, we need to solve the differential equations in (12) for $p_r(t)$. However, it is not easy to find a closed form expression for $p_r(t)$. Instead, we introduce the following transform to directly solve R from the equations in (12):

$$P_n = \int_0^\infty p_n(t)\, e^{-\mu t} dt \qquad i = 1,2,..,c,r \tag{15}$$

Since (using integration by parts),

$$\int_0^\infty p_n'(t)\, e^{-\mu t} dt = p_n(t)\, e^{-\mu t}\Big|_0^\infty + \mu \int_0^\infty p_n(t)\, e^{-\mu t} dt\,, \tag{16}$$

we have:

$$P_n = -p_n(0) + \mu P_n \qquad n = 1,2,..,c,r \tag{17}$$

By multiplying the both sides of the equations in (12) by $e^{-\mu t}$ and integrating from 0 to ∞, we have:

$$\begin{aligned}
&\mu P_1 - p_1(0) = -\lambda P_1 + \mu P_2, \\
&\mu P_n - p_n(0) = -(\lambda + (n-1)\mu) P_n + n\mu P_{n+1} + \lambda P_{n-1} \\
&\qquad\qquad\qquad\qquad\qquad\qquad 1 < n < c, \\
&\mu P_c - p_c(0) = -(\lambda + (c-1)\mu) P_c + \lambda P_{c-1}, \\
&\mu P_r - p_r(0) = cR = \lambda P_c, \\
&p_n(0) = \begin{cases} 1, & n = n_0 + 1, \\ 0, & otherwise. \end{cases} \qquad n = 1,2,\ldots,c.
\end{aligned} \tag{18}$$

First of all, by reorganizing (18) we have:

$$\begin{aligned}
&(\rho+1) P_1 = I_1 + P_2, \\
&(\rho+n) P_n = I_n + nP_{n+1} + \rho P_{n-1} \qquad 1 < n < c, \\
&(\rho+c) P_c = I_c + \rho P_{c-1}, \\
&R = \frac{\lambda}{c} P_c, \\
&where, \\
&\rho = \lambda / \mu, \\
&I_n = \begin{cases} 1/\mu, & n = n_0 + 1, \\ 0, & otherwise. \end{cases} \qquad n = 1,2,\ldots,c.
\end{aligned} \tag{19}$$

Starting from P_1, P_n can be found in terms of P_{n+1} and I_i for $n=1,2,..,c$ and $i=1,2,\ldots,n$ as:

$$\begin{aligned}
&P_1 = \frac{1}{(\rho+1)} I_1 + \frac{1}{(\rho+1)} P_2, \\
&P_n = \sum_{i=1}^{n} \beta_n^i I_i + \alpha_n P_{n+1} \qquad 1 \le n \le c, \\
&with, \\
&P_{c+1} \equiv 0.
\end{aligned} \tag{20}$$

From (19) and (20):

$$(\rho+n)P_n = I_n + nP_{n+1} + \rho\sum_{i=1}^{n-1}\beta_{n-1}^{i} I_i + \rho\alpha_{n-1}P_n \qquad 1<n\le c \tag{21}$$

Then, P_n can be found from (21) as:

$$P_n = \sum_{i=1}^{n} \frac{\rho}{(\rho+n-\rho\alpha_{n-1})}\beta_{n-1}^{i} I_i + \frac{n}{(\rho+n-\rho\alpha_{n-1})}P_{n+1} \qquad 1<n\le c \tag{22}$$

with

$\beta_{n-1}^{n} = 1/\rho$

Therefore,

$$\begin{aligned} \alpha_n &= \frac{n}{(\rho+n-\rho\alpha_{n-1})}, \\ \beta_n^i &= \frac{\rho}{(\rho+n-\rho\alpha_{n-1})}\beta_{n-1}^{i} = \frac{\rho}{n}\alpha_n\beta_{n-1}^{i}, \\ \beta_n^i &= \frac{\rho^{n-i-1}}{n(n-1)\ldots(i+1)i}\prod_{j=i}^{n}\alpha_j, \end{aligned} \tag{23}$$

$$for \quad 1<n\le c \quad and \quad \alpha_1 = \frac{1}{1+\rho}.$$

Lemma: *α_n in* (23) *can be found as:*

$$\alpha_n = \frac{n}{\rho}\frac{E(n,\rho)}{E(n-1,\rho)} \qquad 1\le n\le c \tag{24}$$

where, $E(n,\rho)$ is the Erlang Loss Formula given by:

$$E(n,\rho) = \frac{\dfrac{\rho^n}{n!}}{\displaystyle\sum_{i=0}^{n}\frac{\rho^i}{i!}} \tag{25}$$

Proof (by induction): For n=1:

$$\alpha_1 = \frac{1}{\rho}\frac{\dfrac{\dfrac{\rho^1}{1!}}{1+\dfrac{\rho^1}{1!}}}{\dfrac{1}{1}} = \frac{1}{1+\rho} \tag{26}$$

Therefore, (24) *is true for n=1. Now, suppose that* (24) *is true for n≥1,* α_{n+1} *can be found as:*

$$\alpha_{n+1} = \frac{n+1}{\rho + n + 1 - \rho\dfrac{n}{\rho}\dfrac{E(n,\rho)}{E(n-1,\rho)}}$$

$$= \frac{n+1}{\rho + n + 1 - n\dfrac{\dfrac{\rho^n}{n!}\sum\limits_{i=0}^{n-1}\dfrac{\rho^i}{i!}}{\dfrac{\rho^{n-1}}{(n-1)!}\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}} = \frac{n+1}{\rho + n + 1 - \rho\dfrac{\sum\limits_{i=0}^{n-1}\dfrac{\rho^i}{i!}}{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}}$$

$$= \frac{(n+1)\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}{(n+1)\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!} + \rho\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!} - \rho\sum\limits_{i=0}^{n-1}\dfrac{\rho^i}{i!}}$$

$$= \frac{(n+1)\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}{(n+1)\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!} + \rho\dfrac{\rho^n}{n!}} = \frac{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!} + \dfrac{\rho}{(n+1)}\dfrac{\rho^n}{n!}}$$

$$= \frac{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}{\sum\limits_{i=0}^{n+1}\dfrac{\rho^i}{i!}} = \frac{\dfrac{1}{\sum\limits_{i=0}^{n+1}\dfrac{\rho^i}{i!}}}{\dfrac{1}{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}} = \frac{\dfrac{\dfrac{\rho^{n+1}}{(n+1)!}}{\sum\limits_{i=0}^{n+1}\dfrac{\rho^i}{i!}}}{\dfrac{\dfrac{\rho^{n+1}}{(n+1)!}}{\sum\limits_{i=0}^{n}\dfrac{\rho^i}{i!}}} = \frac{n+1}{\rho}\frac{E(n+1,\rho)}{E(n,\rho)}$$

Therefore, our assertion is true.

■

By using (24) in (23):

$$\beta_n^i = \frac{\rho^{n-i-1}}{n(n-1)\ldots(i+1)i}\prod_{j=i}^{n}\alpha_j$$

$$= \frac{\rho^{n-i-1}}{n(n-1)\ldots(i+1)i}\frac{n}{\rho}\frac{E(n,\rho)}{E(n-1,\rho)}\frac{n-1}{\rho}\frac{E(n-1,\rho)}{E(n-2,\rho)}\cdots\frac{i+1}{\rho}\frac{E(i+1,\rho)}{E(i,\rho)}\frac{i}{\rho}\frac{E(i,\rho)}{E(i-1,\rho)} \tag{27}$$

$$\Leftrightarrow \beta_n^i = \frac{1}{\rho}\frac{E(n,\rho)}{E(i-1,\rho)}$$

Then, from (20) P_c can be found as:

$$P_c = \sum_{i=1}^{c}\frac{1}{\rho}\frac{E(c,\rho)}{E(i-1,\rho)}I_i + \alpha_c P_{c+1} \tag{28}$$

Since, $P_{c+1}\cong 0$ and $I_i=0$ for $i\neq n_0+1$(28) can be rewritten as:

$$P_c = \frac{1}{\rho}\frac{E(c,\rho)}{E(n_0,\rho)}I_{n_0+1} \tag{29}$$

Finally, by using $R=\lambda P_c$ and $I_n=1/\mu$ for $n=n_0+1$:

$$R = \frac{\lambda}{c}P_c = \frac{\lambda}{c}\frac{1}{\rho}\frac{E(c,\rho)}{E(n_0,\rho)}\frac{1}{\mu} = \frac{1}{c}\frac{E(c,\rho)}{E(n_0,\rho)} \tag{30}$$

$$R = \frac{1}{c}\frac{E(c,\rho)}{E(n_0,\rho)} \tag{31}$$

A formula similar to (31) was derived earlier for state dependent link cost of *State Dependent Routing* (SDR) [75] in circuit switched networks as:

$$K = \frac{E(c,\rho)}{E(n_0,\rho)} \tag{32}$$

In [75], SDR is formulated as a *Markov Decision Process* to estimate the average number of future rejections on a link if the link under consideration is used to route the request. Therefore, the total cost of a path (i.e., $\Sigma_{i\in p} K_i$) gives the estimate of the mean number of additional future rejections in the network due to accommodating a new call on that path. As a result, a new call is routed on the minimum cost path if there is at least one path with total cost less than one. SDR can easily be applied for RWA in all-optical networking to improve blocking probability performance. However, in this study, our objective is completely different. In MRPR, we are trying to assign the most reliable path to the lightpaths and we need a measure of future blocking probabilities as well, to be minimized. Therefore, we have derived the formula in (31) as the expected value of repacking probability during the lifetime of a lightpath on a link. As a result, we find the path reconfiguration probabilities in terms of (router and link) failure and (link) repacking probabilities as $[1 - \Pi_{(i,j)\in p}\ (1-F_{ij})\ (1-R_{ij})\ (1-F_j)]$ to choose the minimum cost path for a lightpath.

3.3. MRPR in WS Networks

In WS networks, a router cannot change the wavelength of a lightpath passing through itself. Therefore, each lightpath should be assigned to the same wavelength on the links along its route. When a lightpath request arrives, we need to find a route through (usually) multiple links, which have at least one free channel at a common wavelength. To simplify this search process, we construct an auxiliary graph, which is composed of a few disjoint graphs representing the view of the network at a particular wavelength. Therefore, the shortest path over all these sub-graphs will determine the route and wavelength of the lightpath. If there is more than one path with the minimum cost, the one with the smallest index wavelength is selected.

In order to construct the auxiliary graph to establish a lightpath between the routers s and d in a WS network, we first construct a sub-graph $G_w=(N_w,E_w)$ in which each node $r_{iw} \in N_w$ represents the router i and each directed edge $(r_{iw}, r_{jw}) \in E_w$ represents the channels at wavelength w in the link (i,j) from router i to router j in the network. Then, the super nodes r_s and r_d corresponding to source and destination terminals for the lightpath respectively and W of these sub-graphs are combined by the edges (r_s, r_{sw}) and (r_{dw}, r_d) for $w=1,2,..,W$ where W is the number of wavelength channels in each fiber. Then, the cost of edges (r_s, r_{sw}) and (r_{dw}, r_d) for $w=1,2,..,W$ are set to zero and the cost, C_{ijw}, of each edge (r_{iw},r_{jw}) are set to:

$$C_{ijw} = \begin{cases} \infty, & \text{edge can not be used,} \\ -\ln(1-F_{ij}) - \ln(1-R_{ijw}) - \ln(1-F_j), & \text{otherwise.} \end{cases} \quad (33)$$

where,

- F_{ij} is the probability of reconfiguration due to failure on the link (i,j),

- R_{ijw} is the probability of reconfiguration due to repacking at wavelength w on the link *(i,j)*,
- F_j is the probability of reconfiguration due to failure on router j,

for the lightpath to be routed if it is routed through link *(i,j)* at wavelength w and router j, and

- *'edge can not be used'* means that router j or link *(i,j)* has already failed or there is no free channel at wavelength w on the link *(i,j)* to allocate.

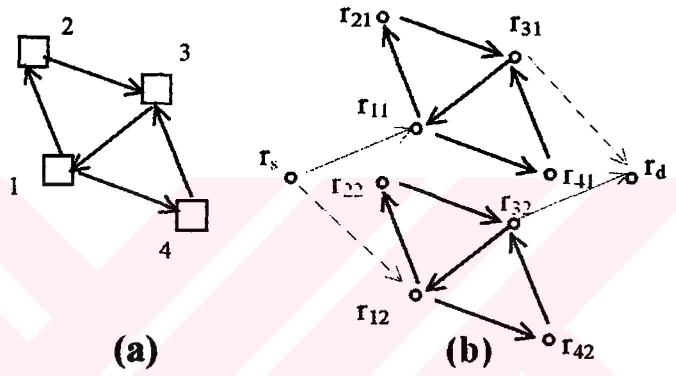


Figure 19 (a) A WS network and (b) its graph representation

In Figure 19, construction of such a graph for a simple WS network (with $W=2$) to route a lightpath from router 1 to router 3 is illustrated.

In WS networks, probability of reconfiguration due to failure on each router and link are the same with the values obtained for WI networks. However, the parameters that determine the probability of reconfiguration due to repacking is different, since, in WS networks, we should consider the lightpaths at the same wavelength independently of the lightpaths assigned to other wavelengths. If we assume that the lightpaths are uniformly distributed over the wavelengths in link *(i,j)* (i.e., arrival rates of lightpaths at different wavelengths are the same), from (31), we can find the probability of reconfiguration due to repacking for a lightpath at wavelength w as:

$$R_{ijw} = \frac{1}{k}\frac{E(k,\rho/W)}{E(k_w,\rho/W)} \tag{34}$$

where,

- k is the number of fibers in link (i,j),
- k_w is the initial number of lightpaths at wavelength w on the link (i,j),
- W is the number of wavelength channels on each fiber, and
- $\rho=\lambda/\mu$ is the load on link (i,j) obtained from gathered statistics.

3.4. MRPR in SPN Networks

In SPN networks, routers have a limited number of wavelength converters. Therefore, it is possible to change the wavelength of a lightpath on its route to solve wavelength conflicts. However, we should use wavelength converters carefully, because, using a wavelength converter unnecessarily in a router may cause blocking of future requests, which need wavelength converters. Therefore, similar to the links, we consider repacking of lightpaths, which are using converters in a router. For this purpose, we use converter usage statistics (i.e., mean arrival rate and mean holding time of lightpaths that use converters), and number of converters in use at the time of routing to determine the cost of using a converter in that router. To facilitate the incorporation of the converter costs in RWA, an extended version of the auxiliary graph presented in Section 3.3 is used.

The auxiliary graph to establish a lightpath between the routers s and d in a SPN network can be constructed as follows:

1. For each wavelength $w=1..W$ and router n, create the nodes i_{nw} and o_{nw} which represent the input and output ports of router n at wavelength w respectively,
2. For each wavelength $v,w=1..W$ and router n, create the edges (i_{nv}, o_{nw}) corresponding to wavelength conversion in router n,
3. For each wavelength $w=1..W$ and link (m,n) from the router m to router n, create the directed edges (o_{mw}, i_{nw}) which represent the channels at wavelength w in link (m,n),
4. Create the nodes r_s and r_d corresponding to source and destination terminals for the lightpath, and
5. For each wavelength $w=1..W$, create the edges (r_s, i_{sw}) and (o_{dw}, r_d).

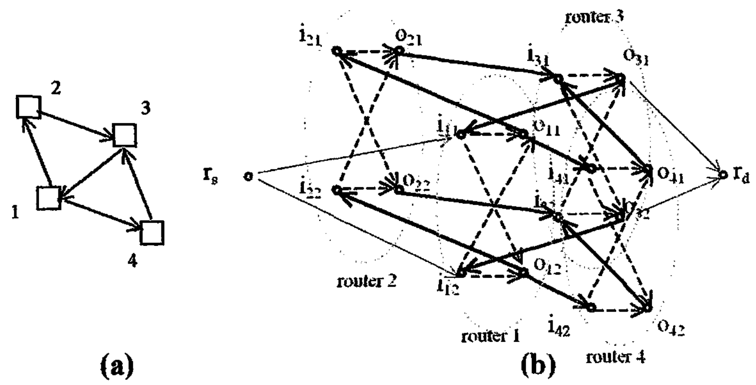


Figure 20 (a) A SPN network and (b) its graph representation

In Figure 20, construction of such a graph for a simple SPN network (with $W=2$) to route a lightpath from router 1 to router 3 is illustrated. After the graph is constructed, for $v,w=1,2,..,W$ and for each router n and m, the cost of edges (r_s, i_{sw}) and (o_{dw}, r_d) for $w=1..W$ are set to zero, the cost of each edge (o_{mw}, i_{nw}) are set to:

$$C_{mnw} = \begin{cases} \infty, & \text{no free channel at wavelength w on (n, m)}, \\ -\ln(1-F_{mn}) - \ln(1-R_{mn}), & \text{otherwise.} \end{cases} \tag{35}$$

cost of each edge (i_{nv}, o_{nw}), for $v \neq w$,

$$X_{nvw} = \begin{cases} \infty, & \text{no free converters in n or n has failed}, \\ -\ln(1-F_n) - \ln(1-R_n), & \text{otherwise.} \end{cases} \tag{36}$$

and the cost of each edge (i_{nw}, o_{nw})

$$X_{nw} = \begin{cases} \infty, & \text{n has failed}, \\ -\ln(1-F_n), & \text{otherwise.} \end{cases} \tag{37}$$

where,

- F_{mn} is the probability of reconfiguration due to failure on the link (m,n),
- R_{mn} is the probability of reconfiguration due to repacking at on the link (m,n),
- F_n is the probability of reconfiguration due to failure on router n,

for the lightpath to be routed if it is routed through link (m,n) and router n, and

- *'edge can not be used'* means that router n or link (m,n) has already failed or there is no free channel on the link (m,n) to allocate.

In SPN networks, the probability of reconfiguration due to repacking for a lightpath on each link and the probabilities of reconfiguration due to failure on each router and link are the same with the values obtained for WI networks. The probability of reconfiguration due to repacking for the converters in each router can be found using the results obtained in Subsection 3.2.2 as:

$$R_n = \frac{1}{x}\frac{E(x,\rho)}{E(x_0,\rho)} \tag{38}$$

where,

- x is the number of converters in router n,
- x_0 is the initial number of converters in use in router n, and
- $\rho=\lambda/\mu$ is the load obtained from the arrival and service rates of the lightpaths using converters in router n.

CHAPTER 4

PERFORMANCE EVALUATION

Performance of the MRPR algorithm has been evaluated by computer simulations and compared with the corresponding minimum congestion adaptive shortest path routing algorithm, which is a modified version of *adaptive unconstrained routing* (AUR) [37]. In the following section, the simulation tool developed for this purpose is presented. Then, verification of this simulation tool based on comparisons with the results presented in the literature is given. Finally, for each network type, *blocking probability* and *reconfiguration probability* performance of MRPR with respect to load, reliability, and some network parameters such as number of wavelength in each fiber, number of fibers per link, and number of converters in each router on different network topologies are presented and compared with the performance of AUR algorithm.

4.1. Simulation Environment

In this study, a general-purpose simulation tool for wavelength routing networks is developed to assess the performance of RWA algorithms. Some of the features of the simulation tool are as follows:

- Network topology on which the simulations are to be carried out can be supplied as a text input file.
- Simulation parameters such as number of wavelengths per fiber, number of fibers per link, number of converters per router can either be specified or read from the input file for each link/router individually.
- Link and router failures can be enabled or disabled. If a failure happens, the lightpaths affected from the failure are re-routed on the restoration routes,

which are computed on-line (i.e., computed on the fly after the failure). If a restoration route cannot be found, the lightpath is assumed to be lost. Two types of routers and links are defined: reliable and un-reliable. For each type of router and link, failure arrival rate and repair rate can be specified.

- Link and lightpath types can be selected as bi-directional/uni-directional links/lightpaths.
- Simulation running parameter can be selected as *load* or *reliability ratio* and its starting value, stopping value and increments in each step can be specified. When one of the running parameters is selected, the other parameter is fixed and its value can also be specified. Reliability ratio is equal to the ratio of un-reliable routers/links to all routers/links in the network. Load is expressed in one of (in erlangs):
  - o Load per wavelength: Load offered to the each wavelength, given by $\lambda_w = (\lambda_T H)/(W^*L)$, where λ_T is the total load offered to the network, H is the average hop distance between the routers, W is the number of wavelengths per fiber, and L is the number of fibers in the network.
  - o Load per node: Load offered to each source router in the network,
  - o Total Load: Total load offered to the network.
- In each step (for each value of simulation running parameter), a certain confidence interval or fixed number of lightpaths to be routed can be specified as stopping criterion.
- As the output, the simulator measures:
  - o Blocking probability: probability of a lightpath request being blocked,
  - o Maximum blocking probability: The maximum of lightpath request blocking probabilities experienced by each source router,
  - o Reconfiguration probability: probability of a lightpath being reconfigured due to a router/or link failure along its path,
  - o Maximum reconfiguration probability: The maximum of lightpath reconfiguration probabilities experienced by each source router.
- The following RWA algorithms have been implemented (separately for WI/WS/SPN Networks):

    - AUR: an extended version of adaptive unconstrained routing to select the minimum congested/minimum hop path between the source and destination routers,
    - MRPR: Minimum reconfiguration probability routing algorithm,
    - MRPR-F: Minimum reconfiguration probability routing algorithm in which repacking probabilities are set to zero,
    - MRPR-R: Minimum reconfiguration probability routing algorithm in which failure probabilities are set to zero.
- It is possible to conduct batch of simulations, which include more than one simulation with different parameters,
- Some screen snapshots of the simulator have been presented in Appendix A,
- The simulator is available for public use[1].

Note: Some simulation data including processing times and referred figures for simulations conducted in this study can be found at Appendix B.

4.2. Verification of Simulation Tool

In order to verify the tool, several simulations have been conducted on different network topologies and results have been compared with the results presented in the literature.

A simple network of two routers and single link with w wavelengths is equivalent to $M/M/w/w$ queue. As the first verification, the blocking probabilities obtained by our simulator and analytical results are compared under different loads and channel capacities. It is known that the blocking probability for an M/M/w/w is equal to the Erlang loss formula given in equation (25). In Figure 21, blocking probability versus total load for w=10 and w=5 is presented. The results indicate that analytical and simulation results are the same.

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[1] Available via http://www.geocities.com/altankocyigit/sim.html

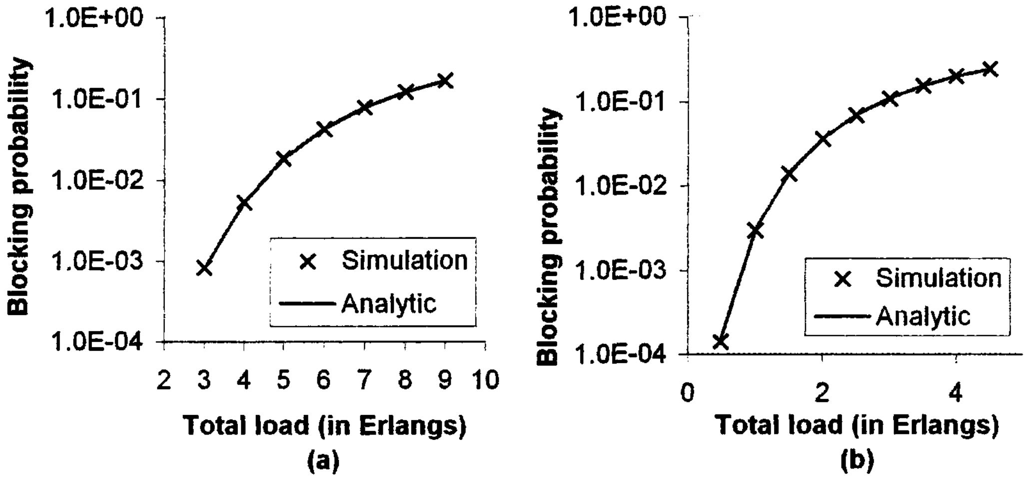


Figure 21 Blocking probability vs. load for M/M/w/w queue for (a) w=10 (b) w=5

In [32], the blocking probability performance of share-per-node networks for different number of wavelength converters per router is presented. In the simulations, ARPA2 network topology that consists of 21 routers and 26 links (shown in Figure 22) is considered, and each link assumed to be formed by two fibers in opposite directions each having 16 wavelength channels and uni-directional lightpaths are established between the routers. Shortest path routing with link costs equal to unity and converter costs equal to 3 is performed on an auxiliary graph similar to the one presented in Section 3.4. In Figure 23, blocking probability performance reported by Lee and Li and measured by our simulator on ARPA2 network for changing load and changing number of converters per router is presented. The results show that the blocking probabilities obtained by our simulator and those presented in [32] are close to each other.

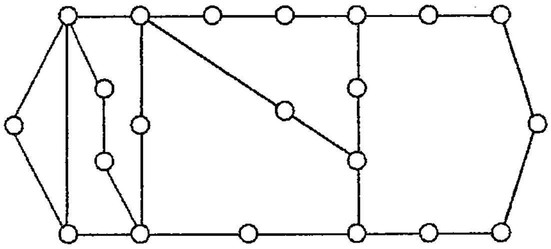


Figure 22 21 node-26 Link ARPA2 Network

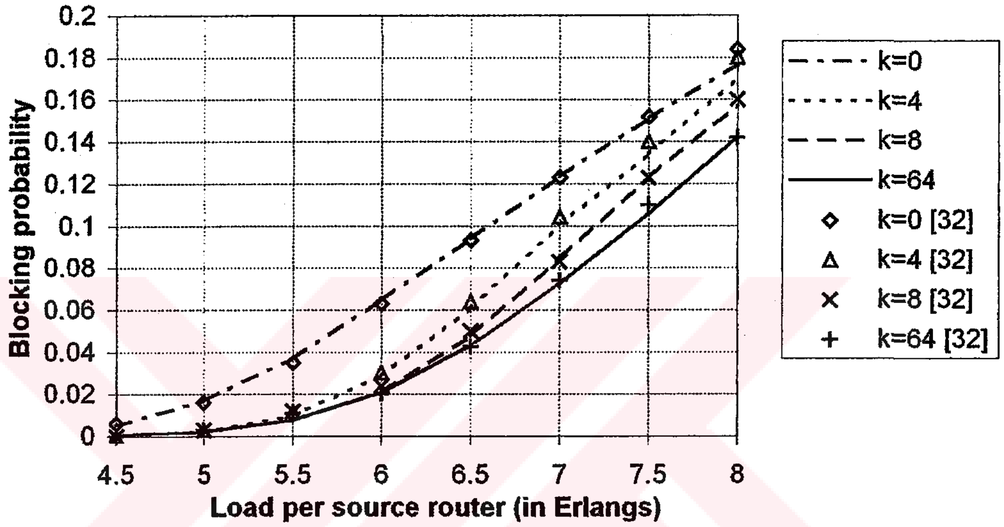


Figure 23 Blocking probability versus Load per route for k=0,4,8,64 wavelength converters per router on ARPA2 Network. Lines show the results obtained from our simulator and marks show the results presented by Lee and Li [32]

In [37], the blocking probability performances of AUR algorithm on a WS Network with randomly generated topology (shown in Figure 24) with number of wavelengths per fiber equal to 4 and 8 are presented. In Figure 25, the results presented by Mokhtar and Azizoğlu and results obtained from our simulator are compared.

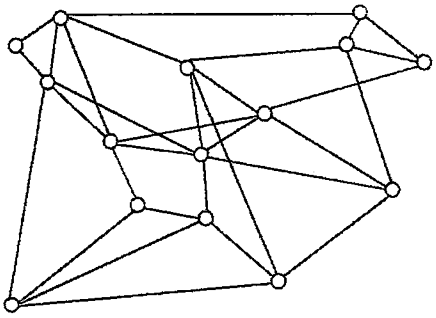
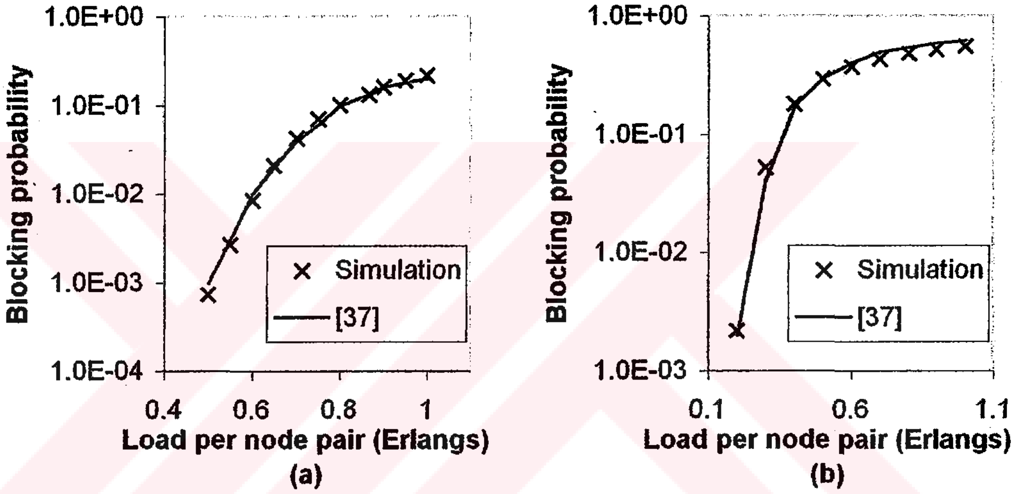


Figure 24 A randomly generated network [37].



(a)

(b)

Figure 25 Blocking probability versus load per node pair on randomly generated topology with number of wavelengths per fiber equal to (a) 8 and (b) 4. The marks show the results obtained from our simulator and lines show the results presented by Mokhtar and Azizoğlu [37].

4.3. Performance of MRPR

In order to assess the benefits of the MRPR algorithm, we compare its performance with the modified version of adaptive unconstrained routing algorithm, which selects the least congested minimum hop route. We select the AUR algorithm among the other alternatives because both AUR and MRPR consider all possible routes in routing computations and if we set all edge costs identical in MRPR, both algorithms behave identically.

In the simulations, we consider two performance measures: *Blocking Probability* (i.e., probability of a lightpath request being blocked) and *Reconfiguration Probability* (i.e., probability of a lightpath being re-routed due to a router or link failure along its route) and we measure the performance under changing load and reliability conditions. In the performance plots, *reliability ratio* is equal to the ratio of un-reliable routers/links to all routers/links in the network, and *load* is expressed as *load per wavelength* (in Erlangs).

In the simulations, each link in the network is composed of bi-directional fibers (i.e., two set of separate fibers in opposite directions) and bi-directional lightpaths (i.e., two separate lightpaths on the same route and at the same wavelength in opposite directions) established between the routers for each request. Lightpath requests arrive at the network as a Poisson process of rate λ_T and are uniformly distributed over the routers (i.e., source and destination routers are selected randomly for a lightpath request) and lightpath holding times are exponentially distributed with unit mean. The blocked lightpath requests are assumed to be lost. In order to assess the performance of MRPR under different failure conditions, we consider two types of links and routers such as reliable and unreliable routers/links. Failures arrive at each reliable and unreliable router/link according to Poisson processes of rates 0.0001 and 0.01 (unless otherwise stated) respectively and repair times are exponentially distributed with unit mean. The lightpaths on a failed link or router are re-routed and restoration routes are computed online.

Performance of the network is highly dependent on the selection of unreliable items in the network. That is, reconfiguration and blocking performances may be considerably different for the networks with different set of unreliable routers/links under the same reliability ratio and load values. Therefore, for each load and reliability ratio value, we have conducted 10 simulations with different set of unreliable routers/links and taken the average to find the corresponding reconfiguration and blocking probabilities. Since failures are rare events compared to lightpath arrivals, extremely large number of samples is required to achieve a specified level of confidence for reconfiguration probabilities. For this reason, instead of specifying a particular confidence level, for each blocking probability and reconfiguration probability value, 1.000.000 lightpaths (unless otherwise specified) have been routed within each one of the 10 simulation runs mentioned above, and it was observed that outcome variations were sufficiently low.

4.3.1. Performance in WI networks

In this section we evaluate the blocking probability and reconfiguration probability performance of MRPR algorithm in WI networks and compare it with the performance of AUR algorithm. AUR algorithm in WI networks routes lightpaths on the least congested minimum hop route. In order to find the least congested minimum hop route, network is represented by a graph like in MRPR and cost of each arc *(i,j)* in this graph is set to:

$$C_{ij} = \begin{cases} \infty, & \text{edge can not be used,} \\ 1 + \dfrac{1}{N^{c-n_0}}, & \text{otherwise.} \end{cases} \tag{39}$$

where,

- N is the number of routers in the network (which is equal to *the number of hops in longest possible cycle free route in an N router network* + *1*),
- c is the capacity of link *(i,j)*,
- n_0 is the number of lightpaths currently on the link *(i,j)*, and
- *'edge can not be used'* means that the link *(i,j)* or router *j* has already failed or link *(i,j)* has no free wavelength channel to allocate.

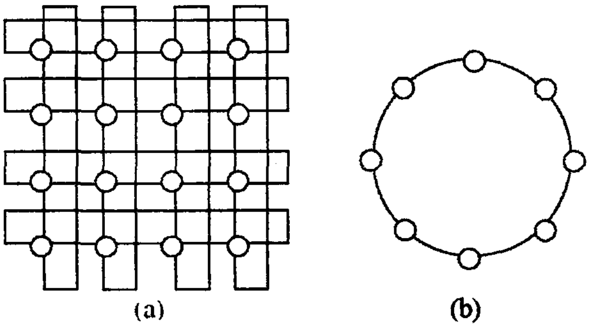

(a) (b)

Figure 26 (a) 16 router, 4x4 mesh-torus network, (b) 8 router ring network

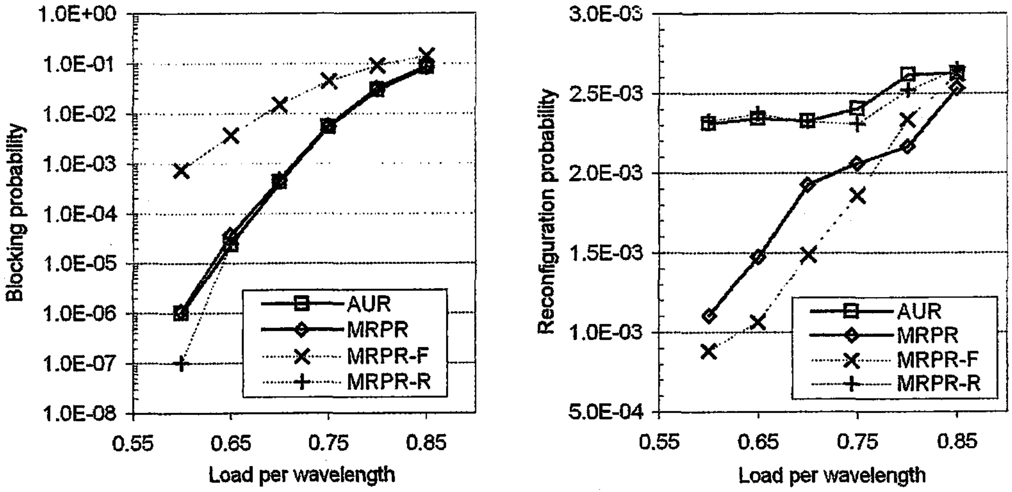


Figure 27 Blocking probability and reconfiguration probability vs. load per wavelength on 4x4 mesh-torus WI network when reliability ratio=0.0625

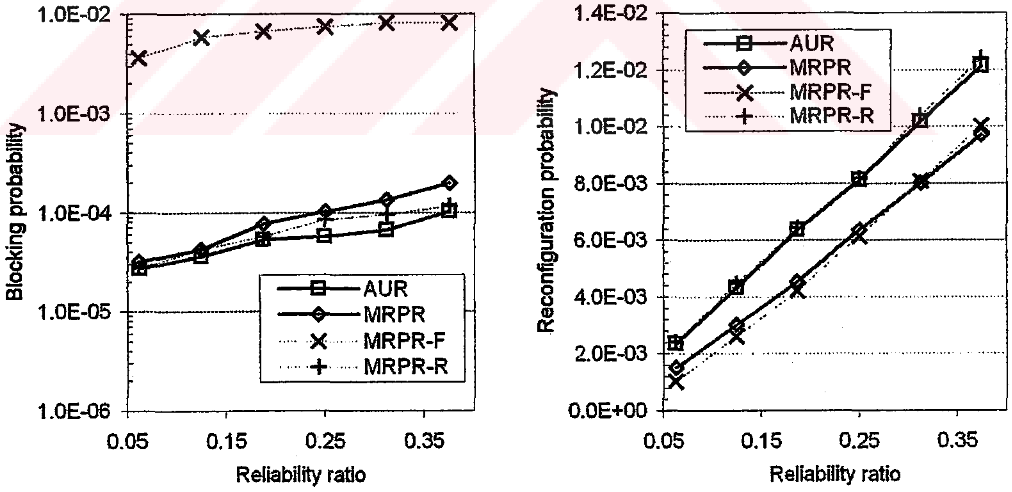


Figure 28 Blocking probability and reconfiguration probability vs. reliability ratio on 4x4 mesh-torus WI network when load per wavelength=0.65

MRPR is mainly designed mainly for the networks with arbitrarily connected mesh topologies. However, in order to demonstrate how MRPR behaves in different topologies, in this section, we performed simulations on three different topologies such as ring, mesh-torus and arbitrarily connected mesh.

In order to demonstrate the effect of cost values corresponding to failure and repacking probabilities on the performance, in this section, we consider three MRPR implementations with different cost assignments:

1. MRPR: Cost values are set according to equation (3),(11), and (31),
2. MRPR-F: Only the cost values associated with failure probabilities are used. That is, R_{ij} is set to zero for all i, j in equation (3),
3. MRPR-R: Only the cost values associated with repacking probabilities are used. That is, F_{ij} and F_j are set to zero for all i, j in equation (3).

In Figure 27, performance of AUR, MRPR, MRPR-F, and MRPR-R in 4x4 mesh-torus network (shown in Figure 26.a) is presented. In this network, each link is composed of two separate fibers in opposite directions and each fiber has 16 distinct wavelength channels. The results show that reconfiguration probability performance of MRPR and MRPR-F are better than AUR. That is, if failure probabilities are used in routing decisions, reconfiguration performance is improved. However, if repacking probabilities are not included in the costs, blocking performance deteriorates. On the other hand, if repacking probabilities are included in the costs, it is possible to improve blocking probability performance at a cost of increased reconfiguration probability. Therefore, by using both repacking and failure probabilities in MRPR, we achieve better reconfiguration probability without deteriorating the blocking probability. Under low loads, failure probabilities are quite effective on costs, hence MRPR behaves like MRPR-F and up to 50% improvement can be achieved in reconfiguration probability compared to AUR. As the load increases, due to high utilization of links much more unreliable items are unavoidably used in routes and reconfiguration probability increases and gain in reconfiguration probability performance drops down to a few percent. Since, there are many alternative routes with equal hop counts in mesh-torus topologies, benefits of MRPR-F at high loads cannot be noticed.

In Figure 28, blocking probability and reconfiguration probability performance with respect to reliability ratio in the 4x4 mesh-torus network under fixed load are shown. The results show that, MRPR-F and MRPR achieves better reconfiguration probabilities compared to AUR and MRPR-R. However, blocking probability for MRPR-F is much higher compared to other algorithms. On the other hand, MRPR is better than AUR regarding reconfiguration probability while they both have near equal blocking probabilities. This also justifies the conclusions drawn from Figure 27.

In Figure 29 and Figure 30 performance of AUR, MRPR, MRPR-R, and MRPR-F algorithms on 8 router ring network (shown in Figure 26.b) is presented. In this network, each link is again composed of bi-directional fibers having 16 distinct wavelength channels. Connectivity in ring topologies is very low and number of alternative routes is much less (only two alternate routes between any two routers) compared to the mesh topologies. Therefore, we may expect all algorithms to behave similarly in such a topology. As it can be seen from the figures, a modest gain about %20 in reconfiguration probability performance is achieved by MRPR and MRPR-F and blocking probabilities are almost same for all algorithms. This is mainly due to the fact that the optimum route in ring topologies is usually the minimum hop route (especially under uniform loads), and reconfiguration probability can only be reduced by selecting the path having least number of un-reliable items on the way for the requests between furthest router pairs.

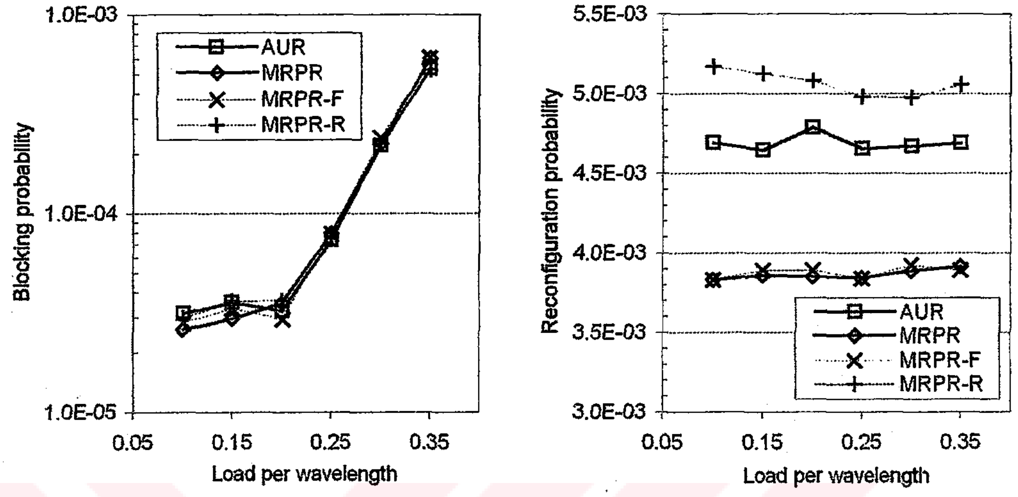


Figure 29 Blocking probability and reconfiguration probability vs. load per wavelength on 8 router ring WI network when reliability ratio=0.125

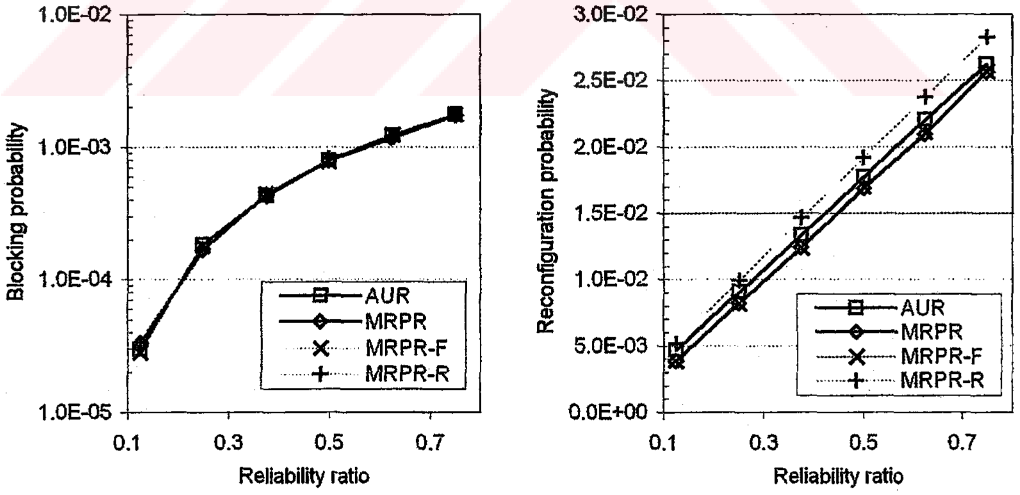


Figure 30 Blocking probability and reconfiguration probability vs. reliability ratio on 8 router ring WI network when load per wavelength=0.1

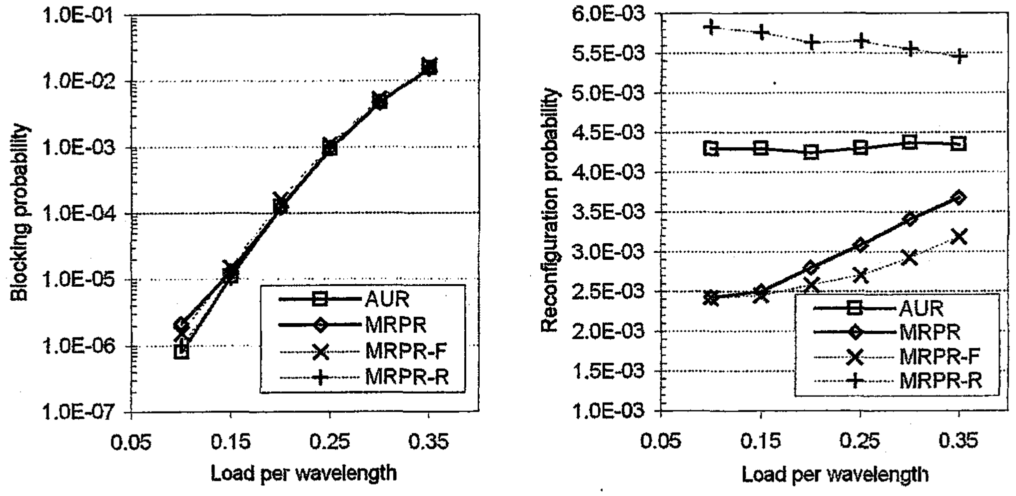


Figure 31 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh WI network when reliability ratio=0.05 and wavelengths per fiber=8

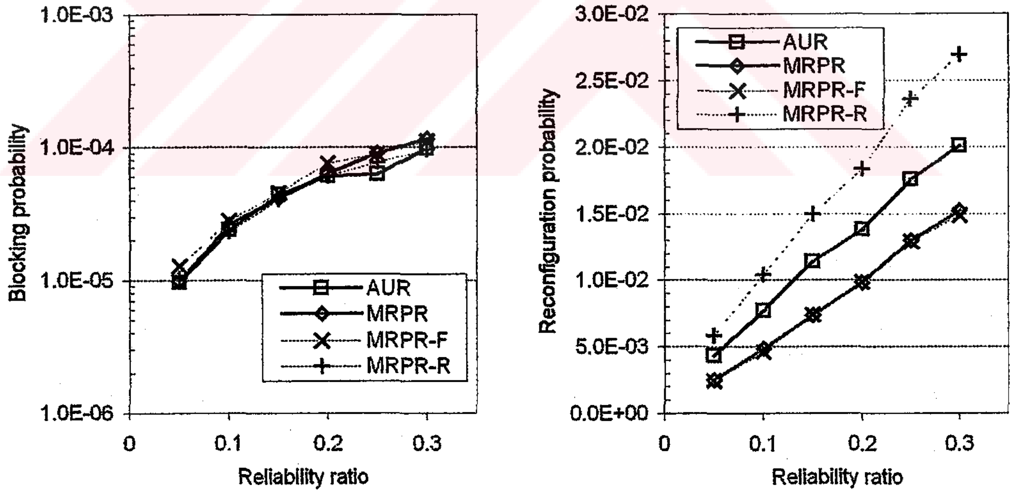


Figure 32 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh WI network when load per wavelength=0.15 and wavelengths per fiber=8

In Figure 31 and Figure 32, performance of AUR, MRPR, MRPR-R, and MRPR-F algorithms on 30 router and 47 link mesh network (shown in Figure 33) is presented. In this network, each link is composed of bi-directional fibers each having 8 distinct wavelength channels. Results show that, like in 4x4 mesh torus network, if failure probabilities are included in the costs reconfiguration probability can be improved whereas if repacking probabilities are not included in the costs, blocking probability gets worse. As results indicate, at low loads MRPR behaves like MRPR-F. This is due to the fact that, at low link utilizations, failure probabilities are much larger compared to the repacking probabilities, and accordingly much effective in route decisions. As the load increases, reconfiguration probability grows much faster in MRPR compared to MRPR-F since repacking probabilities become much more effective at high loads to avoid future blockings.

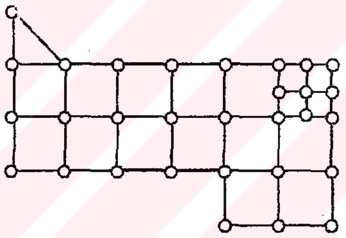


Figure 33 30 Router and 47 link mesh network [23]

Up to now, we have considered overall blocking probability and overall reconfiguration probability, which are the measures of mean quality of service. In Figure 34 and Figure 35, maximum blocking probability (i.e., maximum of the blocking probabilities experienced at all the source routers) and maximum reconfiguration probability (i.e., maximum of the reconfiguration probabilities experienced at all the source routers) are presented. These performance metrics can measure the fairness of our algorithm. As it can be seen from the graphs, maximum blocking and maximum reconfiguration probability performances of each RWA algorithm reveals similar characteristics. At high loads, gain achieved by MRPR with respect to AUR in maximum reconfiguration probabilities and overall reconfiguration probabilities are almost equal. However, the maximum gain (at low loads) in reconfiguration performance achieved by the MRPR with respect to the AUR drops from 45% to 30%. In many cases, minimum hop route between some router pairs passes through some un-reliable items and the other possible routes are much longer. In such cases, use of minimum hop routes may be unavoidable and this may cause modest gain in reconfiguration probability at corresponding routers. The way we obtain equation (11) is also one of the causes of this result. Since equation (11) gives the worst-case failure probability, which is larger than exact failure probability, MRPR-F and MRPR also favor shorter routes. On the other hand, as the reliability ratio increases (i.e., as the number of unreliable items increase), gain in maximum reconfiguration probabilities and overall reconfiguration probabilities get closer to each other.

In order to assess the effect of number of wavelengths on the performance, we have conducted simulations on 30 router mesh network with 16 wavelengths in each fiber. In Figure 36 and Figure 37, outputs of these simulations are presented. If these results are compared with the results in Figure 31 and Figure 32, it can be seen that doubling the number of wavelengths has caused a negligible change in reconfiguration probability performance for the load values corresponding to near equal blocking probabilities.

In more reliable environments, failure probabilities will be much lower and repacking probabilities are expected to be much effective on routing decisions. To demonstrate how MRPR algorithm behaves in more reliable environments we have conducted simulations on the 30-router mesh network with failure arrival rates of 0.00001 and 0.001 for reliable and unreliable routers/links, respectively (i.e., items are 10 times more reliable than the items used in previous simulations). In Figure 38 and Figure 39 blocking and reconfiguration probability performances of AUR, MRPR, MRPR-F, and MRPR-R algorithms under varying load and reliability ratio conditions are presented. As it can be seen, results exhibit similar characteristics with the results obtained in the previous simulations with a scaling of 10. However, in this case, reconfiguration probability for MRPR grows much faster as the load increases since the repacking probabilities are much effective in routing decisions. Reconfiguration probability performances of all algorithms come closer to each other at high loads where resource limitations dominate.

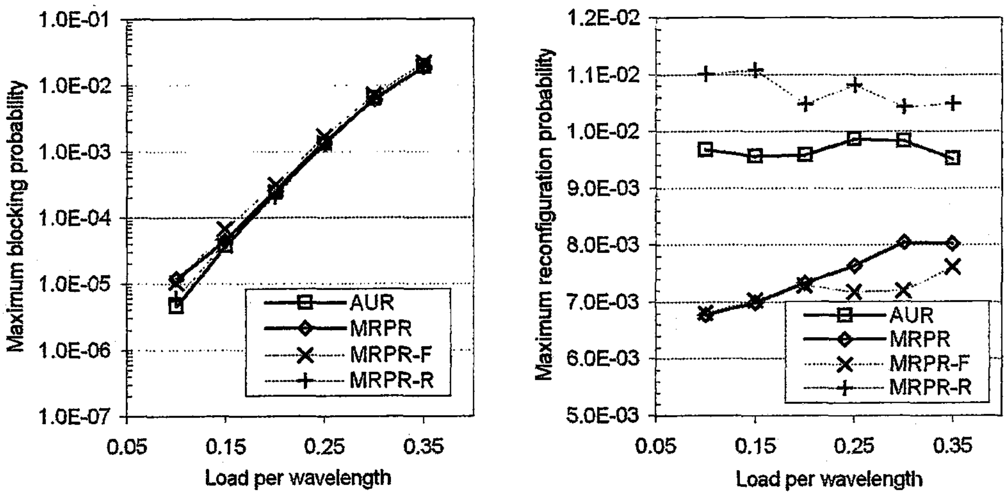


Figure 34 Maximum blocking probability and maximum reconfiguration probability vs. load per wavelength on 30 router mesh WI network when reliability ratio=0.05 and wavelengths per fiber=8

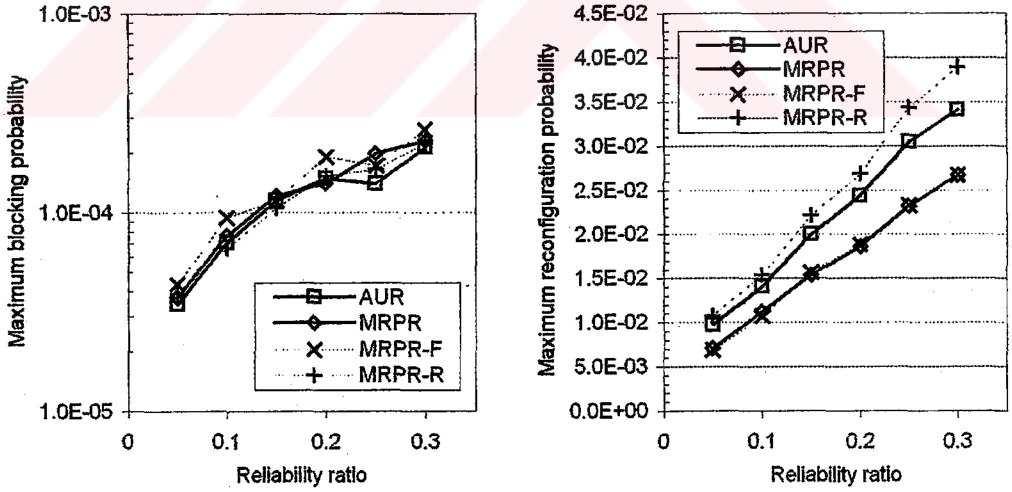


Figure 35 Maximum blocking probability and maximum reconfiguration probability vs. reliability ratio on 30 router mesh WI network when load per wavelength=0.15 and wavelengths per fiber=8

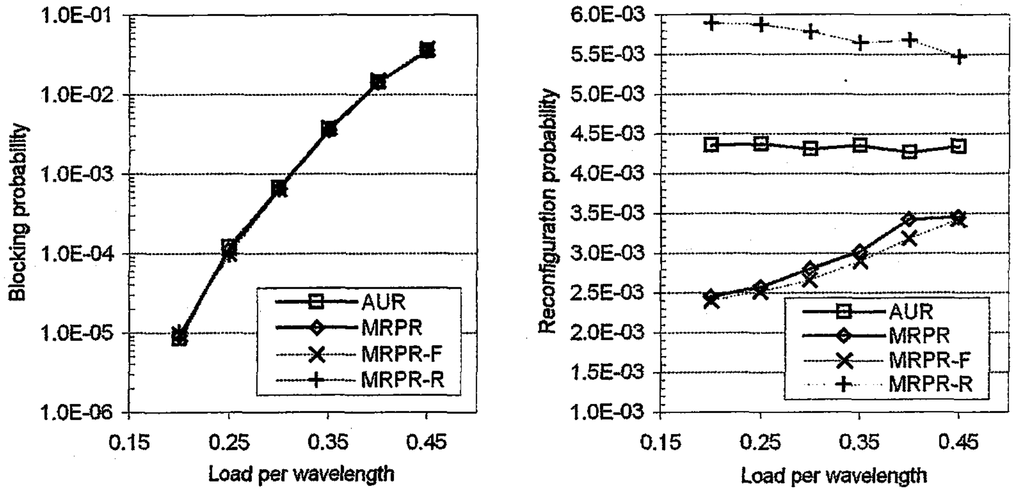


Figure 36 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh WI network when reliability ratio=0.05 and wavelengths per fiber=16

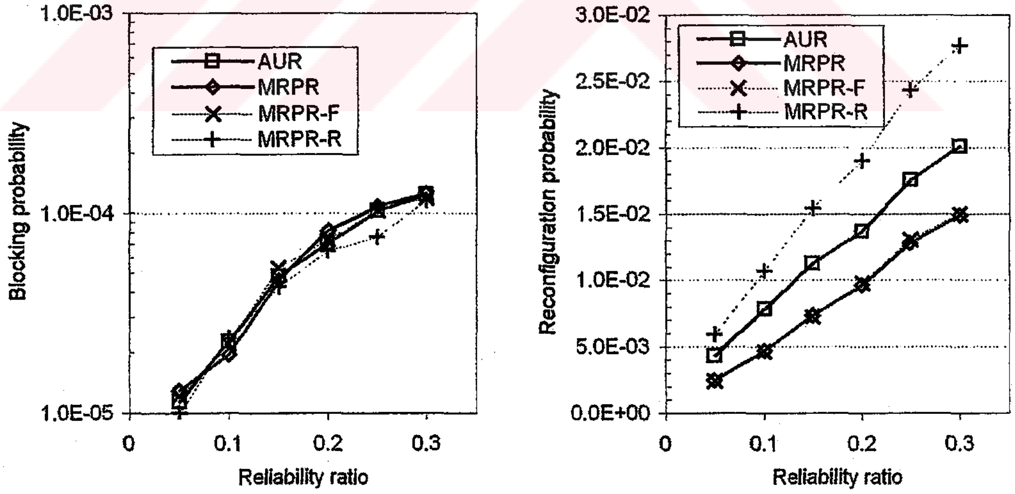


Figure 37 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh WI network when load per wavelength=0.2 and wavelengths per fiber=16

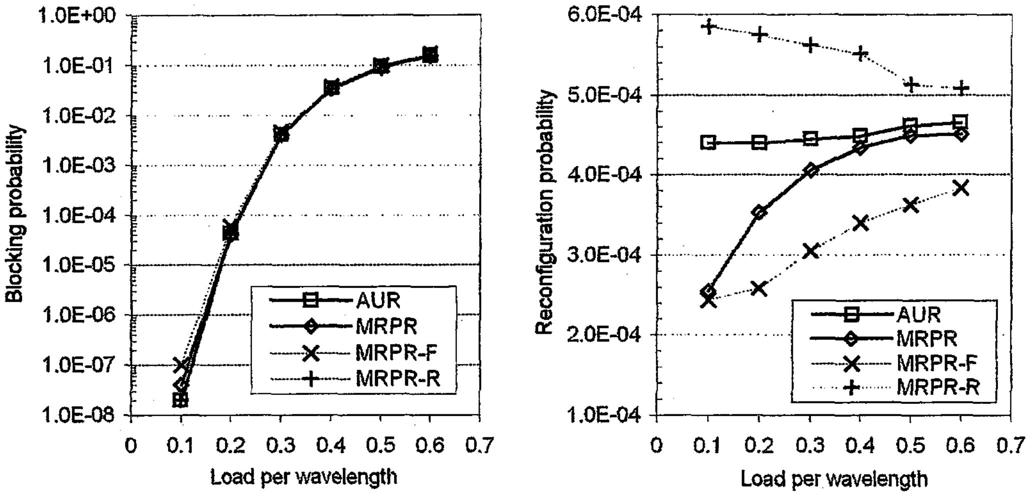


Figure 38 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh WI network when failures are rare, reliability ratio=0.05, and wavelengths per fiber=8

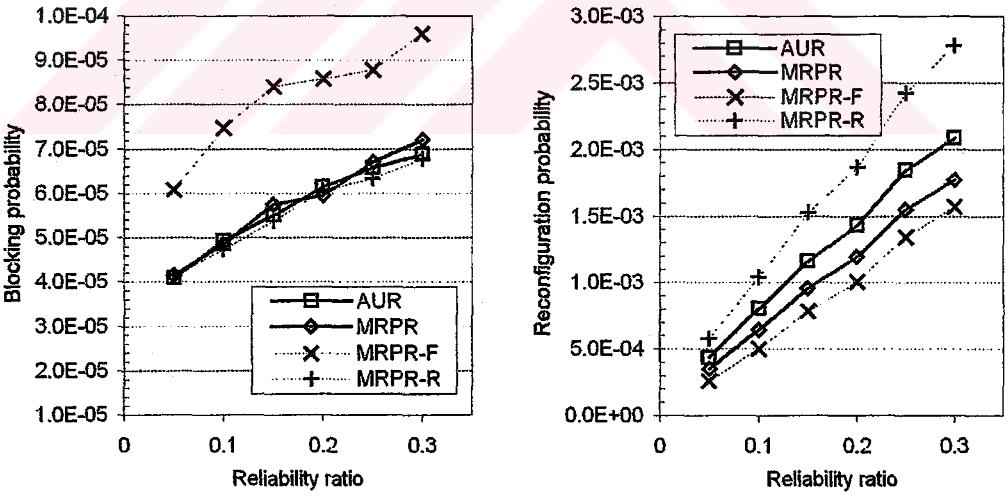


Figure 39 Blocking probability and Reconfiguration probability vs. reliability ratio on 30 router mesh WI network when failures are rare, load per wavelength=0.2, and wavelengths per fiber=8

4.3.2. Performance in WS networks

In this section we evaluate the blocking probability and reconfiguration probability performance of MRPR algorithm in WS networks and compare them with the performance of AUR algorithm. Since MRPR makes use of wavelength congestion information in links to minimize repacking probability, we consider multi-fiber links in the network. In the simulations, we consider 30 router mesh network (Figure 33) where each link is composed of multiple bi-directional fibers, each fiber has 8 distinct wavelength channels and bi-directional lightpaths established between the router pairs.

In MRPR, an auxiliary graph is used in RWA and edge costs in the graph are set according to equations (33), (34), and (11). The AUR algorithm in WS networks routes lightpaths on minimum hop route and assigns the least congested wavelength on this route. If there are more than one minimum hop routes, the one with the least wavelength congestion, is selected among them. In order to find the least congested minimum hop route, the auxiliary graph constructed for MRPR can be used and cost of each arc (r_{iw}, r_{jw}) in this graph is set to:

$$C_{ijw} = \begin{cases} \infty, & \text{edge can not be used,} \\ 1 + \dfrac{1}{N^{k-k_w}}, & \text{otherwise.} \end{cases} \tag{40}$$

where,

- N is the number of routers in the network (which is equal to *the number of hops in longest possible cycle free route in an N router network* + *1*),
- k is the number of fibers in link *(i,j)*,
- k_w is the number of lightpaths at wavelength w currently on the link *(i,j)*, and
- *'edge can not be used'* means that the link *(i,j)* or router j has already failed or link *(i,j)* has no free wavelength channel at wavelength w to allocate.

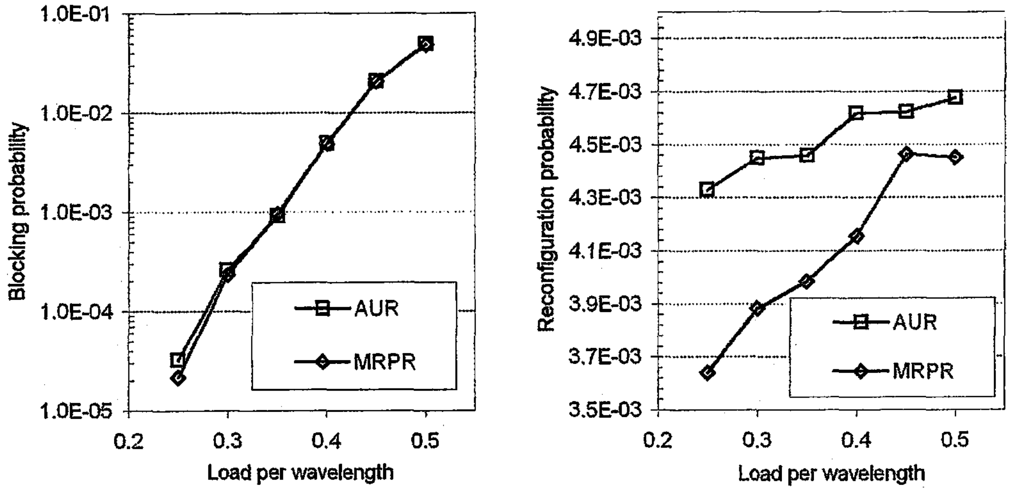


Figure 40 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh WS network when reliability ratio=0.05 and fibers per link=4

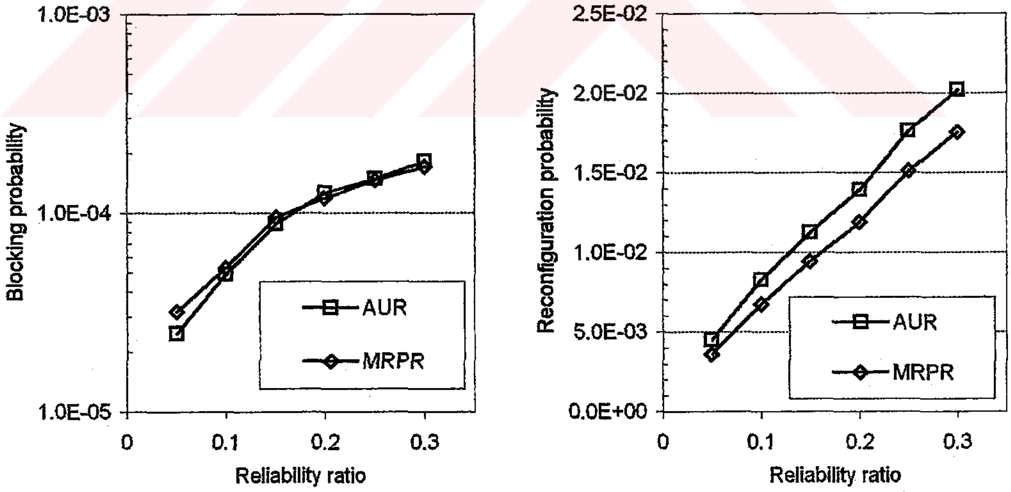


Figure 41 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh WS network when load per wavelength=0.25 and fibers per link=4

In Figure 40 and Figure 41, blocking and reconfiguration probability performances of AUR and MRPR algorithms under changing load and reliability conditions are presented. The simulations are carried out on the 30 node network in which each fiber link is composed of 4 bi-directional fibers and each fiber has 8 wavelength channels. The results show that MRPR has better than AUR regarding the reconfiguration probability performance while they both achieve close blocking probability performance under changing load and reliability ratio. Like in WI networks, the gain in reconfiguration probability performance much pronounced under low loads, and decreases as the link utilizations increase. Since, in repacking probability computations, the link capacities (at a wavelength) are taken as 4 (since 4-fiber links are used) which is very small compared to 8 in the WI networks considered in previous section, the maximum gain (at low loads) in reconfiguration probability performance is reduced to 16% (which is 45% in WI networks). That is, since repacking probabilities much more effective in route selections, reconfiguration probabilities get higher.

In Figure 42 and Figure 43 behavior of AUR and MRPR algorithms if number of fibers is set to 8 is presented. The results indicate that reconfiguration probability performance of MRPR is much better (32% at low loads) compared to the reconfiguration probability performance in the network with 4 fibers per link and reconfiguration probabilities get closer to the results obtained for WI network presented in previous section for the same blocking probabilities. This result also agrees with the explanation that we made in previous paragraph.

In Figure 44 and Figure 45 maximum blocking probability and maximum reconfiguration probability experienced by the routers in 30 router mesh network with 4 fibers on each link is presented. As we have stated in previous section, maximum blocking and maximum reconfiguration probability performance can be taken as a measure of fairness of RWA algorithms. The results show that, maximum blocking probability and maximum reconfiguration probability performance have similar characteristics with the overall blocking probability and overall reconfiguration probability performance under changing load and reliability conditions.

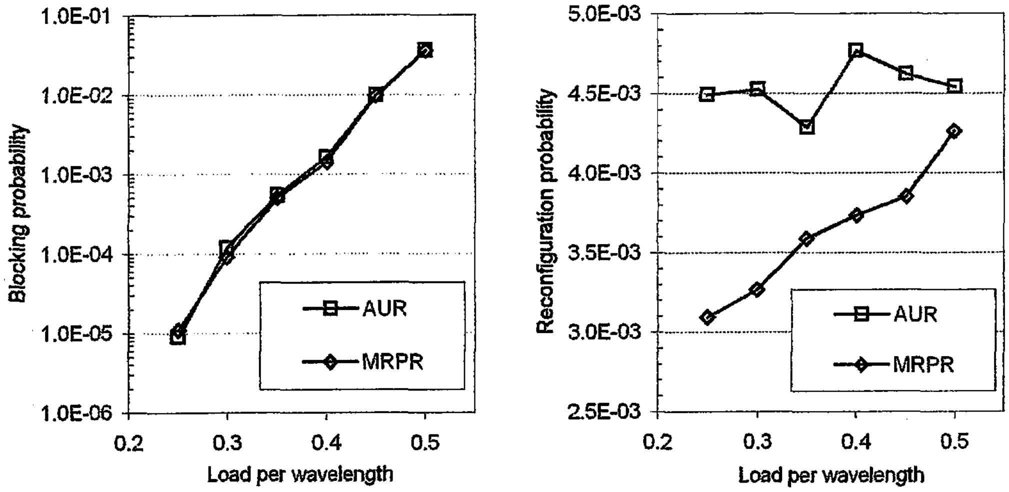


Figure 42 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh WS network when reliability ratio=0.05 and fibers per link=8

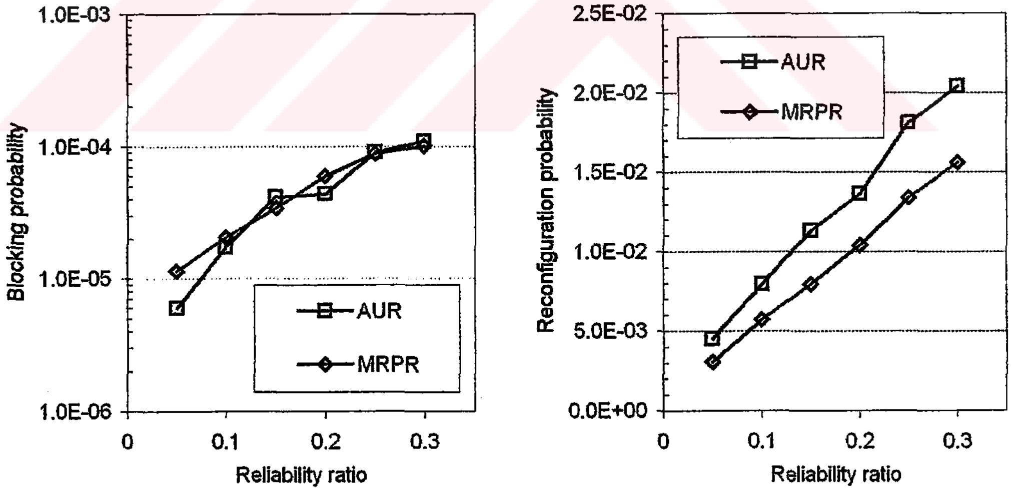


Figure 43 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh WS network when load per wavelength=0.25 and fibers per link=8

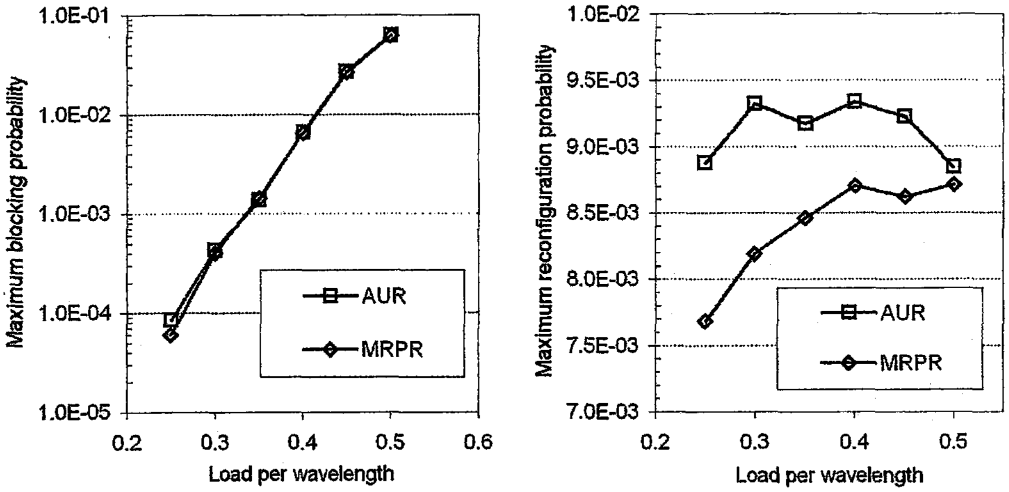


Figure 44 Maximum blocking probability and maximum reconfiguration probability vs. load per wavelength on 30 router mesh WS network when reliability ratio=0.05 and fibers per link=4

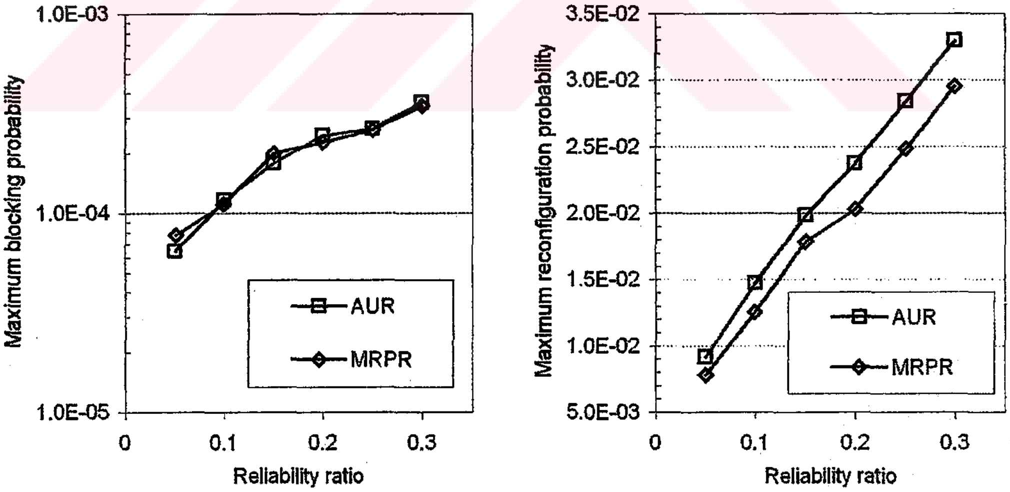


Figure 45 Maximum blocking probability and maximum reconfiguration probability vs. reliability ratio on 30 router mesh WS network when load per wavelength=0.25 and fibers per link=4

4.3.3. Performance in SPN networks

In this section we evaluate the blocking probability and reconfiguration probability performance of MRPR algorithm in SPN networks and compare it with the performance of AUR algorithm. We conducted the simulations on 30 router mesh network in which links are composed of bi-directional fibers each having 8 wavelength channels, bi-directional lightpaths established between the routers and routers have limited number of wavelength converters.

In MRPR, an auxiliary graph is used for RWA and edge costs in the graph are set according to equations (35)-(38), and (11). The AUR algorithm in SPN networks routes lightpaths on least congested (according to link and converter usage level) minimum hop route and assigns the wavelengths accordingly. In order to find the least congested minimum hop route, network is represented by a graph like in MRPR and cost of edges in this graph are set according to (cf. [32]):

$$C = \begin{cases} \infty, & \text{edge can not be used,} \\ 1 + \dfrac{1}{N^{c-n_0}}, & \text{for the edges } (o_{nw}, i_{mw}), \\ 3 + \dfrac{1}{N^{x-x_0}}, & \text{for the edges } (i_{nw}, o_{nv}),\ w \neq v, \\ 0, & \text{for the edges } (i_{nw}, o_{nw}). \end{cases} \tag{41}$$

where,

- N is the number of routers in the network (which is equal to *the number of hops in longest possible cycle free route in an N router network + 1*),
- c capacity of link (n,m),
- n_0 is the number of lightpaths currently on link (n,m),
- x is the number of wavelength converter pairs in router n,
- x_0 is the number of lightpaths using a converter on router n, and,
- *'edge can not be used'* means that the link (m,n) or router n has already failed or link (m,n) has no free wavelength channel to allocate.

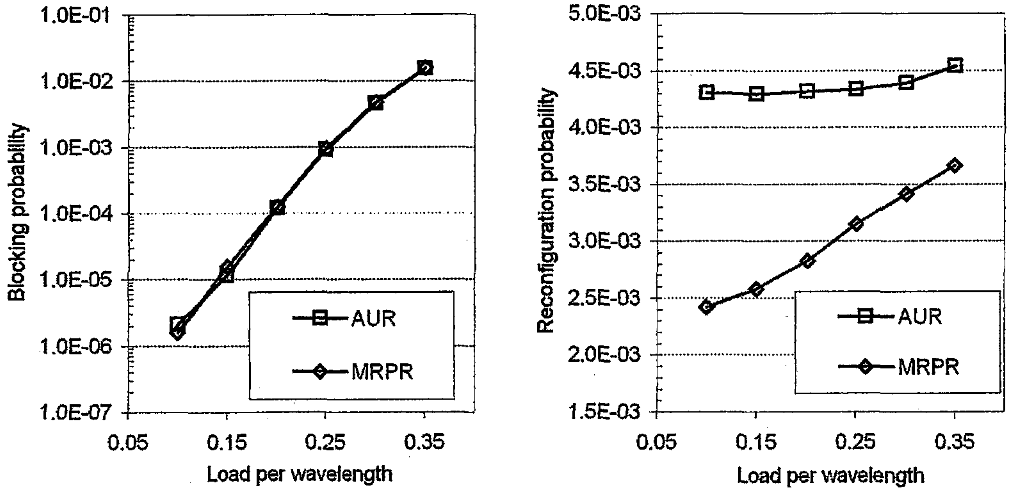


Figure 46 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh SPN network when reliability ratio=0.05 and converter pairs per router=4

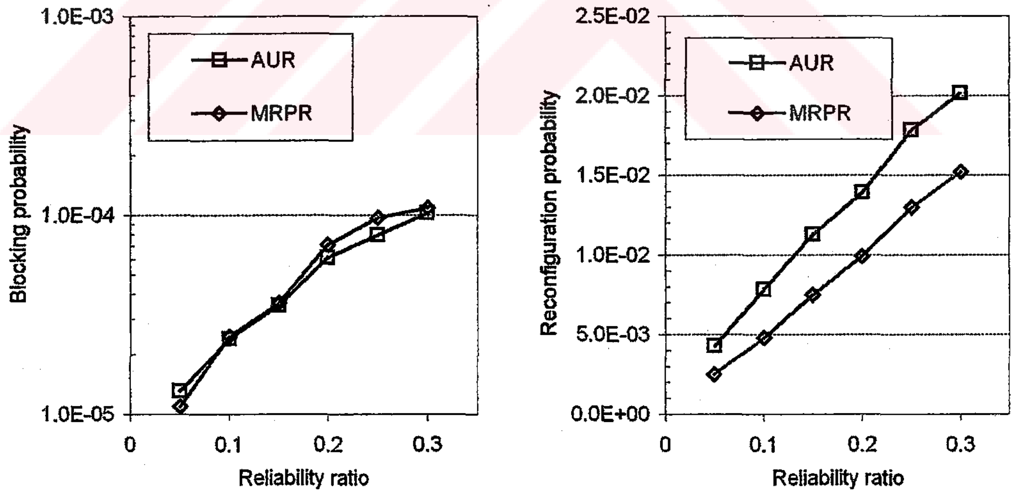


Figure 47 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh SPN network when load per wavelength=0.15 and converter pairs per router=4

In Figure 46 and Figure 47 blocking probability and reconfiguration probability performance of AUR and MRPR algorithms are presented. In the simulations, each router in the network has 4 pair (since bi-directional lightpaths are established, lightpaths use wavelength converters in pairs) of converters. Except limited wavelength conversion in the routers, WI networks used in Section 4.3.1 are very similar to the network used in this section. Therefore, we may expect that both networks behave similarly in reconfiguration probability performances. This argument can be confirmed by comparing the results presented in Figure 46 and Figure 47 with the results presented in Figure 31 and Figure 32. Note that, blocking probability performance of both AUR and MRPR are very close to each other. This also shows that MRPR effectively uses wavelength converters as good as AUR to minimize blocking probability.

In Figure 48 and Figure 49 blocking probability and reconfiguration probability performance of MRPR and AUR algorithms on 30 router mesh network with 8 pair of wavelength converters per router is given. Reconfiguration probability performances are very close to the results obtained for 4-pair of wavelength converters per router case as expected. On the other hand, our comment in the previous paragraph about the efficient converter usage is verified again. Therefore, it can be said that, in SPN networks, MRPR effectively uses converters to minimize both reconfiguration and blocking probability performances.

In Figure 50 and Figure 51 maximum blocking probability and maximum reconfiguration probability performances for AUR and MRPR under varying load and reliability conditions are plotted. Like in WI networks, the maximum gain achieved (at low loads) in maximum reconfiguration probability performance (about 30%) is lower than the gain achieved in overall reconfiguration probability performance (about 45%). The reason for this phenomenon is probably the same with the argument made in Section 4.3.1.

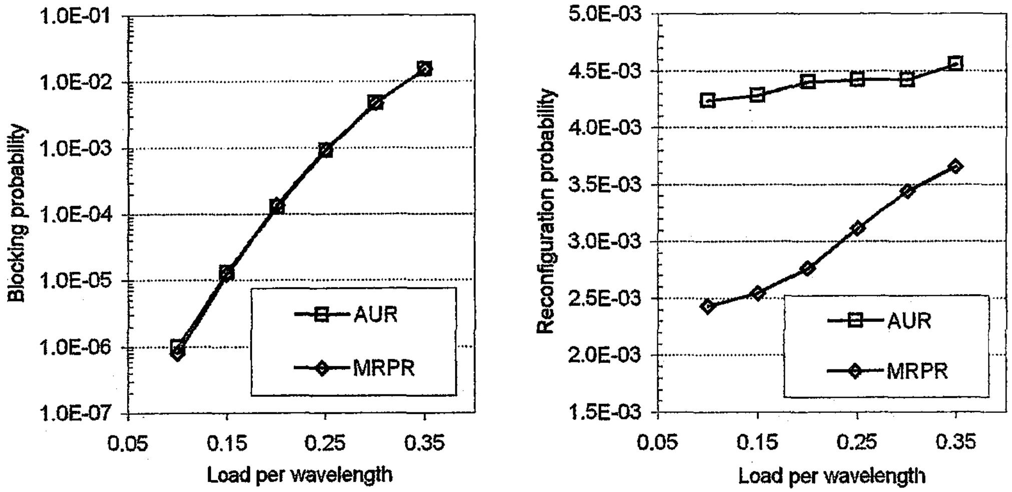


Figure 48 Blocking probability and reconfiguration probability vs. load per wavelength on 30 router mesh SPN network when reliability ratio=0.05 and converter pairs per router=8

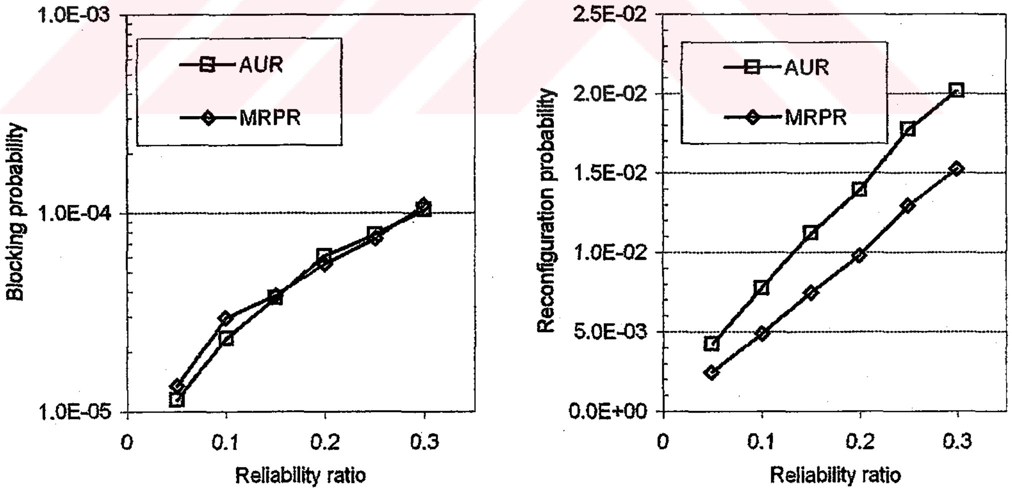


Figure 49 Blocking probability and reconfiguration probability vs. reliability ratio on 30 router mesh SPN network when load per wavelength=0.15 and converter pairs per router=8

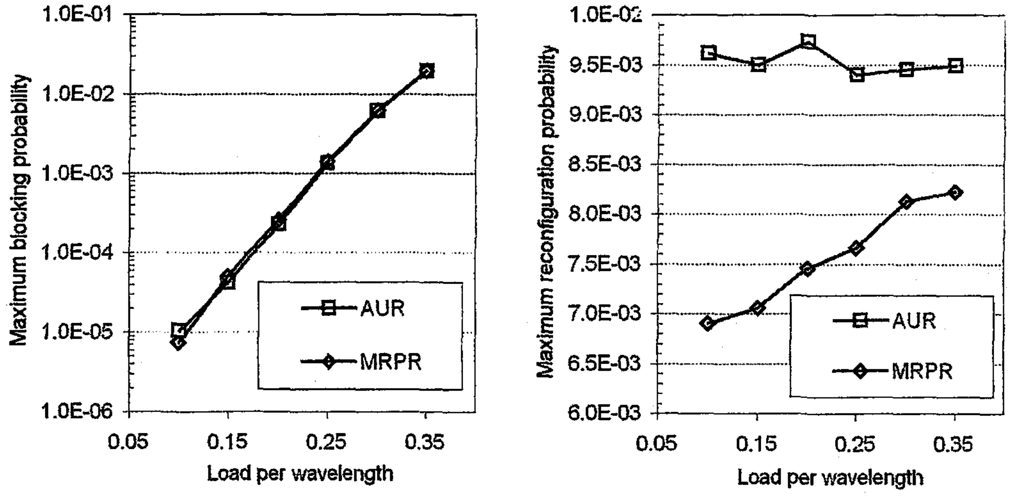


Figure 50 Maximum blocking probability and maximum reconfiguration probability vs. load per wavelength on 30 router mesh SPN network when reliability ratio=0.05 and converter pairs per router=4

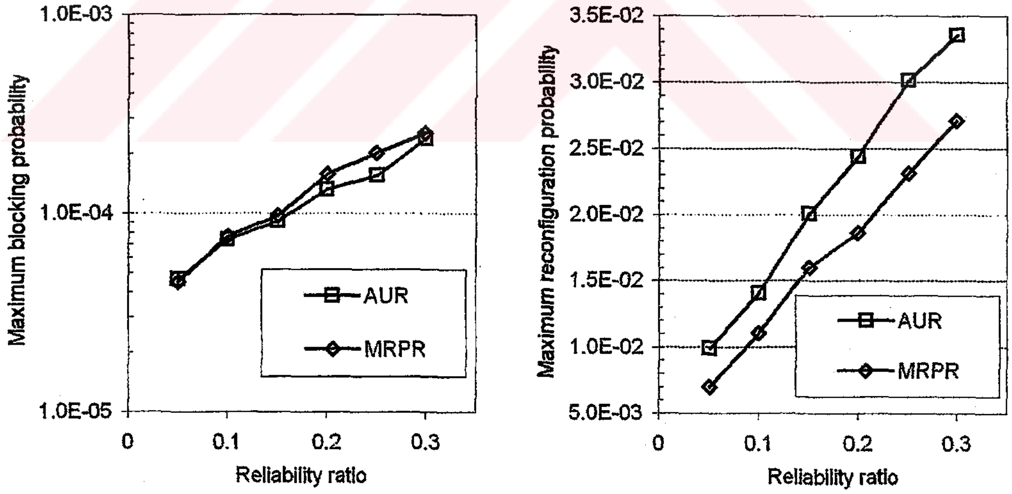


Figure 51 Maximum blocking probability and maximum reconfiguration probability vs. reliability ratio on 30 router mesh SPN network when load per wavelength=0.15 and converter pairs per router=4

CHAPTER 5

CONCLUSION

In this dissertation routing and wavelength assignment (RWA) techniques in all optical wavelength routing networks are studied and an algorithm for statistically predictive optimal RWA is proposed. The concept of statistical prediction is a novel approach to RWA in all-optical networks. The idea behind statistically predictive optimal RWA is to predict the future behavior of the network from its past operation by using the gathered operational statistics. Hence optimality of route and wavelength assignments for the lightpaths is preserved throughout the network operation and RWA algorithm is more robust against failures and adapts to changes in traffic demand.

In Chapter 3, the statistically predictive dynamic RWA algorithm called minimum reconfiguration probability routing (MRPR) has been introduced and its performance has been evaluated in Chapter 4. An originally developed all-optical network simulator has been used for performance evaluation.

The objective of MRPR is the joint minimization of the probability of lightpath reconfiguration due to failures in the network (such as a fiber cut or a wavelength router failure) and probability of blocking. Therefore, probability of service disruption and effect of failures such as number of lightpaths broken due to a failure is minimized without deteriorating overall blocking probability. In other words, survivability is improved without worsening other performance criteria. The performance evaluation by simulations has revealed that, especially under low loads, reconfiguration probability can be reduced considerably without causing significant changes in blocking probability as compared to the adaptive RWA algorithms that do not take failures into account. For example, on a 4x4 mesh-torus network with 16 wavelengths per fiber, up to 50% improvement can be achieved in reconfiguration probability as compared to adaptive unconstrained routing algorithm. At high loads the gain in reconfiguration probability drops as the algorithm tries to minimize blocking probability.

In MRPR, two causes of reconfigurations are considered: failure and repacking. The probability of reconfiguration due to failure is used to minimize probability of disruption caused by a failure in the future and the probability of repacking is used to minimize the probability of having a blocked call in the future. The probability of reconfiguration due to failure on a resource (link or router) is derived in terms of moments of failure interarrival times on that resource and lightpath holding times obtained from the operational statistics. The derived formula gives an upper bound on the probability of failure on a resource during the lifetime of a lightpath, is used as the worst-case probability of reconfiguration due to failure on that resource. Since the worst-case failure probability is much larger than the exact failure probability MRPR tends to choose shorter routes. This works as a secondary mechanism in addition to repacking to improve blocking probability. However, it might be possible to further minimize reconfiguration probability by using a prediction expression that closely estimates the failure probabilities. For example, as a second method, the failure interarrival times and holding times can be modeled by well-known distribution functions and prediction expressions can be directly derived from these functions. As a future work, alternative derivations can be found for probability of reconfiguration due to failure and advantages and disadvantages of each method can be investigated.

In MRPR, although no lightpaths are re-routed to make room for a blocked request, repacking is introduced to foresee and avoid potential blockings in the network. It is shown by previous studies (such as [50], [76]) on circuit switched and all-optical networks that by re-routing or changing wavelength of some existing connections to alternative routes or wavelengths to free up some space for an already blocked request, it is possible to minimize overall blocking probability. Therefore, in MRPR, by minimizing the probability of repacking (or re-routing due to blocking) the potential blockings during the lifetime of the lightpath is minimized thereby minimizing the overall blocking probability. To derive probability of reconfiguration due to repacking on a resource (link or converter block on a router) a Markov process is constructed and probability of having a blocked call during the lifetime of a lightpath is derived in terms of present state information and lightpath arrival and holding time statistics collected from the network operation. Similar approaches are used previously in routing in circuit switched networks to minimize blocking probability by estimating the transient blocking probabilities on each link [77], quantifying the expected number of additional blocked calls by routing a connection on each link [75], etc. to select the optimum route. However, the approach in MRPR is slightly different from these. In MRPR, repacking is introduced to predict the probability of reconfiguration due to repacking which can be used in conjunction with probability of reconfiguration due to failures to jointly minimize reconfiguration due to failure and blocking probability.

To cover the wide range of possibilities, according to wavelength converter usage level in wavelength routers three types of wavelength routing networks such as wavelength interchanging (WI), wavelength selective (WS), and share per node wavelength interchanging (SPN) networks are considered. Although probability of reconfiguration due to failure on a link or router is the same for all network types, different parameters are used to evaluate probability of reconfiguration due to repacking to reflect the characteristics of each network type. For example, in WI networks, link congestion are taken into account whereas in WS networks, wavelength congestion on the links are taken into account. In SPN networks, in addition to link congestion, wavelength converter congestion is used to optimize for wavelength converter usage. Therefore, a meaningful converter cost assignment scheme has been proposed for RWA in networks where limited number of converters placed on each router.

Since statistics are used together with present state information to derive probability of reconfiguration due to repacking on each resource, MRPR can adapt to changing traffic demands easily. Usually data traffic exhibits non-Poisson characteristics and in many studies time series models are used to capture statistical characteristics of actual traffic [78], [79], [80]. As an improvement to MRPR, time-series analysis can be employed to forecast the lightpath arrival rates to each resource in the network at certain time intervals to follow time-of-day/day-of-week seasonal variations in traffic demands. The performance of the algorithm should also be investigated under such non-uniform and non-stationary traffic demands.

In derivation of probability of reconfiguration due to repacking several (independence and cost separability) assumptions have been made. As a future work, such assumptions may be verified via simulations and if necessary some corrections can be made in the derived formulas accordingly. In addition, in derivations, arrival rate of lightpaths to a link (or wavelength converter bank in a router) are considered to be independent of the state of the link. However, due to feedback effect, as the initial number of lightpaths on the link gets larger, link is used with a small probability to accommodate the request. That is, the arrival rate of lightpaths to the links is state dependent. Therefore, instead of using constant lightpath arrival rate to the links, state dependent arrival rates can be used (in corresponding differential equations in Chapter 3) to enhance the approximation. On the other hand, the chance of repacking for an existing lightpath in the case of a blocking is assumed to be equal for all lightpaths on the link. However, longer lightpaths are much likely to be selected for re-routing compared to shorter ones. Therefore, hop count can also be included in probability of reconfiguration due to repacking.

In this dissertation, both reconfiguration due to failure and repacking probabilities are used in routing decisions with equal weights. However, in real life, certain applications are much more sensitive to disruptions and others may not impose similar constraints. Therefore to improve the efficiency, several classes of services can be introduced. For example, in routing decisions, only failure probabilities may be used for some failure sensitive critical applications and only repacking probabilities may be used for applications that may tolerate long disruptions.

The implementation details are kept outside the scope of this study. Hence, for simplicity, a centralized routing and wavelength assignment method is considered and online restoration is assumed. However, there are several advantages of distributed RWA such as enhanced scalability, distribution of communication and processing overhead over network, and coping with failures easily. Since, cost of using each network element such as link, router, and converter is computed using locally collected information and sum of the costs of network elements along a path gives the total cost of the path, distributed routing schemes based on distributed shortest path algorithms can easily be applied to develop a distributed MRPR. On the other hand, offline restoration schemes offer faster recovery from the failures. Hence, distributed implementation of the MRPR approach together with offline restoration can be considered as a future work.

While implementation details have not been considered, it should be noted that the fundamental proposal made in this dissertation is to incorporate network performance statistics in the calculation of routing costs. For the proposed method to be of any practical value, obviously, the process of taking statistics should not imply prohibitive costs. This is the case, as counting resource failures and blocking events has merely constant complexity.

In MRPR, all possible routes and wavelengths between the source and destination routers are considered in routing decisions for a lightpath request. However, the cost functions derived for MRPR can easily be used in alternate routing where a predefined set of routes is searched to accommodate the request. Therefore, much more simplified network operation can be achieved and processing requirements can be reduced considerably. As a future work, alternate routing version of MRPR can be developed and performance of the resulting algorithm can be compared with the performance of other adaptive alternate routing algorithms such as least loaded routing, max sum routing etc.

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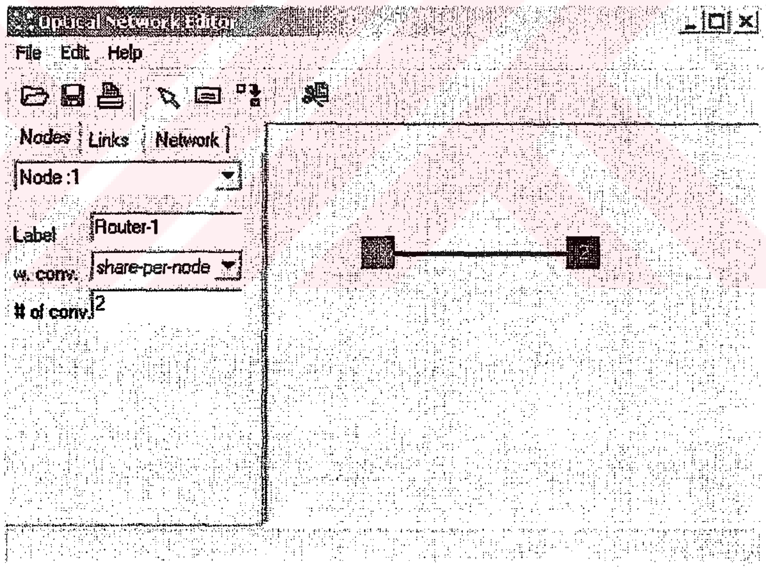
APPENDIX A

SCREEN SNAPSHOTS OF SIMULATOR

In the following, screen snapshots of the simulator and network editor tools that are used in this study are presented. Both tools are available online via http://www.geocities.com/altankocyigit/sim.html.



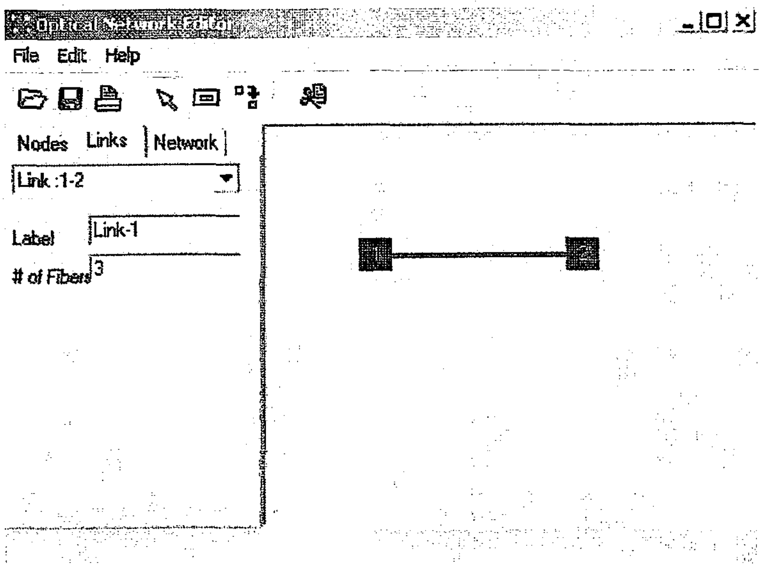
Node :1

Label Router-1

w. conv. share-per-node

# of conv. 2

Figure 52 Network editor - Node properties

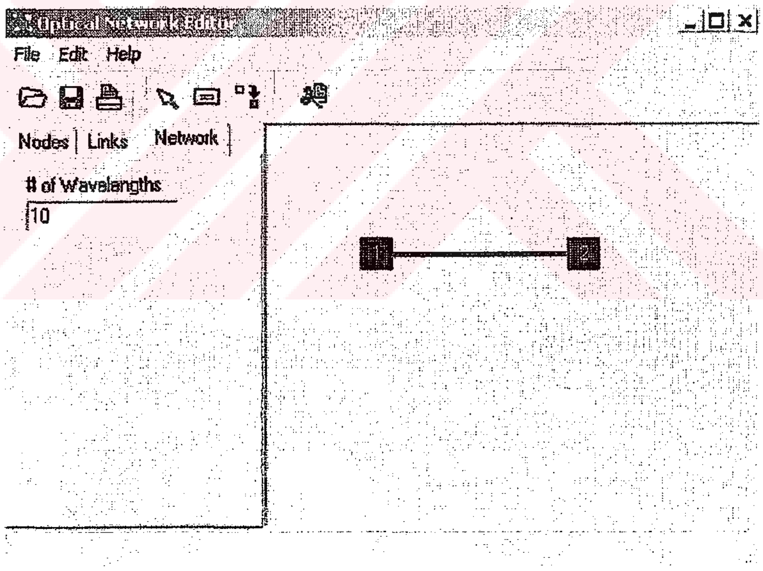


Link :1-2

Label Link-1

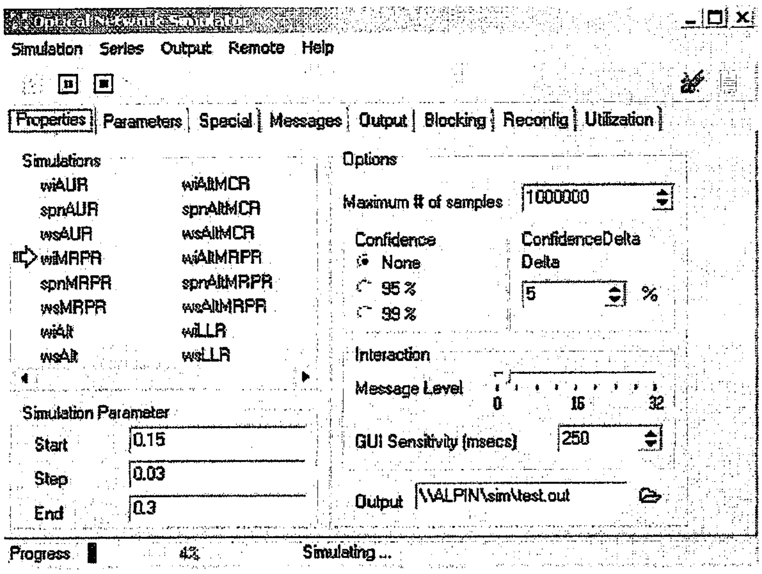
# of Fibers 3

Figure 53 Network editor - Link properties



# of Wavelengths 10

Figure 54 Network editor - Network properties



Simulations

wiAUR	wiAltMCR
spnAUR	spnAltMCR
wsAUR	wsAltMCR
wiMRPR	wiAltMRPR
spnMRPR	spnAltMRPR
wsMRPR	wsAltMRPR
wiAlt	wiLLR
wsAlt	wsLLR

Simulation Parameter

Start 0.15

Step 0.03

End 0.3

Options

Maximum # of samples 1000000

Confidence ● None ○ 95 % ○ 99 %

ConfidenceDelta Delta 5 %

Interaction

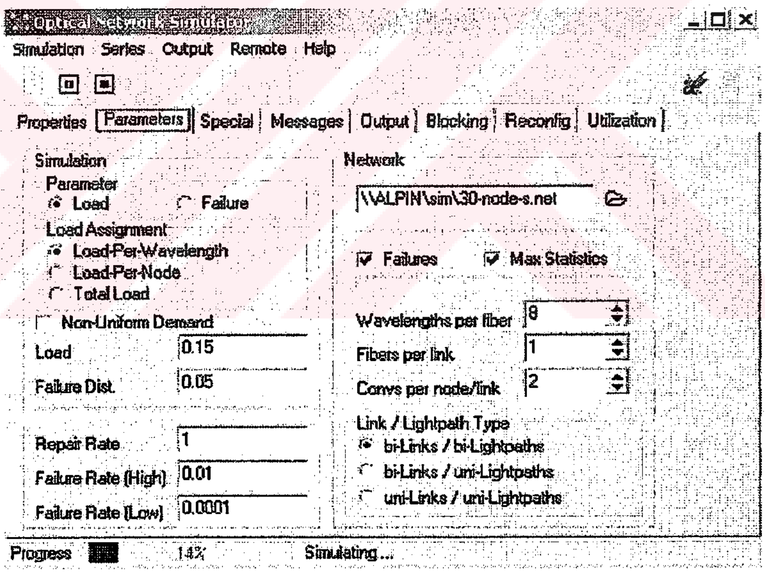
Message Level 0 16 32

GUI Sensitivity (msecs) 250

Output \\ALPIN\sim\test.out

Progress 4% Simulating ...

Figure 55 Network simulator - Simulation properties



Simulation

Parameter ● Load ○ Failure

Load Assignment
● Load-Per-Wavelength
○ Load-Per-Node
○ Total Load

☐ Non-Uniform Demand

Load 0.15

Failure Dist. 0.05

Repair Rate 1

Failure Rate (High) 0.01

Failure Rate (Low) 0.0001

Network

\\ALPIN\sim\30-node-s.net

☑ Failures ☑ Max Statistics

Wavelengths per fiber 8

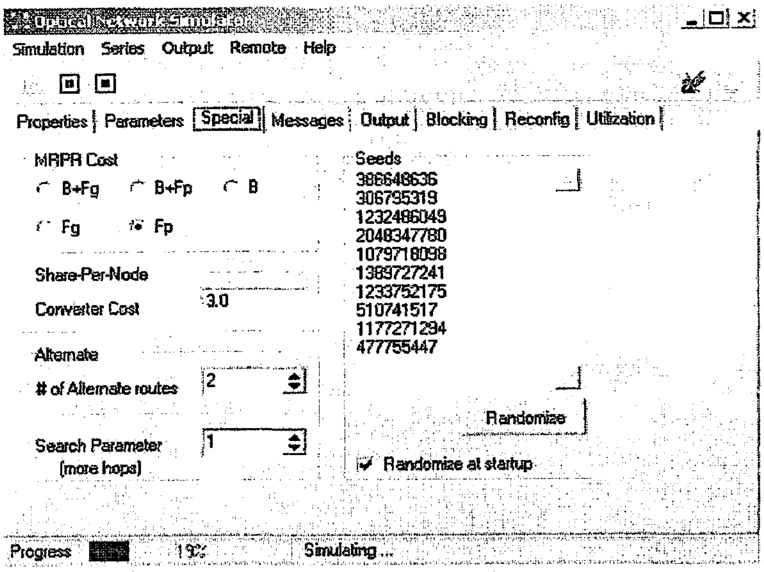
Fibers per link 1

Convs per node/link 2

Link / Lightpath Type
● bi-Links / bi-Lightpaths
○ bi-Links / uni-Lightpaths
○ uni-Links / uni-Lightpaths

Progress 14% Simulating ...

Figure 56 Network simulator - Simulation parameters



MRPR Cost
○ B+Fg ○ B+Fp ○ B
○ Fg ● Fp

Share-Per-Node

Converter Cost 3.0

Alternate

# of Alternate routes 2

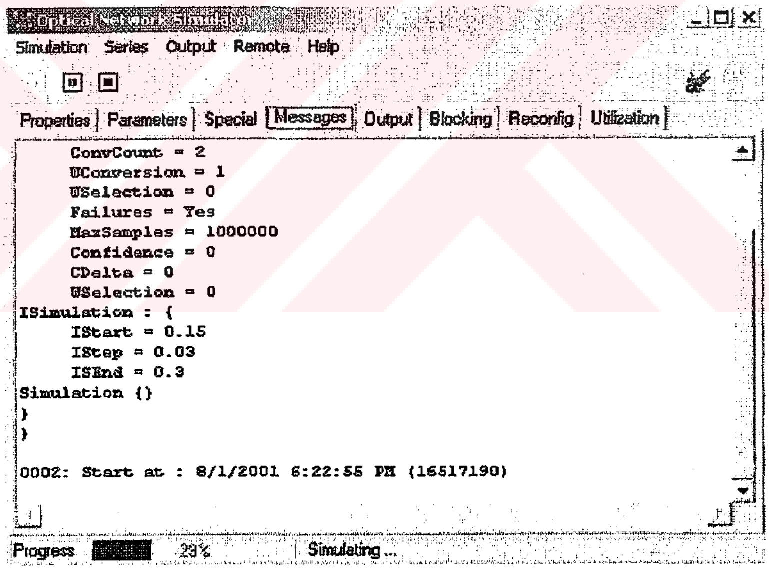
Search Parameter (more hops) 1

Seeds
386648636
306795319
1232486049
2048347780
1079718098
1389727241
1233752175
510741517
1177271294
477755447

☑ Randomize at startup

Progress 19% Simulating ...

Figure 57 Network simulator - Simulation specific parameters

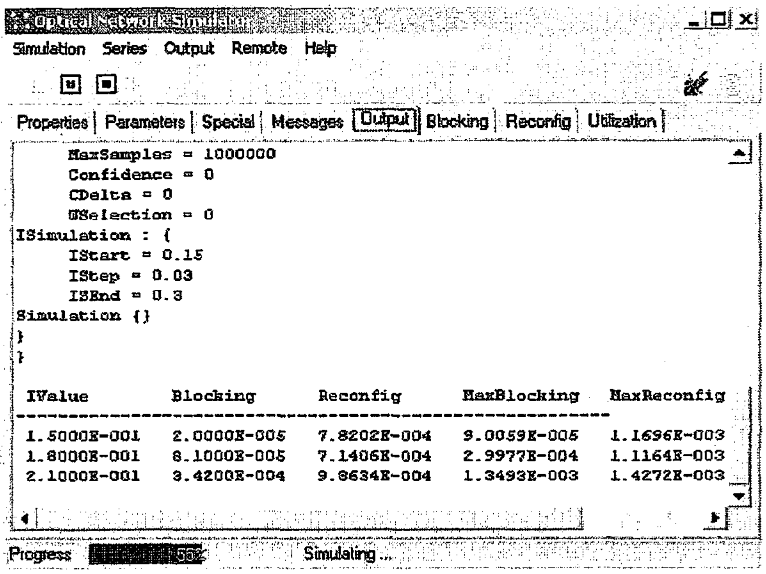


```
     ConvCount = 2
     WConversion = 1
     WSelection = 0
     Failures = Yes
     MaxSamples = 1000000
     Confidence = 0
     CDelta = 0
     WSelection = 0
ISimulation : {
     IStart = 0.15
     IStep = 0.03
     ISEnd = 0.3
Simulation {}
}
}

0002: Start at : 8/1/2001 6:22:55 PM (16517190)
```

Progress 23% Simulating ...

Figure 58 Network simulator - Simulation messages



```
     MaxSamples = 1000000
     Confidence = 0
     CDelta = 0
     WSelection = 0
ISimulation : {
     IStart = 0.15
     IStep = 0.03
     ISEnd = 0.3
Simulation {}
}
}

 IValue        Blocking      Reconfig      MaxBlocking   MaxReconfig
------------------------------------------------------------
 1.5000E-001   2.0000E-005   7.8202E-004   9.0059E-005   1.1696E-003
 1.8000E-001   8.1000E-005   7.1406E-004   2.9977E-004   1.1164E-003
 2.1000E-001   3.4200E-004   9.8634E-004   1.3493E-003   1.4272E-003
```

Figure 59 Network simulator - Simulation output

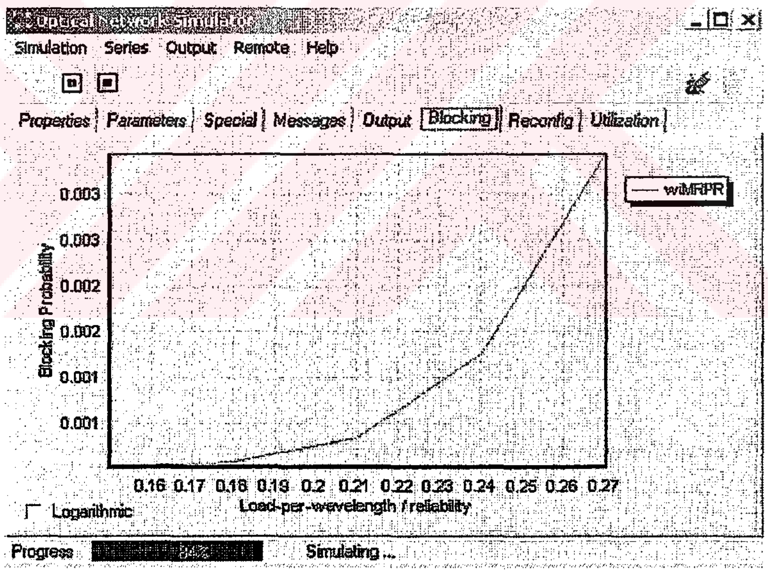


Figure 60 Network simulator - Output graphs

APPENDIX B

SIMULATION DATA

In this study, we have conducted 21 sets of simulations for the purposes of the verification of simulation tool and the performance evaluation of the MRPR algorithm. The simulations are carried out on a Microsoft Windows 2000 Workstation running on a PC with Intel Celeron 466MHz processor and 128 MB RAM. In the following, data related to these simulations are presented.

SIMULATION SET #1:

Referred in	Figure 21
Network	2 Router – 1 Link (M/M/w/w Queue)
Network type	WI
Fibers per link	1
Wavelengths per fiber	10
Link/Lightpath type	Bi-directional links / bi-directional lightpaths
Simulation parameter	Total Load
	Start = 3 Step = 1 Stop = 9
Failures	No
Confidence	g=99%, Δ=0.05[2]
Maximum # of samples	10,000,000
Simulation	AUR
Elapsed time[3]	138 secs

---

[2] Δ and g stand for the neighborhood and probability, respectively. That is, g=99%, Δ=0.05 means, ±5% neighborhood with 0.99 probability.

[3] Since simulations are carried out in a multi-tasking environment, *elapsed times* are not absolute values.

SIMULATION SET #2:

Referred in	Figure 21
Network	2 Router – 1 Link (M/M/w/w Queue)
Network type	WI
Fibers per link	1
Wavelengths per fiber	5
Link/Lightpath type	Bi-directional links / bi-directional lightpaths
Simulation parameter	Total Load
	Start = 0.05 Step = 0,05 Stop = 0.45
Failures	No
Confidence	g=99%, Δ=0.05
Maximum # of samples	10,000,000
Simulation	AUR
Elapsed time	153 secs

SIMULATION SET #3:

Referred in	Figure 23
Network	21 router – 26 link ARPA2 (Figure 22)
Network type	SPN
Fibers per link	1
Wavelengths per fiber	16
Link/Lightpath type	Bi-directional links / uni-directional lightpaths
Simulation parameter	Load per router
	Start = 4.5 Step = 0.5 Stop = 8
Failures	No
Confidence	g=99%, Δ=0.05
Maximum # of samples	10,000,000
Simulation	AUR

Simulations	Converters per router	Elapsed time (secs)
	0	227
	4	595
	8	618
	64	635

SIMULATION SET #4:

Referred in	Figure 25
Network	Randomly generated network (Figure 24)
Network type	WS
Fibers per link	1
Wavelengths per fiber	8
Link/Lightpath type	Bi-directional links / uni-directional lightpaths
Simulation parameter	Load per node pair
	Start = 0.50 Step = 0.05 Stop = 1
Failures	No
Confidence	g=99%, Δ=0.05
Maximum # of samples	1,000,000
Simulation	AUR
Elapsed time	101 secs

SIMULATION SET #5:

Referred in	Figure 25
Network	Randomly generated network (Figure 24)
Network type	WS
Fibers per link	1
Wavelengths per fiber	4
Link/Lightpath type	Bi-directional links / uni-directional lightpaths
Simulation parameter	Load per node pair
	Start = 0.20 Step = 0.1 Stop = 1
Failures	No
Confidence	g=99%, Δ=0.05
Maximum # of samples	1,000,000
Simulation	AUR
Elapsed time	450 secs

SIMULATION SET #6:

Referred in	Figure 27	
Network	4x4 Mesh Torus (Figure 26.a)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	16	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Load per wavelength Start = 0.60 Step = 0.05 Stop = 0.85	
Reliability ratio	0.0625	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)[4]
	AUR	180
	MRPR	260
	MRPR-F	170
	MRPR-R	260

SIMULATION SET #7:

Referred in	Figure 28	
Network	4x4 Mesh Torus (Figure 26.a)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	16	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Reliability ratio Start=0.0625 Step=0.0625 Stop = 0.375	
Load per wavelength	0.65	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	190
	MRPR	270
	MRPR-F	180
	MRPR-R	270

---

[4] Elapsed time for each of 10 simulations.

SIMULATION SET #8:

Referred in	Figure 29	
Network	8 Router Ring (Figure 26.b)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	16	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Load per wavelength	
	Start = 0.10 Step = 0.05 Stop = 0.35	
Reliability ratio	0.125	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	90
	MRPR	110
	MRPR-F	90
	MRPR-R	110

SIMULATION SET #9:

Referred in	Figure 30	
Network	8 Router Ring (Figure 26.b)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	16	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Reliability ratio	
	Start = 0.125 Step = 0.125 Stop = 0.750	
Load per wavelength	0.10	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	90
	MRPR	110
	MRPR-F	90
	MRPR-R	110

SIMULATION SET #10:

Referred in	Figure 31, Figure 34		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WI		
Fibers per link	1		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Load per wavelength		
	Start = 0.10	Step = 0.05	Stop = 0.35
Reliability ratio	0.05		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001		Un-Reliable = 0.01
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation		Elapsed time (secs)
	AUR		220
	MRPR		350
	MRPR-F		240
	MRPR-R		380

SIMULATION SET #11:

Referred in	Figure 32, Figure 35		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WI		
Fibers per link	1		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Reliability ratio		
	Start = 0.05	Step = 0.05	Stop = 0.30
Load per wavelength	0.15		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001		Un-Reliable = 0.01
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation		Elapsed time (secs)
	AUR		250
	MRPR		390
	MRPR-F		260
	MRPR-R		410

SIMULATION SET #12:

Referred in	Figure 36		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WI		
Fibers per link	1		
Wavelengths per fiber	16		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Load per wavelength		
	Start = 0.20	Step = 0.05	Stop = 0.45
Reliability ratio	0.05		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	250	
	MRPR	380	
	MRPR-F	260	
	MRPR-R	390	

SIMULATION SET #13:

Referred in	Figure 37		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WI		
Fibers per link	1		
Wavelengths per fiber	16		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Reliability ratio		
	Start = 0.05	Step = 0.05	Stop = 0.30
Load per wavelength	0.20		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	250	
	MRPR	390	
	MRPR-F	260	
	MRPR-R	410	

SIMULATION SET #14:

Referred in	Figure 38	
Network	30 Router – 47 Link Mesh (Figure 33)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	8	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Load per wavelength	
	Start = 0.10 Step = 0.10 Stop = 0.60	
Reliability ratio	0.05	
Failures	Yes	
Failure arrival rate	Reliable = 0.00001	Un-Reliable = 0.001
Repair rate	1	
Samples (for each load value)	10,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	2200
	MRPR	3450
	MRPR-F	2100
	MRPR-R	3700

SIMULATION SET #15:

Referred in	Figure 39	
Network	30 Router – 47 Link Mesh (Figure 33)	
Network type	WI	
Fibers per link	1	
Wavelengths per fiber	8	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Reliability ratio	
	Start = 0.05 Step = 0.05 Stop = 0.30	
Load per wavelength	0.20	
Failures	Yes	
Failure arrival rate	Reliable = 0.00001	Un-Reliable = 0.001
Repair rate	1	
Samples (for each load value)	10,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	2500
	MRPR	3900
	MRPR-F	2600
	MRPR-R	4100

SIMULATION SET #16:

Referred in	Figure 40, Figure 44		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WS		
Fibers per link	4		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Load per wavelength		
	Start = 0.25	Step = 0.05	Stop = 0.50
Reliability ratio	0.05		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1580	
	MRPR	2700	

SIMULATION SET #17:

Referred in	Figure 41, Figure 45		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WS		
Fibers per link	4		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Reliability ratio		
	Start = 0.05	Step = 0.05	Stop = 0.30
Load per wavelength	0.25		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1830	
	MRPR	2790	

SIMULATION SET #18:

Referred in	Figure 42		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WS		
Fibers per link	8		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Load per wavelength		
	Start = 0.25	Step = 0.05	Stop = 0.50
Reliability ratio	0.05		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1650	
	MRPR	2790	

SIMULATION SET #19:

Referred in	Figure 43		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	WS		
Fibers per link	8		
Wavelengths per fiber	8		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Reliability ratio		
	Start = 0.05	Step = 0.05	Stop = 0.30
Load per wavelength	0.25		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1830	
	MRPR	2790	

SIMULATION SET #20:

Referred in	Figure 46, Figure 50	
Network	30 Router – 47 Link Mesh (Figure 33)	
Network type	SPN	
Fibers per link	1	
Wavelengths per fiber	8	
Converters per router	4 (pairs[5])	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Load per wavelength Start = 0.10 Step = 0.05 Stop = 0.35	
Reliability ratio	0.05	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	1050
	MRPR	1380

SIMULATION SET #21:

Referred in	Figure 47, Figure 51	
Network	30 Router – 47 Link Mesh (Figure 33)	
Network type	SPN	
Fibers per link	1	
Wavelengths per fiber	8	
Converters per router	4 (pairs)	
Link/Lightpath type	Bi-directional links / bi-directional lightpaths	
Simulation parameter	Reliability ratio Start = 0.05 Step = 0.05 Stop = 0.30	
Load per wavelength	0.15	
Failures	Yes	
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01
Repair rate	1	
Samples (for each load value)	1,000,000	
Number of simulations	10	
Simulations	Simulation	Elapsed time (secs)
	AUR	1060
	MRPR	1300

---

[5] Bi-directional lightpaths use wavelength converters in pairs.

SIMULATION SET #22:

Referred in	Figure 48		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	SPN		
Fibers per link	1		
Wavelengths per fiber	8		
Converters per router	8 (pairs)		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Load per wavelength		
	Start = 0.10	Step = 0.05	Stop = 0.35
Reliability ratio	0.05		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1150	
	MRPR	1340	

SIMULATION SET #23:

Referred in	Figure 49		
Network	30 Router – 47 Link Mesh (Figure 33)		
Network type	SPN		
Fibers per link	1		
Wavelengths per fiber	8		
Converters per router	8 (pairs)		
Link/Lightpath type	Bi-directional links / bi-directional lightpaths		
Simulation parameter	Reliability ratio		
	Start = 0.05	Step = 0.05	Stop = 0.30
Load per wavelength	0.15		
Failures	Yes		
Failure arrival rate	Reliable = 0.0001	Un-Reliable = 0.01	
Repair rate	1		
Samples (for each load value)	1,000,000		
Number of simulations	10		
Simulations	Simulation	Elapsed time (secs)	
	AUR	1020	
	MRPR	1270	

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Publications:

Koçyiğit A., Bilgen S., "Statistically Predictive Optimal Wavelength Routing," Proceedings of The Fifteenth International Symposium on Computer and Information Sciences (ISCIS XV), pp. 358-366, October 2000, İstanbul, Turkey.

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