BLOCKING PERFORMANCE OF CLASS OF SERVICE DIFFERENTIATION IN SURVIVABLE ALL-OPTICAL NETWORKS

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ABSTRACT

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This thesis evaluates the performance of service differentiation with different class of services namely protection, reservation and the best effort services on the NxN meshed torus and the ring topology, which are established as survivable all-optical WDM networks. Blocking probabilities are measured as performance criteria and the effects of different number of wavelengths, different type of services and different topology size with wavelength selective lightpath allocation schemes are investigated by simulations with respect to increasing load on the topologies.

Keywords: All optical networks, survivable networks, class of service differentiation, protection, restoration.

ÖZ

DEVAMLILIĞI SAĞLANAN TÜMÜYLE OPTİK AĞLARDA SERVİS TİPLERİNİN AYRIMININ TIKANMA PERFORMANSI

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Bu tezde, devamlılığı sağlanan tümüyle optik WDM ağlarda yedekleme, paylaşma ve hata anında geri yükleme servis tiplerinin ayrımının NxN torus ve halka ağ üzerindeki başarım incelenmiştir. Performans kriteri olarak tıkanma olasılığı kullanılmış ve farklı sayıdaki dalgaboylarında, farklı ağ boyutlarında ve farklı tip servislerde başarımın değişimi simulasyon yoluyla incelenmiştir.

Keywords: Tümüyle optik ağlar, devamlılığı sağlanan ağlar, servis ayrımı, yedekleme, paylaşma.

To My Lovely Wife

For her help and patience

Although she has a serious health problem

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CHAPTER 1

INTRODUCTION

Bandwidth requirements in today's networks are increasing everyday. Transport network providers use optical networks such as SONET/SDH or ATM, which use initially single fiber for each connection in their infrastructure. This is the waste of resources since fiber optic cable that is the transport medium of optical networks has a huge amount of bandwidth. Wavelength-division multiplexing (WDM) is the solution for using single fiber cable for multiple connections. Different wavelength channels can be established by WDM on a single fiber and traffic can flow on these channels simultaneously. Optical networks have adapted to use WDM in their backbone. However, on intermediate nodes, conversion of optical signals to electronic signals, which is called electro-optical conversion, is the bottleneck that faced on optical networks. The reason for this bottleneck is that electronic devices can operate at a few gigabit/s on the contrary to optical cables that can carry a few terabit/s. This conversion must be done to route the network traffic when WDM is on physical layer for optical networks and upper layers find routing paths.

1.1. All Optical Networks

Electro-optical conversion bottleneck on intermediate nodes is solved by all optical networks (AON) by introducing a new optical layer. AON is composed of equipments totally made up of glass material [1]. Therefore, data travels only as light. IBM's Rainbow-I [4] and Rainbow-II [7] are examples for AON. In AON, network traffic can flow on the path called lightpath between end-nodes without electro-optical conversion on intermediate nodes. The popular architectures of such networks are passive optical networks (PON), broadcast and select networks and wavelength routing networks. We will deal with wavelength routing networks (WRN) [2] in this thesis.

1.2. Wavelength Routing Networks

A WRN consists of wavelength routers interconnected by fibers each having multiple wavelength channels. WRN finds the route through the network and establishes the lightpath between the source and the destination end-nodes by choosing the appropriate wavelength. WRN can use different kinds of routers such as wavelength selective optical cross-connects (WSXC) and wavelength interchanging optical cross-connects (WIXC). When establishing the lightpath, the former uses the same wavelength on all links along the route, which is known as wavelength continuity constraint on wavelength assignment and the latter may use different wavelengths on different links along the route using the wavelength converters in the routers. Hence WI uses network resources more efficiently than WS since there is no wavelength continuity constraint. However WIXC costs too much due to the need for wavelength converters [4]. Combination of WSXC and WIXC networks can also be established to provide partial wavelength conversion capability in the network.

1.3. AON Survivability

Some failures may occur in an AON as in all other networks, such as link, node or device failures. These failures cause lightpaths, which are using those resources, are broken and this leads to the loss of huge amount of traffic and service interruptions. Hence survivability is inevitable to protect traffic from failures. The network that has restoration capability from failures requires redundant capacity or spare resources. In [12], restoration strategies are proposed as link-based restoration (LR), path based restoration (PR) and path based restoration with link-disjoint route (PRd). The first strategy tries to recover failures by using local rerouting; the second strategy by using from source to destination rerouting and the last strategy is the same as PR except using disjoint path. More information about restoration techniques can be found in [10].

1.4. Services from the Survivability Point of View

There are some kinds of services given on all-optical networks for survivability such as protection, reservation and best effort. Protection service backs-up the requested lightpath called the primary lightpath with the additional lightpath called backup lightpath. This provide fast recovery from failures, however, too much spare resources are needed since the backup lightpath does not allow sharing with other backup lightpaths. Reservation service reserves a path namely reservation path for the primary lightpath that enables the sharing of reserved path with the other primary lightpaths' reservation paths. Sharing of the resources provides effective use of available resources and may reduce overall blocking probability of the network. Best effort service does not establish a backup path or reserve any resource. In the case of failure, it tries to find a path that is a replacement of the broken primary lightpath. If it fails, then traffic that uses that lightpath has lost. Hence it does not guarantee a 100% restoration on the contrary to the protection and the reservation services.

1.5. Problem Statement

Service differentiation is an important issue for survivable all-optical networks. All lightpaths have to behave as they request the same service quality without service differentiation. If service differentiation is established, lightpath allocations are made according to their service requirements. For example, while the primary lightpath that requires protection service needs to allocate a backup lightpath; the other one may require a best effort service needs to allocate only primary lightpath not an extra backup lightpath if service differentiation is in place. Hence, service differentiation shall be established on optical layer in order to use resources efficiently.

Our proposed solution will try to decrease the blocking performance by differentiating the services that are requested. That is, not all lightpath request the same service from the network. This provides more lightpaths to be served and may merely reduce the blocking probability for the lightpath requests.

1.6. Thesis Organization

Chapter 2 presents literature survey and discussions on all-optical networks, wavelength division multiplexing (WDM), wavelength routing networks (WRN), routing wavelength assignments (RWA) with the perspective of survivability and survivability techniques. Survivability techniques are classified by optical channel and multiplexing section at the top, then predesigned and dynamic in the middle and dedicated and shared resources at the bottom level. Chapter 3 introduces the service differentiation approach. The performance is evaluated by simulations, and results are discussed. Performance is measured for ring and NxN meshed torus networks with changing number of wavelengths per link, network size and load. Chapter 4 concludes the study and shows possible directions for future research.

CHAPTER 2

LITERATURE SURVEY

Very rapid growth of technology on Internet and multimedia applications causes more bandwidth consumptions. Copper wires are not suitable medium to carry this amount of traffic. Fiber cables are used as a medium, which has 25 THz, 2dB/km and low bit error rate between $10^{-9} - 10^{-15}$ [1]. This makes fiber very suitable transport medium for networks, which are called optical networks.

2.1. Traditional Optical Network Architectures

Since enormous bandwidth on fiber is very attractive, lots of research is going on optical networks. Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH), Asynchronous Transferring Mode (ATM) and IP networks uses fiber to provide tens of Gb/s bandwidth. Optical networks may be constructed by many layers interacting together [13]. Here IP, ATM, SONET/SDH and optical layers take place from top down layered design. Optical networks were using one fiber cable for one connection. However this was not efficient because fiber can carry much more traffic. This problem has been solved by using different wavelengths to enable sharing of a single fiber by many connections.

2.2. Wavelength Division Multiplexing

In the layered architecture, optical layer is referred as Wavelength Division Multiplexing (WDM) layer, which is responsible for providing the lightpaths to the upper layers. WDM divides the huge bandwidth available on a fiber into many non-overlapping wavelength channels and enables data traffic to flow over these channels. When the connection is established between source and destination nodes on a channel, bit rate, framing type, signalling standards, etc can be chosen freely at least between the electronic switches. This provides a very useful transparency on communication. In addition, investments on the WDM infrastructure make possible usage of protocols and/or technologies that will be developed in the future. There are other multiplexing techniques. Optical Time-Division Multiplexing (OTDM) is a method of carrying information across a network in the form of ultra short optical pulses at very high rates [14]. In addition, Dense WDM (DWDM) technology provides to use more than 100 channels over a single fiber [15].

2.3. All Optical Networks

In optical networks, WDM layer just form physical layer and give the job of routing to the upper layers that use electro-optical conversion to route the requested traffic. Between intermediate nodes data traffic flows on lightpaths. When data reach the intermediate nodes, electro-optical conversion is necessary to process the requests to route the correct direction.

This is the main reason that we cannot use all available bandwidth in the fiber cables.

Electro-optical conversion shall be avoided, if we want to use huge bandwidth on fibers. All-optical network (AON) is the answer for this problem by allowing optical layer to establish lightpath from source to destination node between intermediate nodes. Many AON are constructed for tests such as IBM's Rainbow-I [4] and Rainbow-II [7], LAMBDANET [8] and SURVNET [9] for LAN and MONET, RACE, MWTN and ONTC for WAN. Many researches are going on for these networks to evolve the all-optical networking.

2.4. Wavelength Routing Networks

Three popular AON architectures are passive optical networks (PON), broadcast and select (BSN) and wavelength routing network (WRN). WDM link also accepted as one of the type of AON since it is the first step towards all-optical networking [2]. In PON, there is central office and customers connect to this central office. This provides centralized control and routing. BSN networks broadcast data to entire network to find the destination node. It can be used for local area networks but it is not suitable for wide area networks due to splitting loss and lack of wavelength reuse [4]. We will only deal with WRN in our work.

2.4.1. Wavelength Selective and Wavelength Interchanging WRN

WRN use wavelength routers such as wavelength selective optical cross-connects (WSXC) and wavelength interchange optical cross-connects (WIXC) in order to route requests [1]. WS network assigns the same wavelength along the lightpaths' route. This is called in the literature as wavelength continuity constraint. WS networks shall find an unused wavelength for all links along the route. However, this increases the rejecting of lightpath request due to wavelength conflicts. Instead of using WSXC, wavelength convertible, namely wavelength interchangeable optical cross-connects (WIXC), can be used. Any wavelength can be used on a link when establishing a route by changing the signals wavelength-by-wavelength converters available in the routers appropriately. This increases the effective use of resources and reduces the blocking probability [10].

2.5. Routing Wavelength Assignment

There are many algorithms proposed to find a route and assign a wavelength for a lightpath through a WRN. The RWA algorithms can be broadly divided into two categories: static and dynamic RWA. Table 1 shows the summary of the RWA classification and some example algorithms.

Table 1 Commonly Used Routing Wavelength Assignment Methods

<table>
<tr><td rowspan="4">Static</td><td colspan="3">Route formulation</td></tr>
<tr><td colspan="3">Flow formulation</td></tr>
<tr><td colspan="3">Minimization of the flow in each link</td></tr>
<tr><td colspan="3">Minimizing total facility cost</td></tr>
<tr><td rowspan="4">Dynamic</td><td rowspan="2">Fixed</td><td>Random</td><td rowspan="4">Alternate Routing</td></tr>
<tr><td>First Fit</td></tr>
<tr><td rowspan="2">Adaptive</td><td>LLR</td></tr>
<tr><td>LCP</td></tr>
</table>

2.5.1. Static RWA

In Static routing wavelength assignment, all lightpath requests in the topology are known at the beginning. In Table 1, for static RWA, four algorithms have given as examples. First is the route formulation. It calculates how many times a route is used. Then it uses these statistics when lightpaths are established. The second one is the flow formulation, which uses flows on the link generated through each source and end-node pair. In addition to flow formulation, there is also minimization of the flows in each link. It tries to minimize the flow in each link that is on the route. The last one is minimization of the total facility cost, which wavelength assignment method bases on the minimization of the resources usage.

2.5.2. Dynamic RWA

For dynamic routing wavelength assignment there are two approaches: fixed and adaptive. Fixed RWA has two commonly used types: random and first-fit. Former checks a predetermined route whether it has enough free capacity and chooses the wavelength among possible ones randomly. This provides distributing the load all over the wavelength. Latter allocates the smallest index wavelength among the possible on the predetermined route. Both random and first-fit wavelength allocation methods can use alternate routing which enables to search for more than one predefined routes in a given order. Alternate routing decreases the blocking probability of the lightpath requests. As for the adaptive RWA, it keeps the current state of the network. There are many protocols proposed for adaptive RWA. For example, Least Loaded Route (LLR) chooses the wavelength that has the least traffic over links on the route. It finds all least loaded links and wavelengths for a request Least Congested Path (LCP) works like LLR with the difference that it uses least congested wavelengths instead of least loaded ones. Alternate routing can also be employed for LCP and LLR. In [10], the blocking probability is measured and discussed with various algorithms such as LLR, first fit and random selection on WS and WI networks with respect to traffic load per link and link utilization.

2.6. Survivability

Survivability is a guarantee for continuity of the services provided by the network in the case of failures. A lightpath can be established by a RWA algorithm. Besides this, survivability shall also be considered because the allocated lightpaths carry too much traffic and loss of this traffic cannot be disregarded.

2.6.1. Optical Layer Protection

There are many other reasons to provide survivability in the optical layer [13]. Actually, some of the layers above the optical layer could provide protection services. For example, SONET has its own protection schemes and without optical layer protection, it can survive by itself. However other layers such as IP layer may not protect the IP networks by itself. Some joint operation is required with the optical layers. Optical protection also provides the interoperability of the legacy equipment because optical networks are transparent and any signals and protocols can be used on them.

There can be some failure on all-optical networks such that ports, connection equipments and optical-layer equipments on clients, optical layer hardware, fiber cables and node failures [17]. In order to deal with these failures there should be some spare or dedicated resource. Generally, these failures occur because of natural events such as earthquakes, floods, etc. For example, in 2003, in an earthquake in Mediterranean Sea, SMW3 undersea fiber lines have been destroyed and Turkey’s 80% of internet connection capacity has lost. This causes all Internet traffic to be routed to the other lines but these lines are not enough to serve this traffic. Although Internet connection was restored with backup line, it was too slow. Of course, it is because of the inadequate resources on the Internet connection strategy. Hence survivability is indispensable for all-optical networks and it has to be carefully designed in order not to have such phenomenon.

2.6.2. Joint Protection

Survivability shall be considered in all layers. In client, IP, ATM, SONET/SDH layers, they have their protection methods. For example, in IP layer, some routing protocols such as border gateway routing protocol (BGP) are used to route the traffic and when there is a failure, it can find another suitable path for traffic. It is also possible to use many protection schemes on each layer and joint protection can be employed. However it shall be carefully designed so that protection schemes on each layer can compete to recover the failure with each other. This is called race condition. Hence some resilience schemes shall be employed [15], [16].

2.6.3. Techniques for Survivability on Optical Layer

There are many survivability techniques. These techniques can be classified in many ways. In [10], [13], [16], [17], [18], [19] survivability techniques are discussed and classified according to authors' own perspective. In [10] and [18], the authors divide the techniques of survivability as predesigned protection and dynamic restoration. Predesigned protection are classified and explained. In [12], [16], the survivability is classified as optical channel section and optical multiplexing section. The former refers to path restoration and the latter one refers to link restoration. In [12], the authors classified the path restoration with disjoint-path restoration. In Figure 1, we merged all requested classifications of survivability techniques.

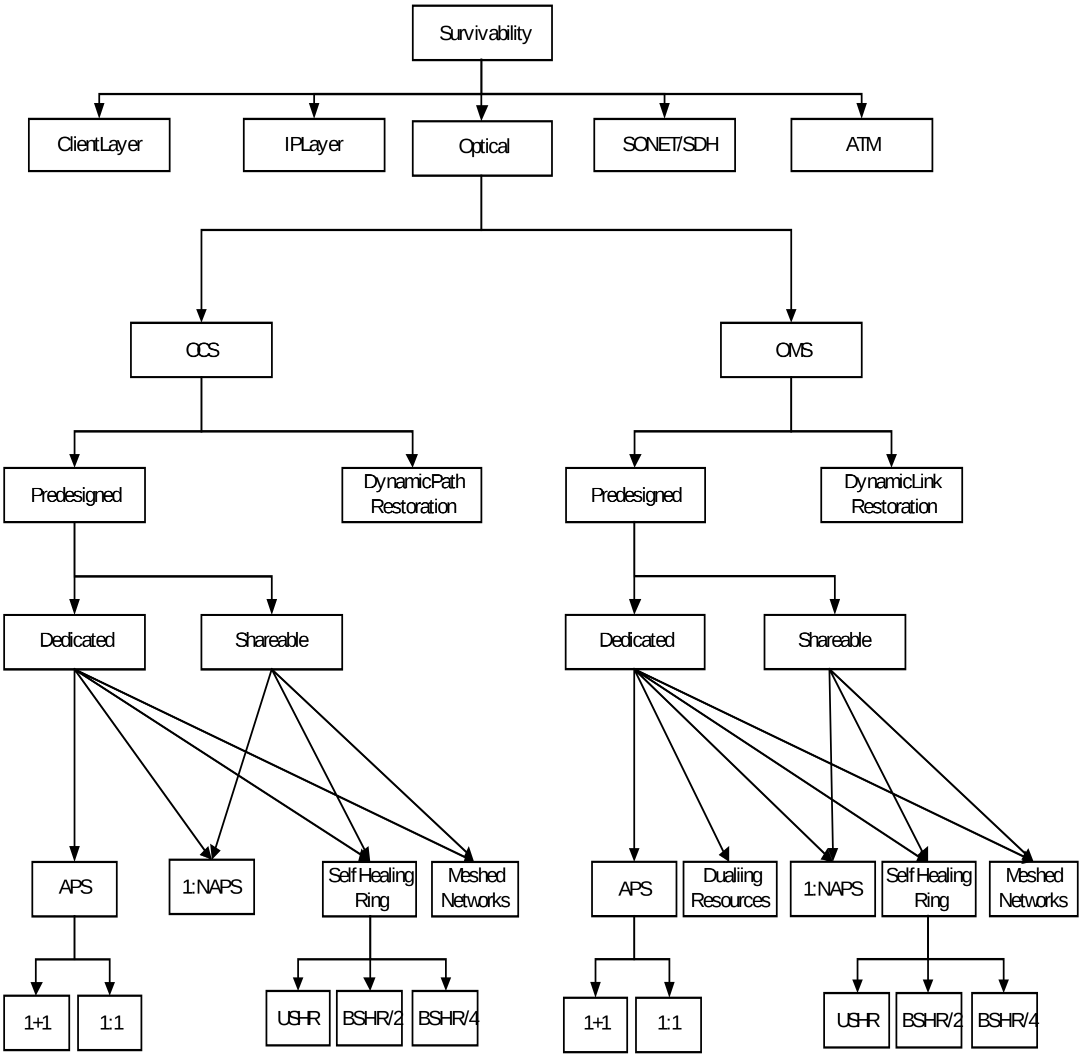


Figure 1 Classification of Survivability Techniques

Now we will explain the survivability techniques by following Figure 1. Our main focus will be on optical layer survivability. We classified survivability in Figure 1 by optical channel section and optical multiplexing section. Optical channel section is on the level of lightpath. It is related with path protection. The first established lightpaths that are to be protected are called primary lightpaths and the other that protects the primary ones is called backup lightpaths. Optical multiplexing section is related with link protection on the topology. We will discuss the survivability techniques according to both path and link protection together.

2.6.3.1. OCS and OMS

Both optical channel section (OCS) and optical multiplexing section (OMS) can be classified by predesigned protection and dynamic restoration. In predesigned protection, method of protection of a path or a link is defined at the beginning. By this way, it is known what will be done when a failure occurs and it can be guaranteed that 100% restorations can be achieved. In Figure 2(a) and (b), link and path protection are illustrated, respectively. Working path for link protection is allocated with N1-N3-N4 path. In (a), N3-N4 link is broken and broken link is replaced by N3-N5-N4 path. Every lightpath that used broken link uses replaced link. In (b), working path is allocated with N1-N3-N5-N4 path. When N5-N4 link is broken, working path is replaced with N1-N3-N4 path. Here only the mentioned working path uses the replaced path since this restores only this lightpath. The others shall use other paths, which are determined before. Dynamic protection does not allocate any resource initially. When there is a failure, it tries to recover path or link. If it cannot find any suitable link to recover in link restoration, all lightpaths using that link are failed. If it cannot find another path for lightpath that uses that failed link in path restoration, only that lightpath is failed. The others can be restored if there are suitable path to recover. Hence dynamic restoration does not guarantee 100% restorations. In (b), path N1-N3-N5-N4 is established. When N5-N4 link is broken, N1-N3 and N2-N5 link are full. Dynamic restoration scheme finds the path N1-N2-N5-N3-N4 and restores the lightpath. However if one of the links on the restoration path is also full, the lightpath could not be restored in this case.

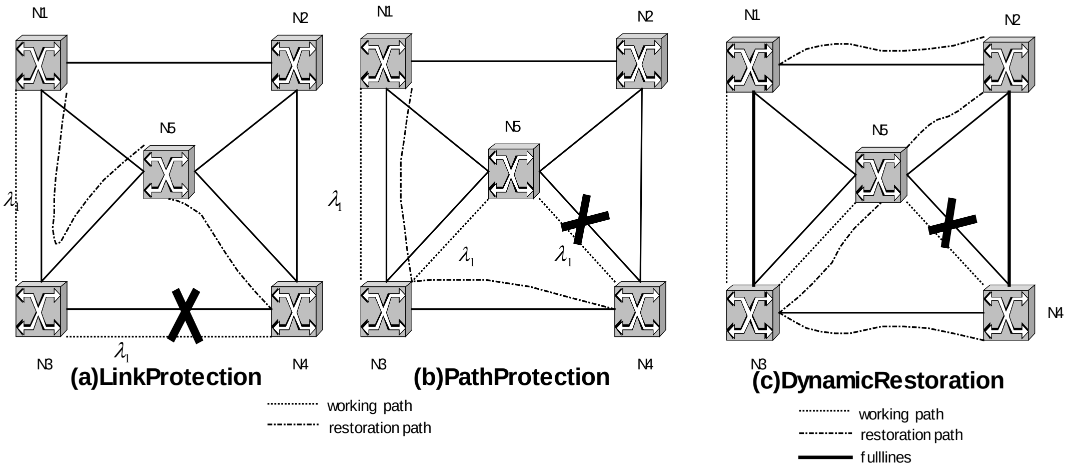


Figure 2 Link, Path protection and Dynamic Restoration

2.6.3.2. Dedicated and Sharable Protection

Predesigned protection can be classified as two methods, dedicated and sharable. The predesigned protection uses dedicated resources at the beginning. In link protection, every link has dedicated links that replaces this link. When this link is failed, these dedicated links are used to recover and traffic uses that failed links move to dedicated links. In path protection, primary lightpaths have dedicated backup lightpaths and these cannot be shared with other primary lightpaths. This provides very fast restoration. Because no extra computation is required since resources are already allocated.

In [18], an integer linear programming (ILP) is proposed to show that which protection scheme have better capacity utilization. Simulations that are done on ring topology show that shared-path protection uses resources more efficient approximately 1 ½ or 2 times less than dedicated-path protection, dedicated line protection and shared line protection.

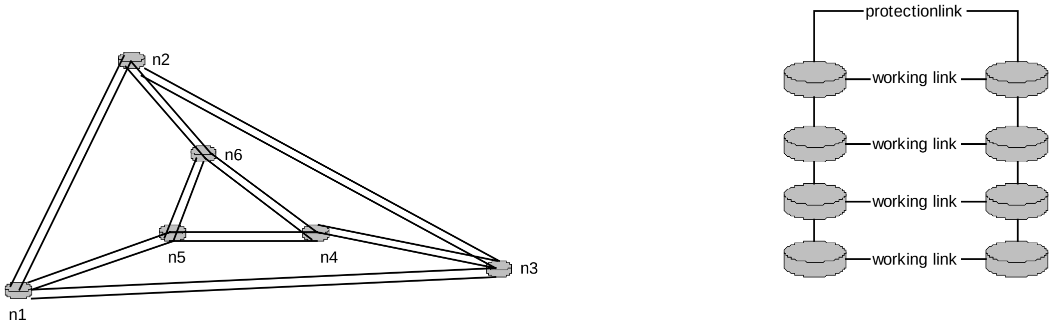
2.6.3.3. Automatic Protection Switching

First we will mention about survivability techniques that predesigned protection with dedicated resource as shown in Figure 1. Automatic protection switching (APS) is generally used in link protection but it can be adapted to the path protection. In Figure 3 APS 1+1, 1:1 and 1: N are illustrated. In Figure 3(a), 1+1 APS, each working link is doubled and source node sends its data to each link and destination node compares the signal on each link and selects the best one. Since data are sent over two links, when there is a failure on one of them, destination node chooses the other one. This is a very fast method; however it uses resources inefficiently.

1:1 APS is uses the same link doubling method. However, this time source node does not sent its data to both link, just uses one as working link and the other is the protection link. When there is a failure, protection link is used. In this method, protection link is idle when there is no failure. This link can be suitable for low-priority traffic to use this traffic since low-priority traffic can be disregarded when there is a failure.

The third protection method for APS is 1:N, illustrated in Figure 3(b). It can be categorized as both dedicated and shared resources protection. It has dedicated resources to protect N working link with one protection link. Therefore, it is dedicated resource protection in this sense. At the same time, there is a sharing between N working paths. Therefore, it is shared in this point of view. When there is a failure, the failed link uses the protection link. However, if one of the others has also failed, it will be blocked. Number of protection link can be increased to serve simultaneous failures at a time.

In path protection, APS can be employed. Every link established between source and destination node has an alternate disjoint path and data are sent through these links. 1+1 and 1:1 has the same property with the viewpoint of path protection. For 1:N APS, there should be a disjoint path for all N working paths that have the same source-destination node pair. Otherwise, this even cannot guarantee the restoration of single failures at a time. Since there is a shared protection link, it should be rerouted to the original link or path when failure is recovered.



(a) 1+1 APS, 1:1 APS

(b) 1:N APS

Figure 3 Automatic Protection Switching a) 1+1 APS,1:1 APS b) 1:N APS

2.6.3.4. Dualing Resources

Dualing Resources is another protection method for dedicated protection, which is classified in Figure 1. This is only related with optical multiplexing layer since optical equipments are related with this level protection. Failures can be any kind such as fiber cut, node, multiplexers, wavelength routers, lasers, etc. Although the failures of such devices are very rare, keeping the backups for some critical places is good for survivability. However, this double the infrastructure cost. This method is not preferred because of this.

2.6.3.5. Self Healing Ring

Self-healing rings are also used for protection, which is classified in Figure 1. Indeed this provides a natural protection because of the shape of the ring topology such that every node is connected to each other and first and last node is also connected to each other as in Figure 4. Self-healing rings (SHR) can be uni-directional (USHR) and bi-directional (BSHR). Uni-directional self-healing rings only use one working direction and the opposite direction is used for protection. Both link and path protection can be applied to uni-directional SHR. BSHR uses both direction as working path. BSHR can be constructed with two or four fiber, BSHR/2 and BSHR/4 respectively.

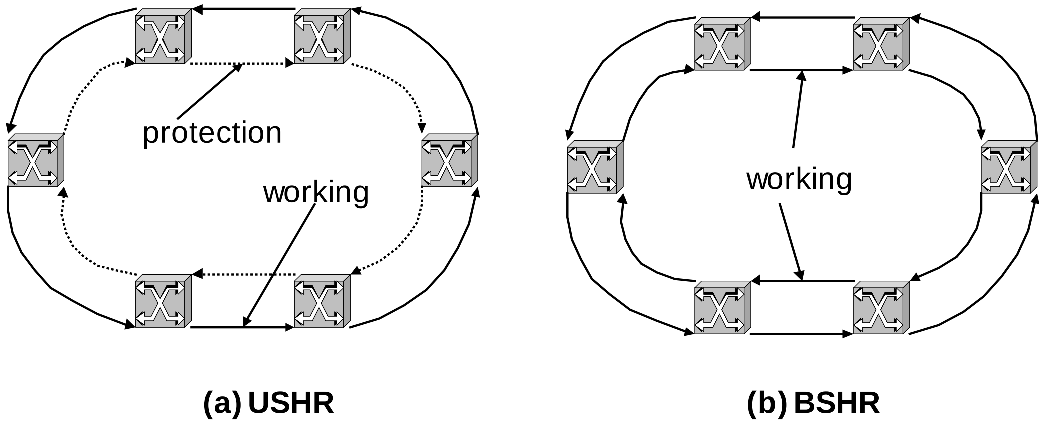


Figure 4 Self-Healing Rings a)USHR b)BSHR

2.6.3.6. Meshed Protection

Meshed network, which is classified in Figure 1, consists of nodes that are connected two or more link to the other nodes. Since one node has two or more link to others, many alternative paths can be found. Hence when there is a failure on a link, alternate path can be found easily. This feature of the meshed networks enables any protection on both optical channel and optical multiplexing layer to be employed. In link layer, automatic protection switching can be employed on meshed networks. In addition, in path layer, disjoint path protection is possible since such paths can be found on the topology. Virtual rings can be established to construct a protection for lightpaths. NSF-NET and ARPA-NET [19] were constructed as meshed networks.

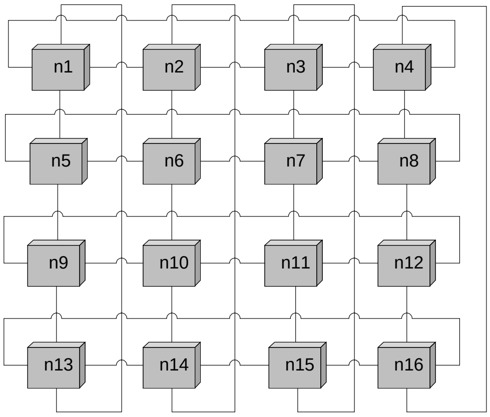


Figure 5 NxN Meshed Torus

2.7. Service Differentiation

We have mentioned about how lightpaths are protected so far. However, all we have mentioned above does not say anything about service differentiation. Service differentiation is the ability to differentiate the services given on the network. Lightpaths can be established according to its service with the service differentiation. This provides to treat to the lightpaths that are not using the same protection scheme and to use of resources more efficiently.

In the literature, there are many researches about QoS, service specific recovery and differentiated services for WDM networks. Transmission quality, percentage of the restoration guarantee, cost, network management, reliability, availability and recovery time and protection bandwidth can be QoS parameters for all-optical networks.

In [22], service specific recovery of connections in WDM networks is discussed. Lightpaths are allocated with the high or low transmission quality and the percentage of the restorability. Some wavelengths require 100% restorability and for some 50% restorability is enough. Also the transmission quality and the shared, dynamic path and link protection schemes are taken into account for the services given on the network. Four different services are constructed with the mentioned criteria above and the performances of these services are measured for the restorability and blocking probability. Also uniform or non-uniform requests in terms of service distributions are inspected. This work shows that differentiation can be done in many different ways.

In [23], various methods, such as differentiated reliability (DiR), quality of protection (QoP), quality of recovery (QoR), that have been proposed for providing service differentiation in survivable WDM networks and their performance is discussed. DiR method calculates the failure probability of the links and under single link failure assumption, the failure probability of a path is given by the sum of the failure probabilities of all the links along the path. It introduces the maximum failure probability (MFP) that is assigned to each connection. So unless the MFP requirement is met, the connection cannot be routed. In DiR, higher-class connections can preempt the lower-class connection when single link failure occurs. Another method mentioned is Quality of Reliability (QoR). The connection that requests reliability is called a reliable connection (R-connection). Unlike single-failure, it allows multiple failures. The reliability of resource is defined as the probability that it functions correctly over an interval of time. The primary lightpath can use a full backup lightpath or partial. If only a portion of the primary lightpath is considered as less reliable, only for that portion, backup lightpath is provided. The last method mentioned is Quality of Protection (QoP), which is defined as the probability that the connection will survive through a failure. This work provides us different point of view to the service differentiation method.

These works is different from our work in that we differentiate the class of services such as the best effort, the protection and the reservation. That is, they do not differentiate services according to our criteria.

CHAPTER 3

SERVICE DIFFERENTIATION APPROACH FOR WRN SURVIVABILITY

3.1. Service Differentiation Approach

Our aim is to show that the lightpath allocations with the class of service differentiation have better performance than the classical lightpath allocations that do not differentiate services.

In all optical networks, lightpaths are established according to a RWA algorithm. However, most of the RWA algorithms do not consider service differentiation. In this thesis, we take into account the class of the service requests namely the protection, the reservation and the best effort. The class of service differentiation provides us to behave differently to different lightpath requests. For example, there is no need to establish a backup lightpath to all primary lightpaths unless otherwise is stated. Therefore, treating all requests in the same manner may lead to inefficient use of resources.

The terminology used for the class of service perspective is nearly the same as optical layer protection. Protection namely backup service stands for dedicated protection that means resources are allocated initially when lightpath is created. Reservation stands for shared protection that primary lightpath allocates resources and backup path namely reservation path is reserved not allocated. Hence another backup of another primary lightpath can also share the path if two primary lightpaths do not have common link on their routes. Best effort stands for dynamic protection that does not allocate any resources for protection purposes. It is activated only when there is a failure and tries to find a restoration path. The path finding can be predetermined or really dynamic that tries all possible paths to restore the broken primary lightpath.

3.1.1. Protection Service

It is obvious that the protection service uses more resources than the reservation services since there is no sharing of resources. Using it for all lightpaths is not suitable since there is always low priority traffic, which needs not to be restored in a short time. Thus, providing protection for all lightpaths increases the overall blocking probability since it consumes too many resources compared to reservation based recovery service.

Protection service is illustrated in Figure 6. Primary lightpath pl_1 and another primary lightpath pl_2 are allocated with the requirement of protection service. So backup lightpath bl_1 and backup lightpath bl_2 are also allocated for the related indexed primary lightpaths. bl_1 and bl_2 use the same path but cannot share the resources. Because in protection services, backup lightpaths are allocated directly, they cannot be shared with other backup lightpaths. As seen, it is the waste of resources; however the protection is very fast because of having already established backup resources.

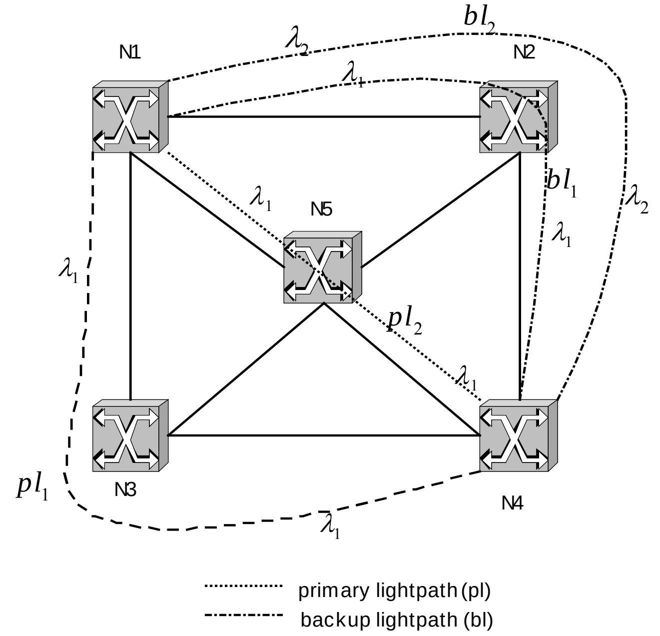


Figure 6 Protection Service Example

3.1.2. Reservation Service

Reserving some capacity to restore primary lightpaths in the case of failure makes possible sharing of resources for the restoration of lightpaths that do not share any resource on their primary path. However, providing the reservation services alone is not suitable in many cases. The reservation services need complex operations in order to restore lightpaths when there is a failure. Hence, the protection services have better restoration time compared with the reservation services.

Restoration service is illustrated in Figure 7. Primary lightpath pl_1 and another primary lightpath pl_2 are allocated with the requirement of reservation service. The reservation lightpath rl_1 can be used for both pl_1 and pl_2 since they are disjoint and can be restored by rl_1 when one of the links that they used is broken. rl_1 is not allocated, it is reserved. Unlike protection service, restoration service shares resources. This provides efficient use of resources.

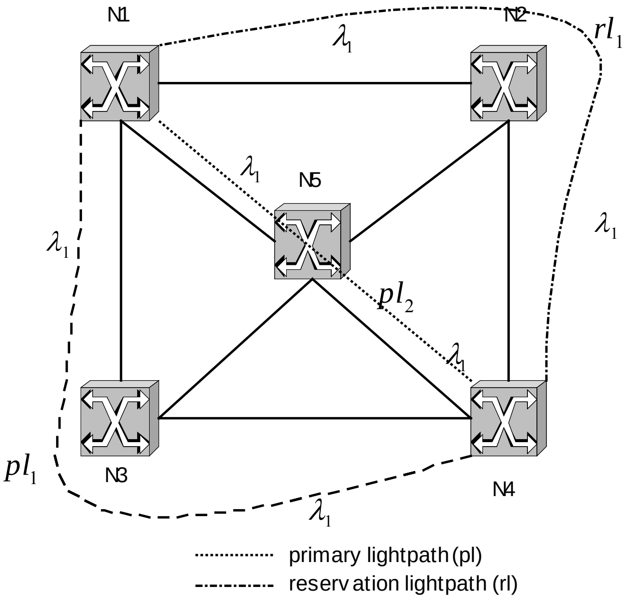


Figure 7 Reservation Service Example

3.1.3. Best Effort Service

A similar discussion can be made over reservation and best-effort services. A best effort service will not allocate any resources for the primary lightpaths; so much more resources will be available for further requests. However, treating the all lightpaths as if they have the best effort services does not make sense. Because if there is no protection path or no reserved resources, service restoration may take too much time since a new route and wavelength need to be found after the failure. Moreover, it may not be even possible to establish such a new lightpath. Therefore, there will always be service disruption for sensitive lightpaths that need the reservation or the protection services. Although there is no such a requirement, in the case of a failure, it may be possible to restore the best effort traffic after the protection and reservation based services restored. This would lead efficient use of resources while providing survivability but this time no 100% restoration guarantee exists.

The Best Effort service is illustrated in Figure 2(c) as dynamic protection. When the link that is used for a lightpath is broken, it tries to find a restoration path. If it finds one, the lightpath is restored. Otherwise the traffic that flows on the lightpath is lost.

3.2. Other Approaches

In the literature, there are many researches about QoS, service specific recovery and differentiated services for WDM networks. Transmission quality, percentage of the restoration guarantee, cost, network management, reliability, availability and recovery time and protection bandwidth can be QoS parameters for all-optical networks. In [22], the service-differentiated recovery of the wavelength connections in WDM networks is discussed. The services are differentiated according to the transmission quality and the restorability guarantee. In [23], various methods for service differentiation are mentioned. In these methods, the connections are established according to the probability of reliability and the probability of the protection. These works give the sense that differentiation can be done in many ways for given services. Unlike these works, we differentiate the services according to their service classes.

3.3. Class of Service Differentiation Based RWA

Figure 8 shows the flow diagram of the service differentiated connection setup with two alternate paths (inspired from [21]).

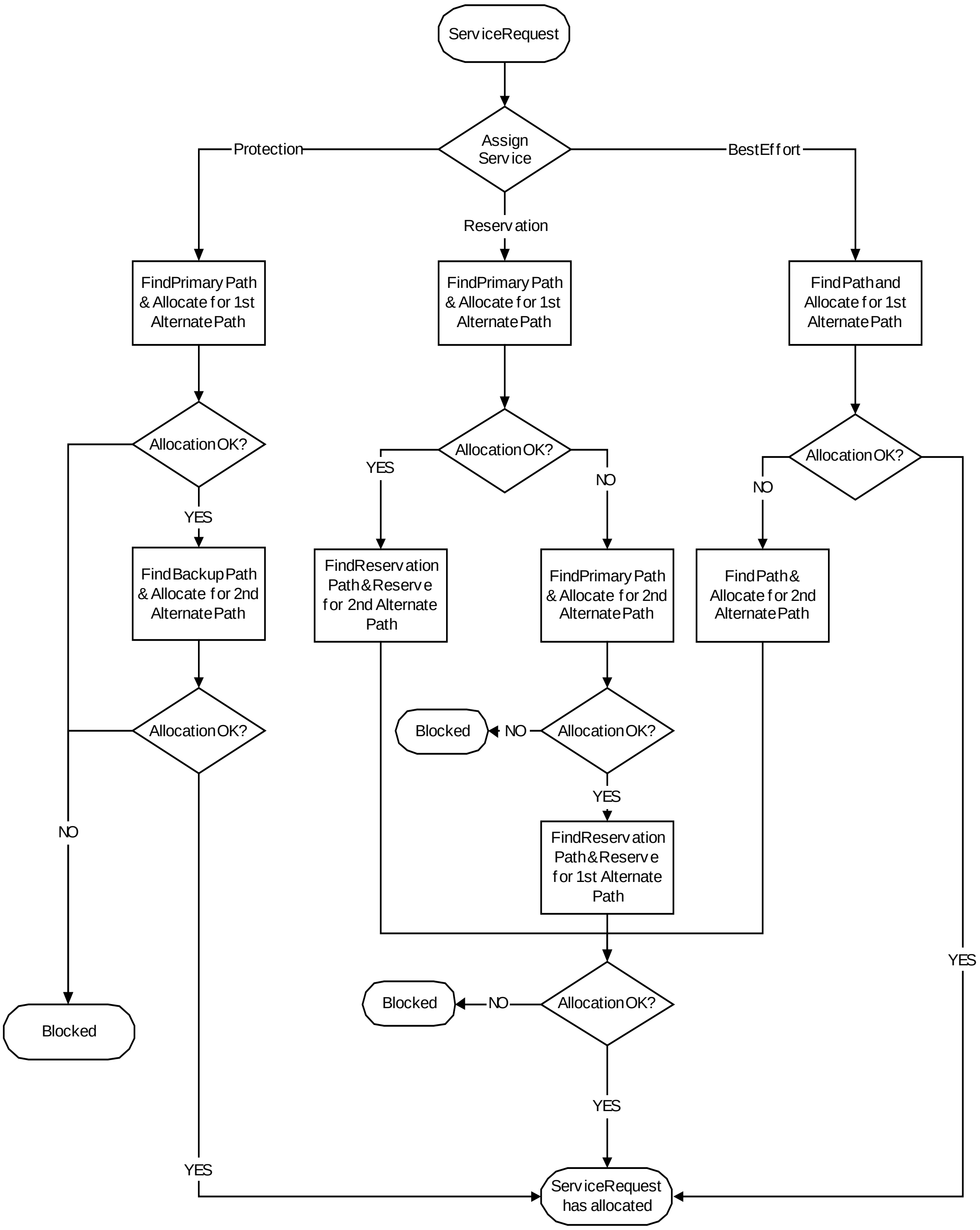


Figure 8 Service Differentiated Connection Setup

When clients request for service, allocation is done according to the service. The following assumes that fixed alternate path routing with two alternate paths is considered for RWA, and only one link failure can be in the network at a time.

When the protection service is requested, the first alternate path is calculated. Then it is tried to be allocated. The protection service requires also backup lightpath to be allocated. If the first alternate path is failed, the protection service request is failed, since there are two alternate paths. If the primary lightpath is allocated successfully, the backup lightpath is tried to be allocated. If the allocation of the backup one is failed, then the protection service request is failed. When the both the primary and the backup lightpaths are allocated, the protection service is established.

When reservation service is requested, the first alternate path for the primary lightpath is calculated and then it is tried to be allocated. If it cannot be allocated, the reservation service is not blocked as in the case of the protection service. Then the second alternate path is tried. If it is failed, then the reservation service is blocked. When one of the alternate paths is allocated for the primary lightpath, the other alternate path is tried to be reserved. If the reservation is failed, service request is rejected. Both the primary and the reservation lightpath are allocated and the reservation service is established.

When the best effort service is requested, the first alternate path is calculated for the primary lightpath and then it is tried. If it is failed, the second alternate path is tried. If the one of the two alternate paths is not allocated, the best effort service is blocked. Otherwise the lightpath is established.

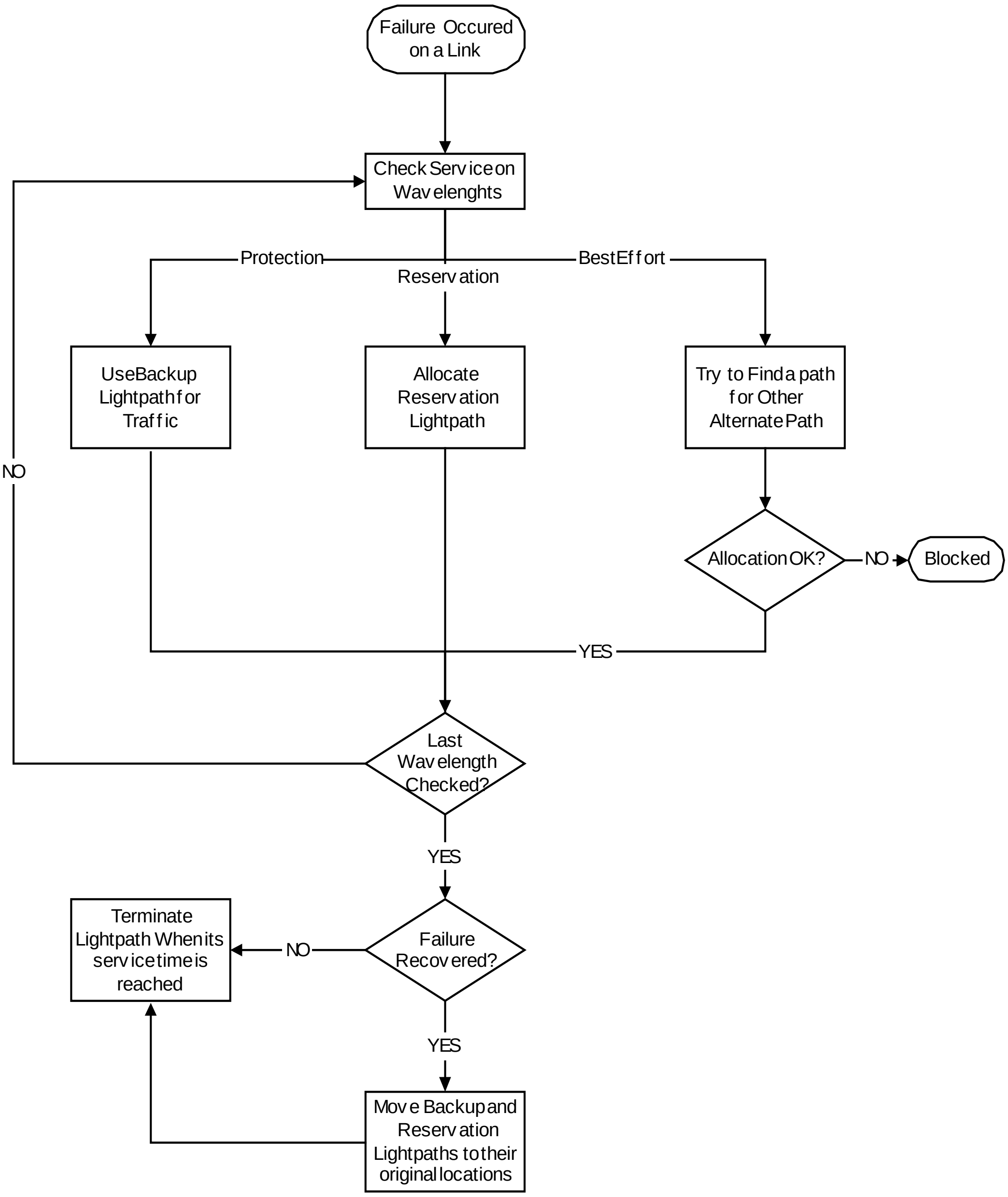


Figure 9 Service Differentiated Connection When Failure Exists

Figure 9 shows the service differentiated connection setup under failures. When one of the links has broken in the network, the lightpaths that use that link are broken. At that time, restoration process tries to restore traffic starting from the lightpath that uses smallest index wavelength of the broken link. If the service is the protection then the backup lightpath takes the role of the primary lightpath. This switching is very quick. If the service is the reservation, some calculations are done to seize the reservation lightpath. After it is seized, the lightpath is restored but now with the best effort services. This does not spoil the service guarantee that is given with the reservation services because of the one-failure at a time. If the service is the best effort, the other alternate path is tried for the restoration. If it cannot find available resources, the best effort service is blocked and the traffic is lost.

3.4. Performance Evaluation

In this section, we try to show by simulations that the class of service differentiated lightpath allocation has better performance than the classical lightpath allocation, which has not the service differentiation. We will measure the blocking probability for the different class of services as the performance criteria with respect to changing load for different topologies, different number of wavelengths per link and different topology sizes. We define the blocking probability as the ratio of the number of unsuccessful service requests to the total number of service requests.

3.4.1. Simulation System

We developed the simulation system, which all simulations are done with. In Appendix A, a few screen snapshots of the simulator are presented. Our simulation system can create two topologies, ring and NxN meshed torus. Size of these topologies, wavelengths/link number, with failures, without failures, failure rate, failure repair rate, the class of services, failure number of the lightpath that is generated through the end of the simulation are the parameters that can be changed or selected. Load starting from the start load is increased with the amount of stepping load until the end load is reached during the simulation. The number of samples is determined in our simulations according to confidence interval of 5% with 95% probability. That is, simulation continues until the desired confidence level is reached. If confidence level is not specified, simulation continues until the specified number of lightpaths has routed. We also add logging mechanism and its levels to verify the simulator operation. Someone can easily trace the simulation outputs by setting the logging level above to zero. Our simulation also supports batch mode that enables series of simulations continuously without any interaction with the predefined values. The graphics have also added to see the results in graphical form. This gives more sense for the simulations that are done with the selected parameters.

We validated our simulation system by running some simulations on both our and the simulator developed by Koçyiğit [3]. We compared the results for the best effort services of 10 node ring and 4x4 meshed torus with 2-alternate path under failures in Figure 10 and Figure 11, respectively. The results are very close to each other with approximately 0,001 % error.

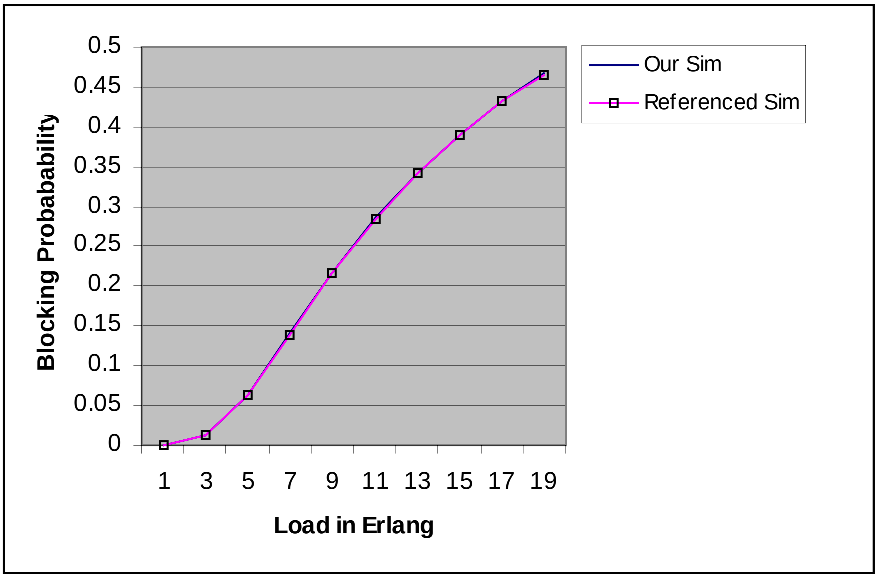


Figure 10 Comparison of Our and Referenced Simulation on 10-node Ring with the best effort services, 2-alternate path and under failures

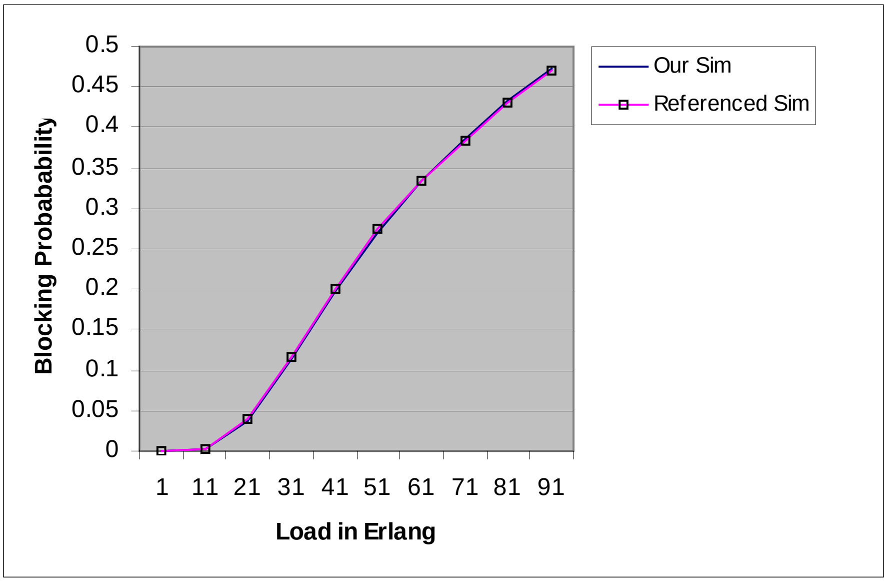


Figure 11 Comparison of Our and Referenced Simulation on 4x4 Meshed Torus with the best effort services, 2-alternate path and under failures

Referenced simulation system cannot handle protection and reservation services. Hence, we only use the referenced simulation system to verify our simulation's operation for best-effort services.

3.4.2. Assumptions

We have made various assumptions during the performance evaluation of the class of service differentiation approach. Some of the simulations may not reflect the real world conditions such as topologies, traffic distributions, etc. However, we can say that the results obtained here give an idea about the expected behaviour in the real networks.

3.4.2.1. Network Type

We work on wavelength selective type WRN networks. Therefore, we have wavelength continuity constraint on wavelength assignment. Routes are searched within predefined alternate paths and wavelength assignments are done with first-fit method. First-fit method works for the protection and the best effort services by selecting the first suitable wavelength starting from the smallest index wavelength. For the reservation services, we have put a little intelligence to use resources more efficiently. We calculate the mostly shared wavelengths along the route that is tried to be reserved. This provides the most used indexes are tried first and if they are sharable, the path is reserved also for the new lightpath.

3.4.2.2. Topologies

We choose to work on NxN meshed torus (Figure 5) and ring (Figure 4) topologies. These are the regular topologies. For NxN meshed torus, every node has four connections to the neighbouring nodes. So it is easy to find a path between start and end nodes. The meshed topologies have more resources to serve the lightpath requests. NxN meshed torus has a $2\mathrm{x}\,N^2$ total links. The arbitrarily connected meshed topologies do not have this amount of links. Like ARPA2 and NSFNET networks, some nodes have 2 links, some are 3 connections, and a few are 4 or more connections. Hence meshed torus may not represent the arbitrarily connected real networks. However, these two extreme topologies reflect the behavior of the algorithms employed in similar topologies up to some extent.

We try to find shortest 2-alternate path for meshed torus. For ring topology, which is very commonly used, finding alternate paths is trivial. On the ring, one direction (the shortest path) is used for the allocation of the primary lightpaths; the other is used for the allocation of the backup and reservation lightpaths. For torus topology, since it's a little complex, we illustrated in Figure 12. When starting node N1 and ending node N16 path is requested, the first shortest alternate path is N1-N4-N16. First, it equalizes the column number of N1 with N16 and then equalizes the row number of N1 with N16. The second shortest alternate path is N1-N13-N16. Unlike first alternate path, first, it equalizes the row number of N1 with N16 and then equalizes the column of N1 with N16. Shortest path is constructed by selecting the direction that has absolute value of row or column index differences less then or equal to N/2, where N represents the size of meshed torus. For both of these topologies, we assume that every link has been constructed with one bi-directional fibers and the number of wavelength channels per link is the same for all links.

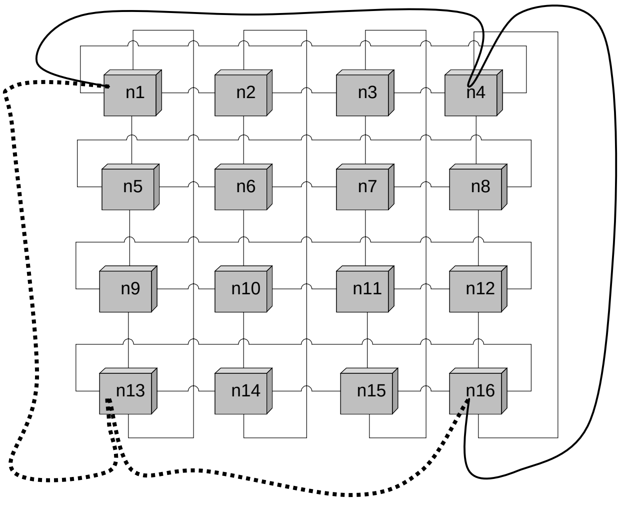


Figure 12 2-Shortest Alternate Path Selection on NxN Meshed Torus

3.4.2.3. Request Arrivals

Total network load determines how frequent lightpath requests come to the network. The lightpaths' start and end nodes are selected randomly. Service requests are assumed to be uniformly distributed. Interarrivals and lightpath holding times are exponentially distributed. The mean holding time is set to one. Since we are working on survivable networks, we also simulate the link failures. If failures are enabled, failed links are selected randomly. Failures are not simultaneous and arrive as one failure at a time manner. That is, in a chosen time, two failures cannot coexist on the network. We also defined repair rate (set to 1 in all simulations) and failure rate (set to 0.01 in all simulations) for the failures, which are also distributed exponentially. Failure rate determines how frequent the failures occur and the repair rate determines how long the failure will remain in the network. Service requirements for the lightpaths are distributed uniformly according to selected services. Services are equally distributed. That is, 33% of lightpaths require protection, 33% require reservation and 33% require best effort service.

3.4.3. Simulations and Discussions

We made series of simulations to measure the blocking probability as the performance criteria under changing load. In this section, we will discuss the results that are gained from the simulations. We evaluate the performance with changing conditions to illustrate the how performance is affected with changing conditions such as topology, network size, etc. The classes of services that are used are the protection, the reservation and the best effort services, which are explained in sections 3.1.1, 3.1.2 and 3.1.3, respectively. The “Differentiated Services” service is the equally (33%) distributed of these three services. In the simulations, number of samples is determined according to the confidence interval of 5% with probability 95%. However, under low load (at most for 3 load values), the number of samples required to satisfy this confidence interval is too large. In such cases, the simulation stops when 100.000 samples are routed, and simulation stopped.

3.4.3.1. Performance on Ring Topology

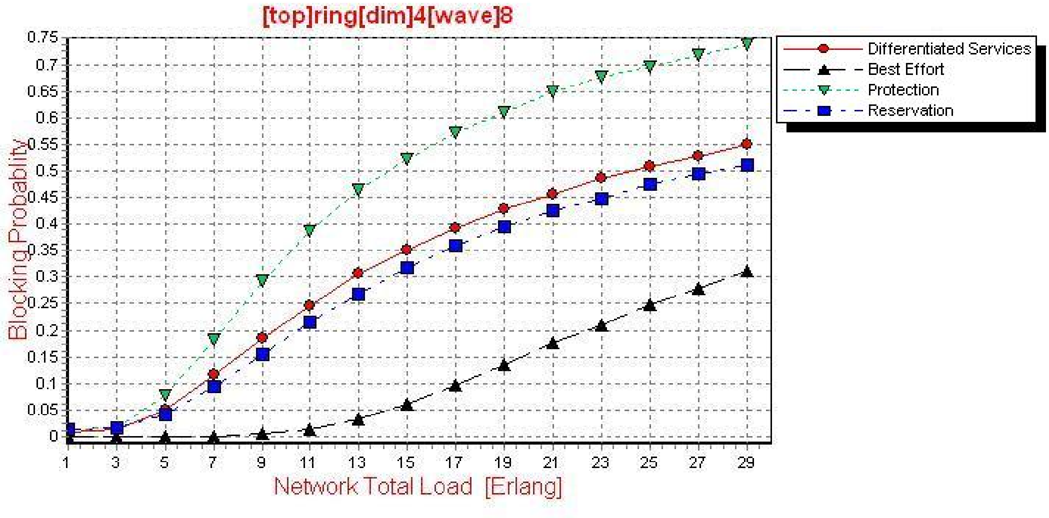


Figure 13 Performance on Ring Topology with Dimension=4, Wavelengths/Link=8

Figure 13 shows the blocking probability versus total network load with differentiated services on ring topology with dimension=4, wavelengths/link=8. The equally distributed services have better blocking than the protection services, as expected. When the load increases, the difference between the protection and the differentiated services increase. For 55% blocking probability, the differentiated service carries 13 Erlangs more traffic than the protection service. However at 25% blocking probability, the difference is 3 Erlangs. This shows that while the load increases the service differentiation performance gain increases. As we expected, reservation service has better blocking than protection service because of sharing of resources and the performance increases while load increases. It is the nearly the parallel to the equally distributed service but a little better. This is because of %33 of the requests requiring the protection service and this increases the blocking. The best effort service has the best blocking, normally. The blocking is started for the best effort nearly at 7 Erlangs. At that time, the reservation has %10 and the protection has %20 blocking probability and when the load is doubled for the best effort, the blocking probability is %40 and %62, respectively. This means when the load increases, if the all requested lightpaths need the best effort service and only the protection or reservation service is given on the topology, the minimum performance loss is about %10 and %20 at minimal loads, and, %25 and %40 at higher loads for the protection and reservation services, respectively. Hence, instead of using the protection service for all lightpaths, differentiated service may be used. Because it has not only better blocking probability, but also the blocking probability is very close to the reservation service one.

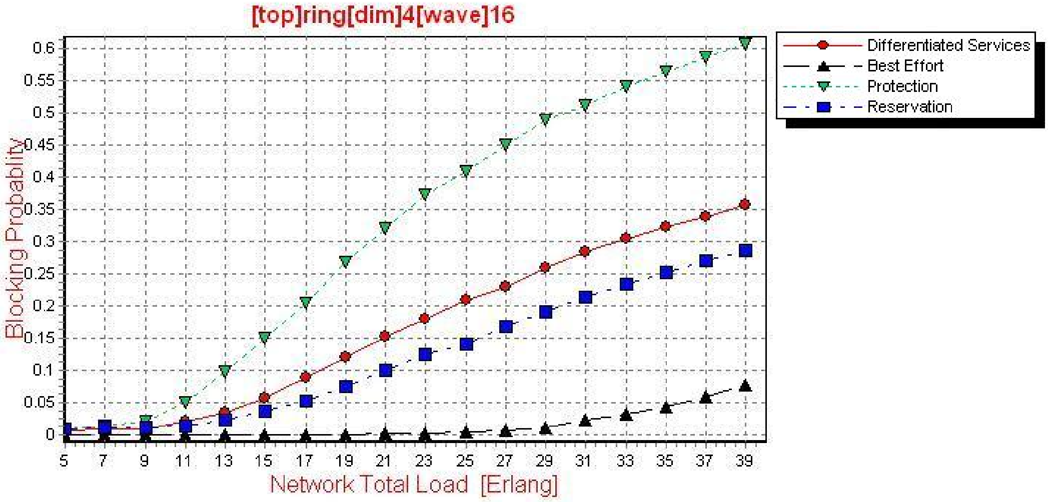
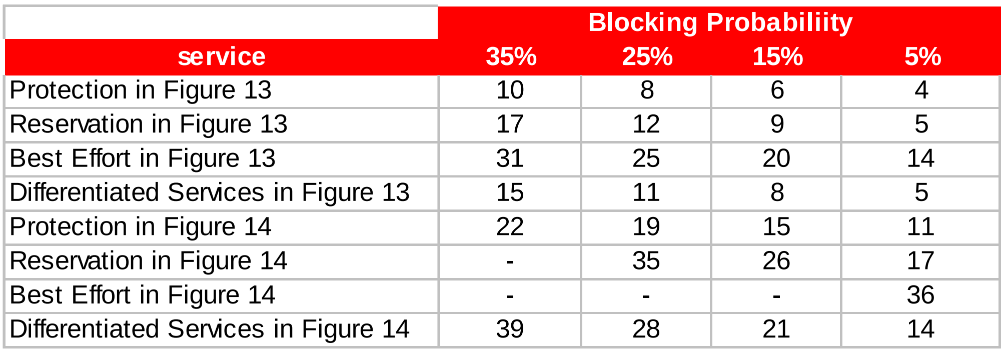


Figure 14 Performance on Ring Topology with Dimension=4, Wavelengths/Link=16

We doubled the number of wavelengths per link to measure how the service differentiation behaves. Figure 14 shows the results for ring topology with dimension=4 and wavelengths/link=8. It is obvious that the blocking probability has reduced for all services since we have more resources to allocate a lightpath request compared with Figure 13. Although, the final load is higher than previous results, the blocking is lower than that. The performance of the services is the same order as the previous results. For the best effort service, blocking is started nearly at 4 Erlangs more load than previous results. The differentiated service and the reservation service show close performance (2 Erlangs) for previous results. But here, the reservation service makes nearly 4 Erlangs difference with the previous and this difference increases while load increases. Because the reservation services find more resources to use for sharing and when the load is increasing, more resources are shared. Hence the new lightpath request with the reservation service requirement has more chance to find a path for primary lightpath with the reservation lightpath.

Table 2 Raw Values for Total Load for Figure 13 and Figure 14



	Blocking Probabiliity			
service	**35%**	**25%**	**15%**	**5%**
Protection in Figure 13	10	8	6	4
Reservation in Figure 13	17	12	9	5
Best Effort in Figure 13	31	25	20	14
Differentiated Services in Figure 13	15	11	8	5
Protection in Figure 14	22	19	15	11
Reservation in Figure 14	-	35	26	17
Best Effort in Figure 14	-	-	-	36
Differentiated Services in Figure 14	39	28	21	14

In Table 2, we show the raw values for the total load of the protection, the reservation, the best effort and differentiated services for Figure 13 and Figure 14 at 35%, 25%, 15% and 5% blocking probability.

Table 3 Values of Differences of Total Load Using Values in Table 2

	Differences with Differentiated Services			
service	**35%**	**25%**	**15%**	**5%**
Protection for Figure 13	-5	-3	-2	-1
Reservation for Figure 13	2	1	1	0
Best Effort for Figure 13	16	14	12	9
Protection for Figure 14	-17	-9	-6	-3
Reservation for Figure 14	-	7	5	3
Best Effort for Figure 14	-	-	-	22

In Table 3, we present the differences of total load with respect to differentiated services. Some values that are out of range in the graphics have shown as "-". Minus values indicates that service has more blocking than the differentiated services. For the protection services, approximately 3 times more than previous results. In addition, while the load is increasing, the difference is increasing. For reservation service, the difference is initially 3 times more than previous results. However it is increasing to 5 times more. For the best effort service, the difference is initially 2 ½. Although the values of the best effort are out-of-range for the given blocking probabilities, graphic shows that the difference tends to increase.

As a result, doubling the wavelengths/link number increases the performance between of the protection, the reservation and the best effort services by approximately between 3 and 4, 5, 2 ½ times, respectively. This means that the differentiated service performance is tripled compared with the protection service while doubling the wavelengths/link number.

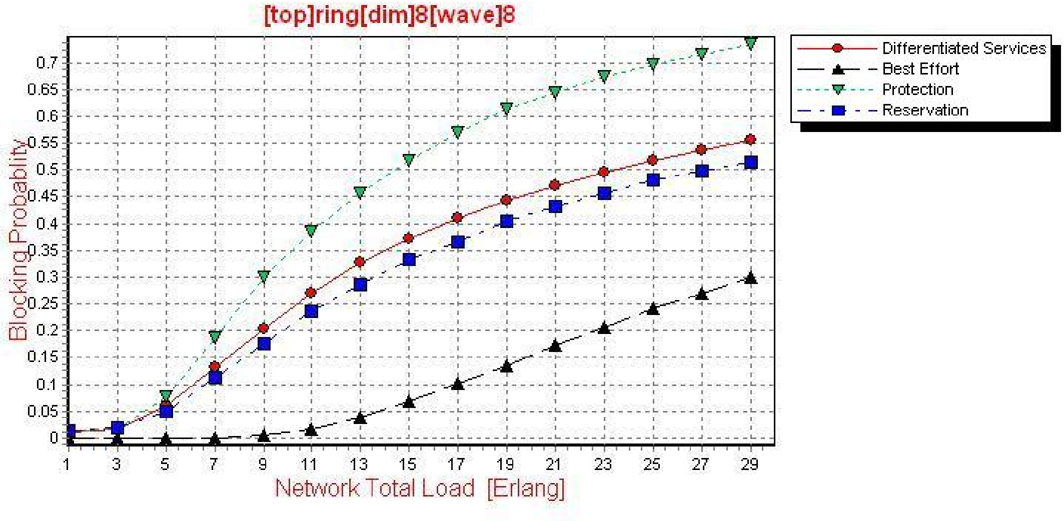


Figure 15 Performance on Ring Topology with Dimension=8, Wavelengths/link=8

Figure 15 shows the results for ring topology with dimension=8, wavelengths/link=8 results. If this graphic and Figure 13 are carefully inspected, It can be seen that they are very nearly the same. This shows that size does not so matter for the ring topology by keeping the wavelengths/link the same. Because when establishing a lightpath request on the ring topology, there are only 2 ways to establish and when establishing the lightpath, all links are traversed from start to end node and then allocated. However there is some size limitation for this. If ring with below 4 nodes are used, the blocking increases since the start and end node random selection to generate the path is restricted. In 2-node ring, there is only 1 path choice and in 3-node ring there are 3 path choices regarding the bi-directional links.

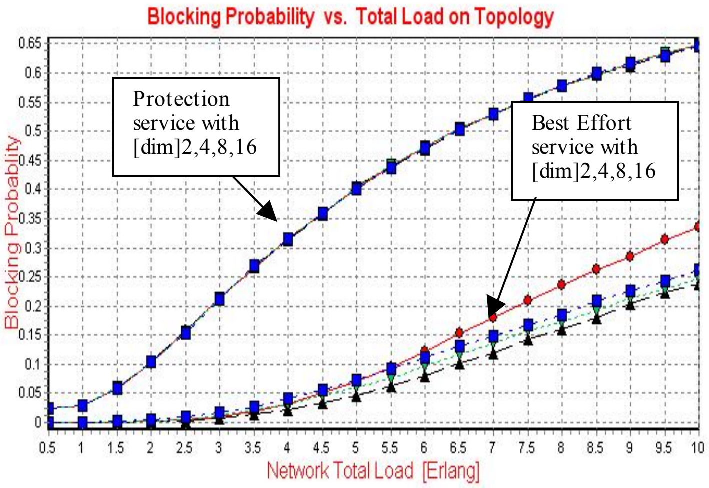


Figure 16 Dimension Effects on Ring Topology

In Figure 16, we made the simulation with dimension 2, 4, 8 and 16 for the protection and the best effort service to clarify the effects of increasing the dimension for the ring topology. The graphic shows that the protection service does not affect from the dimension change, however the best effort service has little difference. Hence, whether we change the size or not does not matter for ring topology in terms of the class of service differentiation performance.

3.4.3.2. Performance on NxN Torus Topology

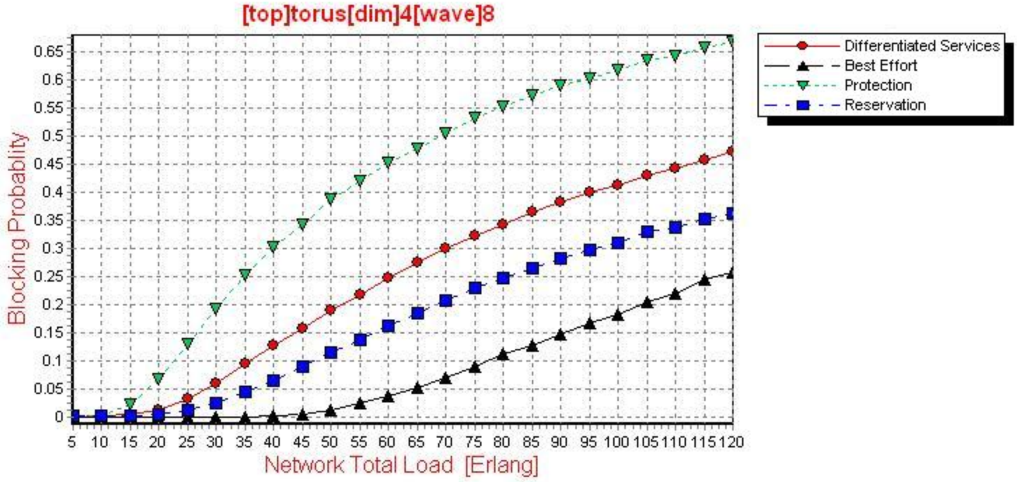


Figure 17 Performance on Torus Topology with Dimension=4, Wavelengths/link=8

Figure 17 shows the results for torus topology with dimension=4, wavelengths/link=8 results. The results show that although the load is so high with respect to ring topology, blocking is very low. For example, at 20% blocking, the difference in loads with the differentiated services are 2, 1, 13 Erlangs for ring and 20, 17, 55 Erlangs for torus, for the protection, the restoration and the best effort, respectively. Results show that performance difference between different classes of services is very significant compared with ring. For reservation service, the difference of blocking probability of the differentiated services is increasing, because the reservation service uses resources efficiently. At %50 blocking, the load difference between the protection service and the differentiated service is approximately 50 Erlangs for meshed torus, while it is 9 Erlangs in ring. This can be interpreted that the meshed torus is the convenient choice for the service differentiation.

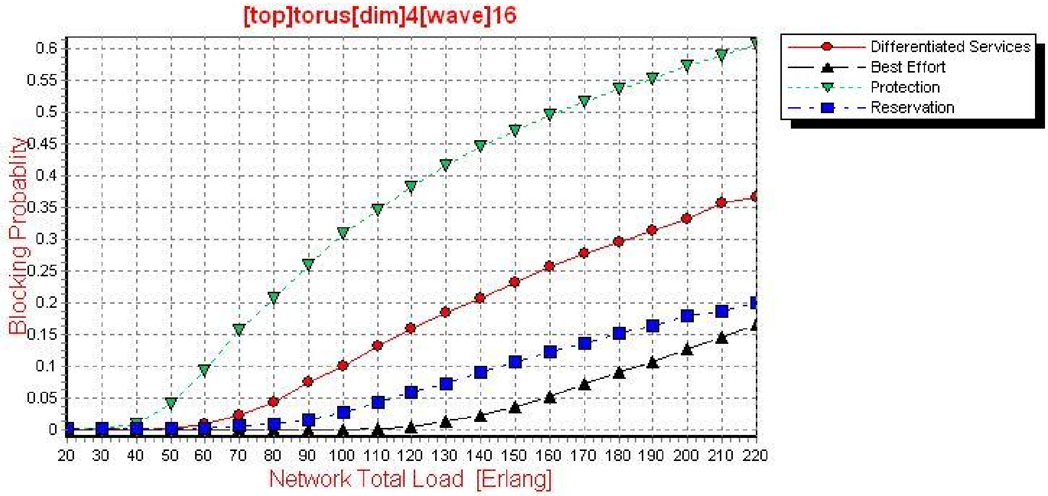


Figure 18 Performance on Torus Topology with Dimension=4, Wavelengths/link=16

Figure 18 shows the results for torus topology with dimension=4, wavelengths/link=16 results. We doubled the number of wavelengths per link as we did in ring topology. The order of the blocking probabilities is the same as all previous results, as expected. However, this time, the difference between the protection and the restoration services are larger compared to previous results.

Table 4 Raw Values for Total Load for Figure 17 and Figure 18

	Blocking Probabilities			
service	35%	25%	15%	5%
Protection in Figure 17	45	35	27	18
Reservation in Figure 17	115	80	55	36
Best Effort in Figure 17	-	115	90	65
Differentiated Services in Figure 17	86	60	44	30
Protection in Figure 18	110	88	69	51
Reservation in Figure 18	-	-	180	112
Best Effort in Figure 18	-	-	210	160
Differentiated Services in Figure 18	206	158	115	80

In Table 4, we show the raw values for the total load of the protection, the reservation, the best effort and differentiated services for Figure 17 and Figure 18 at 35%, 25%, 15% and 5% blocking probability.

Table 5 Differences in Total Load Using Values in Table 4

	Differences with Differentiated Services			
service	35%	25%	15%	5%
Protection for Figure 17	-41	-25	-17	-12
Reservation for Figure 17	29	20	11	6
Best Effort for Figure 17	-	55	46	35
Protection for Figure 18	-96	-70	-46	-29
Reservation for Figure 18	-	-	65	32
Best Effort for Figure 18	-	-	95	80

In Table 5, we present the differences in total load with respect to differentiated services. Some values that are out of range in the graphics have shown as "-". Minus values indicates that service has more blocking than the differentiated services. For protection service difference with the differentiated services, increases while load increases. At 5% blocking probability, the difference is nearly 2 times more. While load is increasing, the difference is also increasing and reaches to 2.7 times more. At 35%

blocking probability, it is closing to 2 times more. For the reservation service, the difference is more than 5 times and this difference is increasing while load is increasing. For the best effort, the difference is a little more than 2 times. However it is closing to 2 times while load is increasing. This comparison shows that the reservation service's performance is very good compared with other services. This is because of the availability of resources are increasing when doubling the wavelengths/link number and more resources are can be shared.

In addition, there is a tendency that the difference between the best effort service and the reservation service blocking probabilities is decreasing under heavy load. Because when the network is full of lightpath, the requests are blocked until some of the lightpaths has been terminated. Both services behave as the same since they are both full under heavy load with the one difference that the reservation service terminate a lightpath with its shares when the lightpath service time has reached. This makes more resource releases. On the contrary, the best effort service terminates only a lightpath. Therefore, the reservation service's blocking is starting to reach the best effort's blocking.

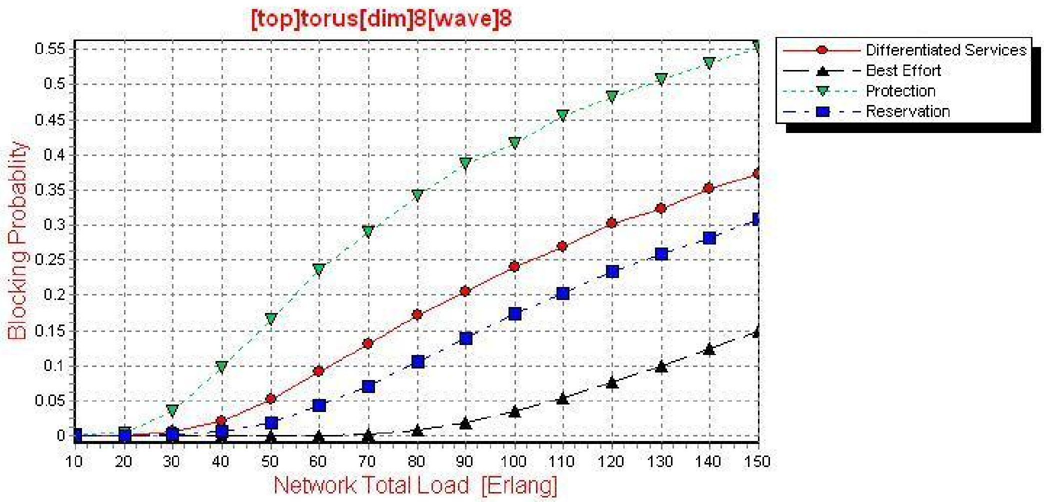


Figure 19 Performance on Torus Topology with Dimension=8, Wavelengths/link=8

Figure 19 shows the results for torus topology with dimension=4, wavelengths/link=16 results. It can be easily seen that changing the dimension effects NxN torus topology very much unlike the ring topology.

Table 6 Raw Values for Total Load for Figure 17 and Figure 19

	Blocking Probabilities			
service	**35%**	**25%**	**15%**	**5%**
Protection in Figure 17	45	35	27	18
Reservation in Figure 17	115	80	55	36
Best Effort in Figure 17	-	115	90	65
Differentiated Services in Figure 17	86	60	44	30
Protection in Figure 19	82	63	48	32
Reservation in Figure 19	-	127	92	62
Best Effort in Figure 19	-	-	150	108
Differentiated Services in Figure 19	139	104	75	50

In Table 6, we show the raw values for the total load of the protection, the reservation, the best effort and differentiated services for Figure 17 and Figure 19 at 35%, 25%, 15% and 5% blocking probability.

Table 7 Differences of Total Load Using Values in Table 6

	Differences with Differentiated Services			
service	35%	25%	15%	5%
Protection for Figure 19	-57	-41	-27	-18
Reservation for Figure 19	-	-	17	12
Best Effort for Figure 19	-	-	75	58
Protection for Figure 17	-41	-25	-17	-12
Reservation for Figure 17	29	20	11	6
Best Effort for Figure 17	-	55	46	35

In Table 7, we have compared the total load difference with the equally distributed services. Some values that are out of range in the graphics have shown as “-“. Minus values indicates that service has more blocking. The differences show that doubling the dimension of the torus topology does not make significant changes than the previous results. For all services, the difference is around 1 ½ time more. Hence doubling the dimension does not make so much difference as the doubling the wavelengths/link.

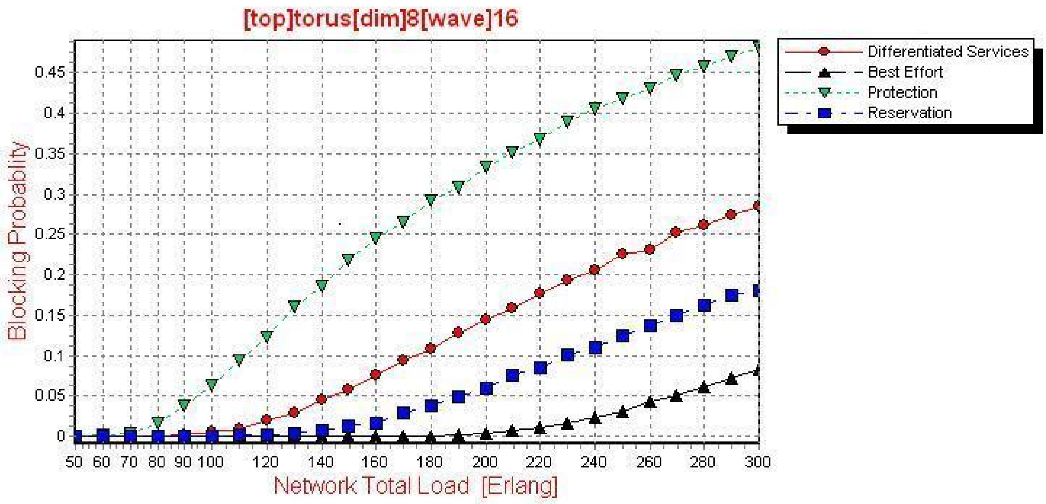


Figure 20 Performance on Torus Topology with Dimension=8, Wavelengths/link=16

Figure 20 shows the results for torus topology with dimension=8, wavelengths/link=16 results. This simulation has been done in order to show that how doubled dimension and wavelengths/link affects the class of service differentiation performance.

Table 8 Raw Values for Total Load for Figure 17 and Figure 20

	Blocking Probability			
service	**35%**	**25%**	**15%**	**5%**
Protection in Figure 17	45	35	27	18
Reservation in Figure 17	115	80	55	36
Best Effort in Figure 17	-	115	90	65
Differentiated Services in Figure 17	86	60	44	30
Protection in Figure 20	210	160	128	95
Reservation in Figure 20	-	-	270	190
Best Effort in Figure 20	-	-	-	270
Differentiated Services in Figure 20	-	270	205	144

In Table 8, we show the raw values for the total load of the protection, the reservation, the best effort and differentiated services for Figure 17 and Figure 20 at 35%, 25%, 15% and 5% blocking probability.

Table 9 Differences of Total Load Using Values in Table 8

	Differences with Differentiated Services			
service	**35%**	**25%**	**15%**	**5%**
Protection for Figure 20	-	-110	-77	-49
Reservation for Figure 20	-	-	65	46
Best Effort for Figure 20	-	-	-	126
Protection for Figure 17	-41	-25	-17	-12
Reservation vs All for Figure 17	29	20	11	6
Best Effort vs. All for Figure 17	-	55	46	35

In Table 9, we have compared the difference in total load with the equally distributed services. Some values that are out of range in the graphics have shown as “-“. Minus values indicates that service has more blocking. For protection services, the difference is more than 4 times. The restoration has about 5 times more difference and the best effort has about 2 times more difference. Hence doubling both wavelengths/link and the dimension makes more differences than the other doublings.

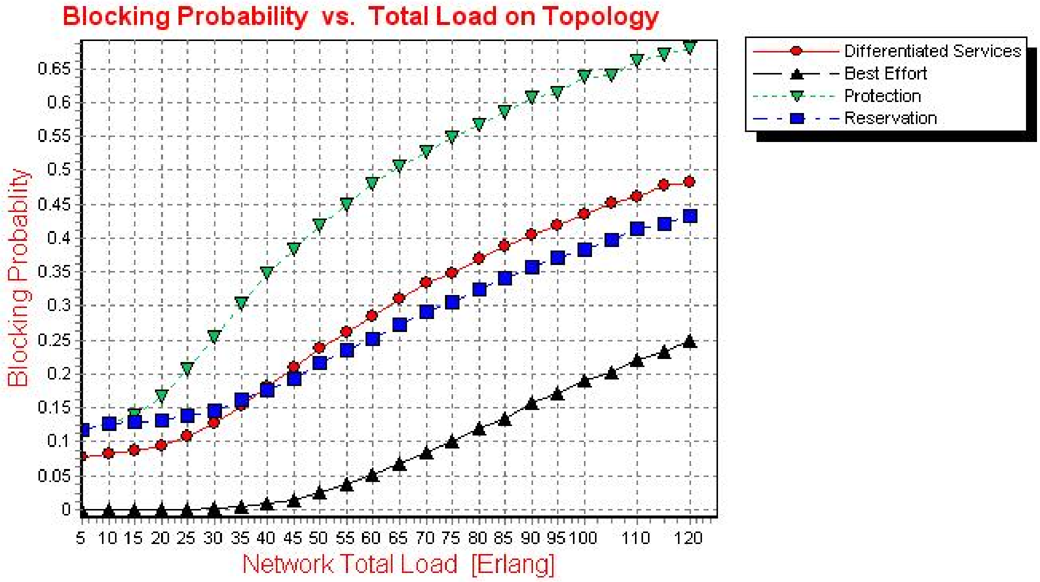


Figure 21 Performance on Torus with Dimension=4, Wavelength=8, Failure Rate=10, Repair Rate=1

Figure 21 shows the results for torus topology with dimension=4, wavelengths/link=16 results. In this case, we increased the failure rate to 10 from 0.01 to measure the performance under frequent the failures. Approximately, all three services have differences between 5 and 10 Erlangs compared to the results obtained before (Figure 17). This is due to increase failure rate. That is, the probability of a lightpaths' path coincides with the failed link is increased. Under low load, the reservation service has more blocking than the differentiated services. This may be because of that the resource sharing is hard initially. When load increases, lightpath request arrivals between failures increase. Therefore the reservation services have better blocking probability then the differentiated services.

CHAPTER 4

CONCLUSIONS

In this thesis, performance of class of service differentiation with the protection, the reservation and the best effort services on survivable all-optical networks was investigated. We have made series of the simulations on selected topology, which NxN torus and ring topology, consisting of wavelength selective optical cross connects. We have changed the variables such as wavelengths/link, dimension in simulations to measure how the blocking probability is affected.

We have tried to show that, the blocking probability of the lightpath requests are reduced when the protection services is not used for all lightpath requests. The best effort service is the best choice according to the blocking probability. However, it does not guarantee 100% restorability. Hence, for the survivability point of view, it is not feasible to choose the best effort for all lightpath requests. If all lightpath requests behave as if they have the protection services, it is waste of resources. Because, there are lightpath requests that do not need to be protected. According to simulation results, we see that the differentiated service's blocking probability is better than the protection services, as expected. These results may show that instead of using the reservation services, differentiated ones may be the choice since its blocking probability is close to the reservation service's one. The differentiated services can also serve the protection service requests unlike the reservation-only services. If the only reservation service is given on a network, the protection service request cannot be served. It is obvious that the reservation service has better blocking probability than the differentiated services. However, with some concessions on blocking probability, the differentiated services may be replacement of the reservation services. Hence, by differentiated services, not only we may gain some performance on the blocking probability but also all requested services can be served.

Our works have shown that changing wavelengths/link number and dimension may make some positive effects on the blocking performance of the class of service differentiation. Doubling the wavelengths/link number increases the performance between 2 and 4 times more in ring and more than 2 times in torus for services in our simulations. Doubling the dimension does not make significant changes on torus in our simulations. It is about 1 ½ times more. For ring topology, increasing the size indeed does not affect the blocking when size is not small since the paths have to traverse all links between source and the destination node in our simulations. For the other topologies, similar results may be obtained in the direction of our results.

In the future, real (or random) network topologies can be used and simulation can be done on these. This provides the performance of a real network under the class of service differentiation. Although ring topology is used frequently, mesh networks are usually connected arbitrarily rather than NxN torus topology. In addition, wavelength interchangeable networks can be studied and comparison with wavelength selective networks can be made. It is clear that WI networks will have less blocking probability than WS networks according to works in the literature, which are done in the past. However, one should analyze the benefits of service differentiation on such networks. Also instead of using 2-alternate path, it can be worked on k-alternate paths (except the ring topology since it is not possible to find more than two link disjoint alternate paths). Performance can be measured with changing the number of predefined alternate paths. Lightpath arrival distribution may be more bursty as in the real life. This necessitates more realistic traffic generation. We treat the arrival rate of requests for the different kinds of services equally. However, weights of the distribution can be changed according to real data.

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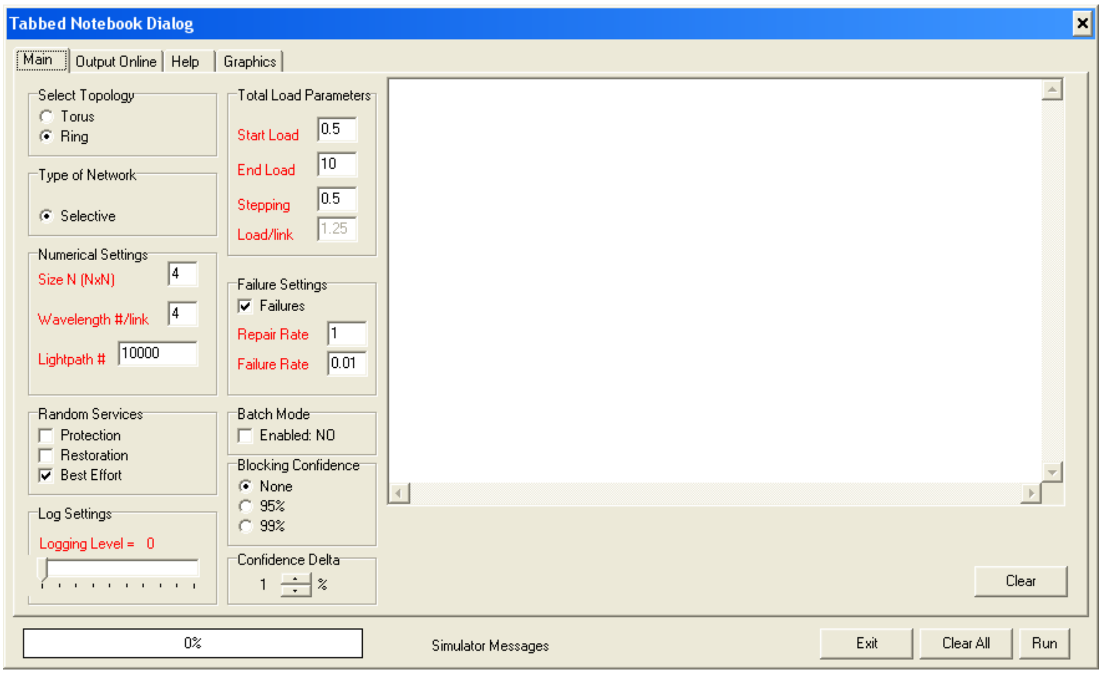
APPENDIX

SCREEN SNAPSHOTS OF SIMULATOR



Select Topology
○ Torus
● Ring

Type of Network
● Selective

Numerical Settings
Size N (NxN) 4
Wavelength #/link 4
Lightpath # 10000

Random Services
☐ Protection
☐ Restoration
☑ Best Effort

Log Settings
Logging Level = 0

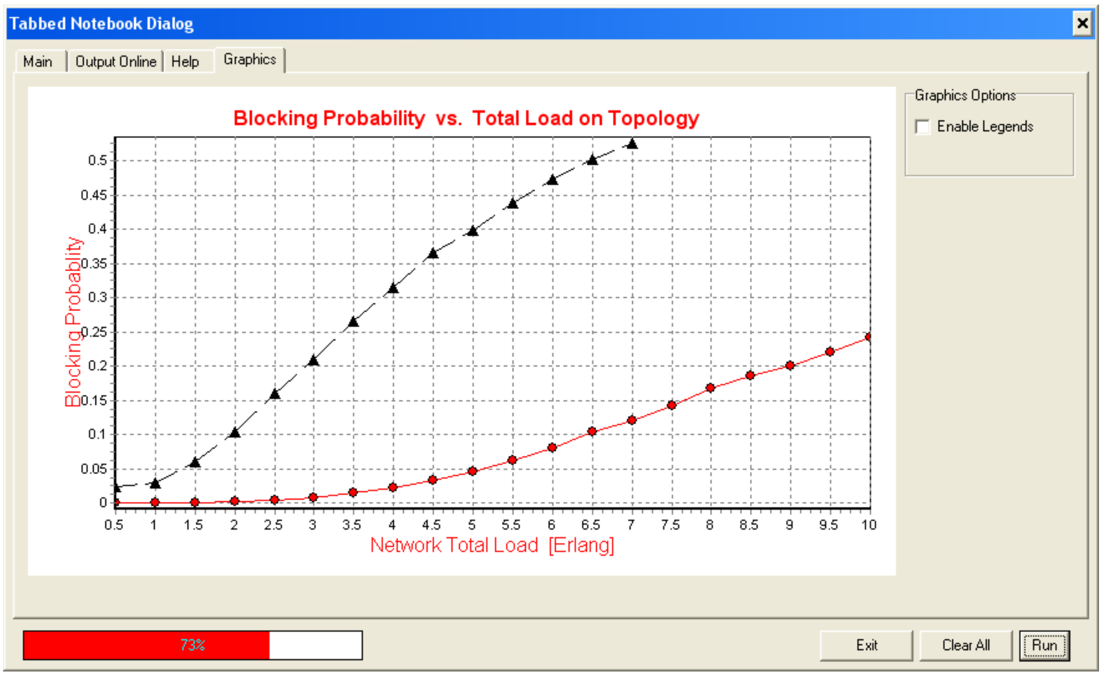
Total Load Parameters
Start Load 0.5
End Load 10
Stepping 0.5
Load/link 1.25

Failure Settings
☑ Failures
Repair Rate 1
Failure Rate 0.01

Batch Mode
☐ Enabled: NO

Blocking Confidence
● None
○ 95%
○ 99%

Confidence Delta
1 %


Tabbed Notebook Dialog
Main
Output Online
Help
Graphics
Blocking Probability vs. Total Load on Topology
Blocking Probability
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
Network Total Load [Erlang]
Graphics Options
☐ Enable Legends
73%
Exit
Clear All
Run