OPTIMIZING ROUTING AND WAVELENGTH ALLOCATION IN OPTICAL CORE NETWORKS

By

Jagrati Shringi

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Committee:

Name	**Accept**	**Department**
Dr. Prashant KrishnaMurthy	____________________	Information Science and Telecommunications
Dr. Joseph Kabara	__________________________	Information Science and Telecommunications

Major Advisor:

Dr. Richard A. Thompson ____________________ Information Science and Telecommunications

Date: ____________________________

DIST Chair: ___________________________ **Date:** ____________________________

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Chapter 1

Introduction

Optical Networks and Wavelength Division Multiplexing are promising candidates for the future wide-area backbone networks. By using the WDM technique such networks make use of the enormous bandwidth of an optical fiber. WDM divides the tremendous bandwidth of a fiber in to many non-overlapping wavelengths (or wavelength channels) which can operate simultaneously, with the fundamental requirement that each of these channels operate at different wavelengths, with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak electronic speed. Thus, by allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge fiber bandwidth, with the corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms.

WDM technology is being extensively deployed on point-to-point links within transport networks in the United States, while WDM point-to-point links are soon to be deployed within Europe[16] .WDM promises advantages for switching and routing as well as for transmission, with the advent of recent advances in optical technologies like optical cross-connect that are currently being developed which can switch an entire wavelength from an input fiber to an output fiber so that large-bandwidth circuits can be routed through the network according to wavelength. High-speed, fixed-bandwidth, end-to-end connections called lightpaths can then be established between different nodes. Networks which use optical cross-connects to route lightpaths through the network are referred to as wavelength-routing networks. Wavelength-routing optical core networks are expected to evolve from the existing separate WDM transmission systems to form optical layers in future transport networks. The advent of Dense WDM (DWDM) in optical networks has further increased the bandwidth available on a single fiber. [16]

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1.1 Routing and wavelength Assignment

In a wavelength –routed WDM network, a channel may be established from a source node to a destination node and it may span multiple fiber links. End-users are connected with one another via all-optical channels referred to as light-paths that require no processing or buffering at intermediate nodes and preferably no intermediate electric/optic conversion. Routing and wavelength assignment algorithms, for establishing this light path can optimize transmission bandwidth over fiber infrastructure so that DWDM network users can get maximum throughput through optically multiplex channels. The RWA problem can be formulated as follows: "given a set of light path that need to be established on the network, and given a constraint on the number of wavelength, we need to determine the routes and wavelengths that should be assigned to the light paths so that minimum light-path blocking probability is achieved." [2] .Optimized routing and wavelength assignment can result in improved performance, eliminating conversion delay, possible signal degradation and also reducing the number of converters needed in network. Another problem that careful allocation can solve is waste of the bandwidth caused by not-fully loaded links.

1.2 Thesis overview

This study paper proposes a heuristic algorithm for the problem of establishing the set of efficient light paths for a given set of connection requests. The effectiveness of the proposed heuristic algorithm is demonstrated by simulation. This study divides the routing and wavelength allocation process in two step problem with a goal of minimizing
Number of wavelength channel and number of wavelength conversion required. The results obtained show that a significant reduction in blocking probability is possible with proposed solution. Number of converters required in a network for a targeted probability of blocking is also seen to be lower compared to current best-result algorithms. This thesis takes the paradigm used for solving this problem from link level to network level. This thesis shows that significant

improvement in performance can be obtained by making use of comprehensive knowledge about the network.

1.3 Thesis outline

This thesis is organized as follows. Chapter 2 provides relevant background on WDM networks and currently studied RWA schemes. In chapter 3 we discuss what serve as a motivation to pick this problem for our study. Chapter 4 proposes details of proposed mechanism, and a mathematical solution in chapter 5. The performance analysis of the proposed schema is presented in chapter 6. Future research direction has been studied in chapter 7. Chapter 8 concludes this thesis.

Chapter 2

Background

The focus of our study is to devise an efficient routing and wavelength allocation scheme. This chapter compiles background required for the study, starting from architecture of WDM network, types of WDM network, traffic characteristics of optical network, and Routing and wavelength allocation algorithms.

2.1 Wavelength Routed network

Fig 1 shows the general structure of wavelength –routed network. These optical networks are consist of interconnected wavelength routes .The wavelength router in responsible for multiplexing an de-multiplexing of wavelength channels sp that the wavelength as the incoming port can be routed to desired output ports . Figure 2 shows architecture of a basic wavelength router. [12]

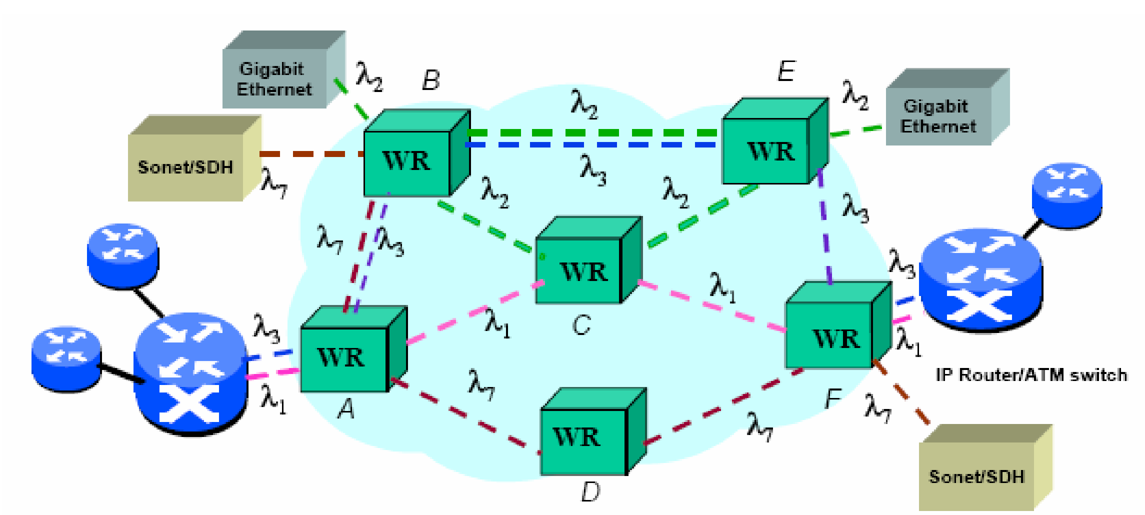


Figure 1: A general wavelength routed network

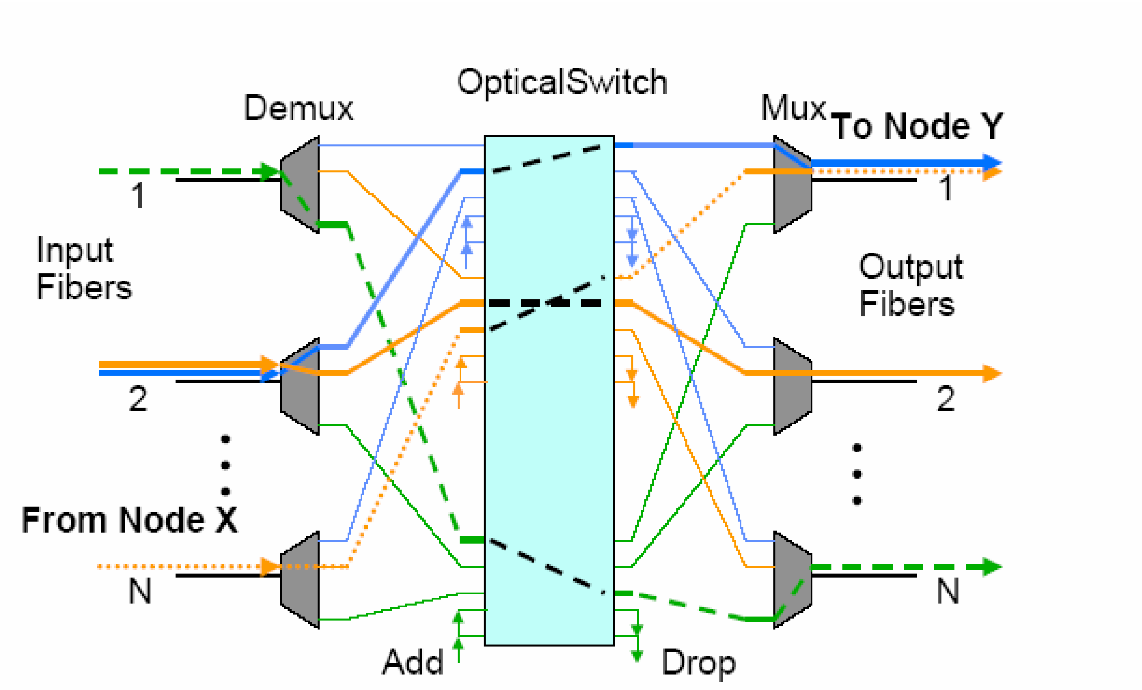


Figure 2 A: architecture of the wavelength routed network

An access node can transmit signals on different wavelength which are coupled into fiber. In the wavelength-routing architectures, the optical switching nodes are equipped with passive wavelength-selective components which, based on wavelength, can select a signal from one of its input port and can route that signal to a different output port.

In all-optical networks, a certain number of optical connections or light paths are established between the desired source-destination node pairs. Each optical connection provides a dedicated path between its two end points via one of the available wavelengths. The optical connection may be routed via several passive wavelength routers before reaching the destination. However, the information travels in optical format throughout the optical connection without undergoing any Intermediate electro-optic conversion or other processing. The primary goal in such networks is to maximize the number of light paths that can be established from a given set of desired connection and for a given network configuration.

Processing and storage of information in optical domain is not near the electronic processing and storage capabilities. Therefore, photonic switching is better suited for the transport layer where routing can be done at the level of multi-gigabit wavelength channels instead of individual packets or individual electronic circuits. Electronic packet or circuit switching operations (*e.g.,* ATM switching) can be performed at the network access nodes in the electronic domain.

Advantages of wavelength routed network:

The major advantages of the wavelength routed network can be summarized as:

- Very high capacity and flexibility of capacity increase without the high first cost experienced with as provided by the optically switched Wavelength Division Multiplexing (WDM) technology.

- Smooth, future proof, migration path from present transport networks to future data centric networks due to flexibility to various data formats and bit rates.

- Seamless integration with present IP network when coupled with GMPLS control plane

2.1 Routing and Wavelength Assignment Problem

The problem of Routing and wavelength assignment becomes very critical in WDM routing networks. In these networks the goal is to maximize throughput by optimally assigning routes and wavelength to a given traffic pattern. The RWA problem can be generalized as an optimization problem in a number of ways using various cost function

Routing algorithms are classified as:

1 Fixed Routing:

The connections are always routed through fixed route for a given source-destination pair. One example of such an approach is fixed shortest path routing. The shortest path route for each source and destination pair is calculated offline using standard shortest path algorithms such as Dijkastara's algorithm.

2. Fixed alternate routing:

In fixed alternate routing multiple fixed routes are considered when a connection request comes .In this approach each node in network is required to maintain a routing table that contains an ordered list of a number of fixed routes to each destination routes. On receiving a connection request all paths are searched, until the connection is successfully established.

3. Adaptive routing:

In adaptive routing the route from source node to destination node is chosen dynamically, depending on the network state .the current network state is defined by the connections that are currently under progress, traffic condition of the network and link health

Proposed Wavelength Allocation schemes

Some of the proposed wavelength-assignment algorithms are:

1. Random wavelength assignment allocates a new connection to a wavelength which is randomly chosen from among the set of available wavelengths.
2. First-fit wavelength assignment is implemented by predefining an order on the wavelengths. Wavelengths are searched in this order and a new connection is established on the first available wavelength.
3. Most-used wavelength assignment, also referred to as the pack scheme allocates a new connection to the wavelength that is used on the greatest number of fibers in the network. If several available wavelengths share the same maximum usage, the wavelength with, say, the

lowest index is chosen. If instead of using the most-used wavelength, we allocate a connection to the least-used wavelength, we implement least-used wavelength assignment.

4. The Maxsum wavelength assignment attempts to minimize network blocking by minimizing the effect of establishing a new connection. Using the MaxSum algorithm, the effect of establishing a new connection is measured in terms of the number of routes whose capacities decrease by one .[16]

2.3 Static and dynamic networks

A number of RWA studies reported so far can be either categorized as static schemes or dynamic schemes. Both of these schemes have their pros as well as cons, as most of the network requests do not consume a full light-path; dynamic routing suffers from problem of poor utilization and latency. Static routes through all network nodes, though improve latency, but are too expensive in terms of resources to be practical. In static routing algorithms the routing procedure does not vary with time and the route(s) for a given source-destination pair is predetermined. In dynamic routing algorithm on the other hand, the routing procedure can vary with time. This algorithm selects a route best suited for current network conditions. Traffic prediction also plays a vital role in deciding the scheme to deploy.

Now as the bandwidth provided by a single light path is expected to far exceed the requirements of most individual calls, light paths may be used to carry a single high-bandwidth call established between two individual users, or for most cases stream of traffic from many different users electronically multiplexed in the time domain. The users of a WDM transport network could be electronic switching equipment, such as SONET/SDH cross-connects, ATM switches or IP routers, or individual workstations or video servers.

The routing algorithm selected for these kinds of networks predominantly depends on traffic predictions. The extent to which light paths are dynamically established due to time-varying fluctuations in the traffic demand is an important issue in network design and analysis, and is dependent on the bandwidth requirements. As discussed above, the bandwidth of individual calls is significantly less than that of a single light path, and then large numbers of calls may be time-division multiplexed onto each light path. Depending on the rate at which overall traffic demand varies, the lightpaths may remain relatively fixed over time, with only occasional changes in the lightpath allocations for restoration (fault recovery) or to follow slowly changing mean traffic requirements through the course of a day. Thus, the traffic offered to a wavelength-routing network would be effectively static, with lightpath requirements fixed over time, although there would be dynamic “burst” of data traffic, which would require lightpaths established on demand. In a realistic network we may expect some combination of both of these cases -- some lightpaths being established semi-permanently, while others are established and torn down as calls are offered and depart from the network. [16]

Dynamic WDM networks may perform online or offline routing. In offline routing, all of the lightpath requests to be routed are known in advance, and the optimum routes and wavelength assignments are determined. If a new lightpath is to be included in an existing set of lightpaths, the wavelength assignments for all lightpaths may need to be recomputed and existing lightpaths rearranged. Optimized wavelength assignment can thus be achieved. However, it may not be practical to rearrange existing established lightpaths. In contrast, networks using online routing establish new lightpaths without changing the wavelength allocations of existing lightpaths, and are better suited for networks with high capacity links. A better optimization could be obtained by coupling dynamic online routing with static routing algorithm. In this scheme a complex static routing algorithm can be deployed for initial path-set-up, leaving maximum resources for dynamic paths. This scheme would reduce the complexity of dynamic allocation there by reducing latency in time critical dynamic paths.

Chapter 3

Motivation

The inner core of Wavelength routed network is expected to be highly interconnected mesh. In this high capacity core network carrying traffic multiplexed from many users, one would not expect the mean traffic flow along routes to fluctuate by large amounts in short times. Accordingly we propose that the traffic static routes should be configured in the inner core, using a static routing wavelength allocation scheme for better allocation and utilization of resources: wavelength channels and wavelength converters.

While designing static routing schemes, the prime objective is to minimize the number of wavelength in order to maximize the number of connection accommodated as the number of wavelength is limited. That would serve dual purpose of minimizing the blocking probability of dynamic traffic as maximum wavelength channel would be free to cater dynamic traffic.

The RWA scheme studies so far suffer from generalization of algorithm, and concentrate on per link allocation, rather than per path allocation. These studies do no take into account that unlike dynamic connection, static connection have knowledge about complete set of required routes and as these routes would not be configured and torn; we can support increased latency in route configuration and therefore can sustain complexity of calculating algorithm. Moreover static core network are normally controlled by a centralized network management system, which has complete knowledge of existing connection and this of resources exhausted, resource available and also of the topology of the network. A comprehensive RWA algorithm which makes use of this knowledge can result in much efficient utilization of network resources.

All the solution provided so far for RWA problem for static connection also suffer from being link oriented than path-oriented. The schemes like Random allocation, first fit, least available and max-available, all compute wavelength on one link at a time and the move on to next link of the path. This study shows that significant improvement in performance on network can be obtained by using a scheme that does path-level allocation of wavelengths.

RWA schemes for a given network and traffic matrix is a combinatorial problem .Routing and wavelength assignment problems are tightly linked together, even though it is approximately divided two interrelated sub problems. First, find the route according to some metric. Second, find the availability wavelength to satisfy wavelength constraints. Both sub problems are strongly related and the solution to one problem can not generate the solution to the overall problem. Since lightpaths are the basic building block their correct and efficient establishment is crucial to the successful implementation of optical core architectures. In this study we aim to analyze light path establishment complexity and provide efficient solution for it.

In this work we propose a sequential scheme to minimize the number of wavelength channels while keeping the number of wavelength converter as low as possible. As the first part of problem we deal with routing algorithm with cost function set to minimizing wavelength channels. The second part deals with wavelength allocation, which would minimize number of channels as well as number of wavelength conversion.

Results of the proposed algorithm are compared with result obtained from first-fit algorithm. First available allocation algorithm is chosen for a comparative study as Previous studies [17] have shown that the blocking probability values of the first policy provides an upper bound on blocking probability for traffic requiring multiple hops. As most of the connection on the core network would be multihop paths, amongst the schemes proposed, first available fits best for optical core networks.

Chapter 4

Proposed Algorithm

This chapter narrates the proposed solution to RWA optimization problem. As the number of variables and equation increases exponentially with the size of the network and number of wavelengths on each fiber we use a small 6 nodes mesh network topology to explain the algorithm.

4.1 Routing

Routing approaches for optical networks can be categorized functionally as:

Sequential Algorithm: Sequential algorithm also, called as greedy algorithms, is the simplest one in that the selection for each light-path is done sequentially. This technique does not change the results of the previous algorithms but it considers the result of previous ones. It requires two sub-function selection order and selection rule. The selection rule is a decision criterion to choose one of the available candidates

Combinatorial algorithms: Combinatorial selection technique consider inter-dependency of light-path routing. Combinatorial logic though provides the best result suffer form huge cost of increased computational complexity and reshuffling of the existing connection.

This study proposes a sequential routing algorithm with optimization function set to minimizing number of wavelengths channels used on a single link of the network

This objective function of minimizing the number of wavelengths can be translated into minimizing number of times a link is used in a path establishment .As each link would use precisely one wavelength channel for watch route it is used for. This problem is modeled as a variant of shortest path algorithm with weight assigned to each link according to number of time it is used. At each point we compare total weight of all

Possible paths and select the path with least weight. While making this decision we also parse the list to load-balance all the links of the network. Thus this algorithm is a simple two step problem

First step is a specific case of fixed-alternative class of routing algorithm, where weighted shorts path algorithm is use to compute the available wavelength. These paths are sorted by there weight. As a second iteration each path is studied for its overall affect on creasing number of wavelength channel is use on each link, a route that increases the upper bound on number of channel on any of the link by the minimum amount is then selected as the final route. The route so calculates not only minimizes total number of wavelengths used by the network, but also minimizes number of channels used on any particular link, thus reducing the total number of wavelength channels used by static route. This frees maximum possible channels and after using an efficient wavelength allocation scheme, maximum number of converters of dynamically configured networks. This improves the probability of blocking for both static and dynamic traffic significantly, as appear ant from simulation results.

Sequential approach is selected to avoided lightpath migration. As each path in care network would carry substantial traffic relocation and restoration should be avoided for such network. Sequential approach also has the advantage of giving comparable performance result with much reduced computation and implementation complexity.

4.1.1: Example

To demonstrate the approached and validate the result of following the proposed routing algorithm we take a simple 6 node network .As most of the practical network is asymmetric we would start with a six asymmetric network as shown below:

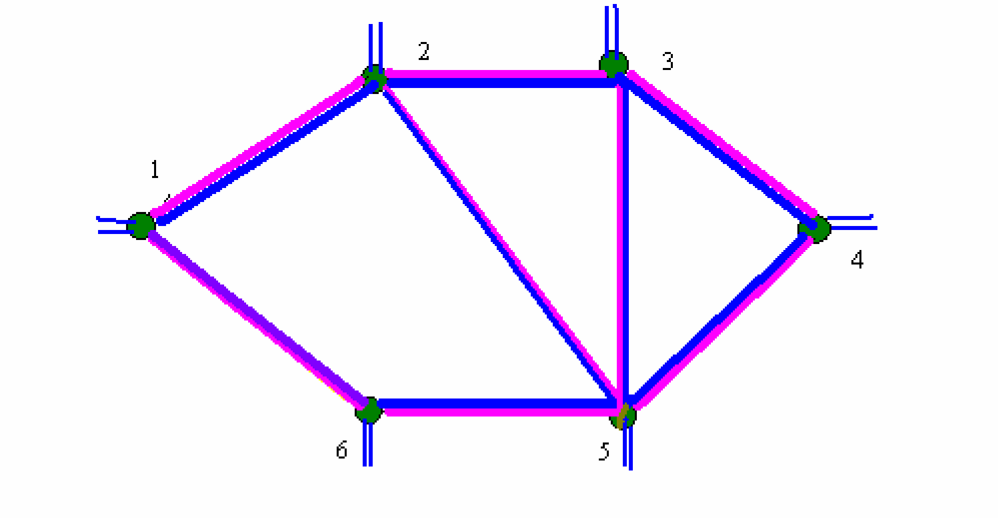


Figure 3: 6 node networks to validate the network model

As these nodes form the statically connected core network, we would assume that each node needs to be connected to every other node. The network above is assumed to have bidirectional fibers running between each pair of nodes. For our path λij would specify the wavelength for channel from source I to destination j. For each node, path to every other nodes are calculated

In this model, any link which has been used for a route would assume weight of 0.5, thus a route using a link that has been used will count it as 1.5 links instead of 1, path selected for a given source to destination would have minimum number of such links.

We will list weight on each link and wavelength used starting with each source node.

Path for node 1:

As there are no already connected routes, computing paths from path node1 to all other nodes is essentially a single step weights shorts path calculation. The table below lists the available paths and weights of each path and finally the selected path for each destination node

Destination Node ID	Available Paths	Weight of each path	Path Selected
2	i. L_{12} ii L_{16}- L_{65}- L_{52}	i)1 ii) 3	(L_{12})
3	i $L_{12}L_{23}$ ii) L16-L65-L53	i)2.5 i) 3	(L_{12})- (L_{23})
4	i)$L_{12}L_{23-L34}$ ii) $L16_{-L65-L54}$	i) 4 ii) 3	L16-L65-L54
5	i)L12-L25 ii)L16-L56	i) 3 ii) 3	L16-L65
6	L16	1	L16

Weight on each link after establishing route to each node from source node:

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5	0.5						0.5			0.5 0.5	0.5 0.5 0.5				

Node 2

Destination Node	Available Paths	Weight of each path	Path Selected
1	i. L_{21} ii L_{16}- L_{65}- L_{52}	i) 2 ii) 5	(L_{21})
3	i)L_{23} ii) L25-L53	i)1.5 ii) 2	(L_{23})
4	i) L_{23-L34} ii) L25-L54	i)3 ii)2.5	L25-L54
5	i)L25 ii)L23-L53	i)1.5 ii)3	L25
6	L21- L16 L25-L56	i) 3.5 ii) 3	L25-L56

Weight on each link after establishing route to each node from source node:

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5	0.5 0.5			0.5		0.5	0.5 0.5			0.5 0.5	0.5 0.5 0.5			0.5 0.5 0.5	

Node 3

Destination Node	Available Paths	Weight of each path	Path Selected
1	i. L_{32} _L21 ii L_{35} – L56 –L61	i) 2.5 ii) 3.5	L_{32}- L_{21}
2	i)L_{32} ii) L35-L52	i)1.5 ii)2	L_{32}
4	i) L34 ii) L35-L54	i)1 ii)2	L34
5	i)L35	i)1	L35
6	i)L35- L56 ii)L34-L45-l56	i)2.5 ii)4	L35-L56

Weight on each link after establishing route to each node from source node:

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5	0.5 0.5	0.5		0.5 0.5		0.5 0.5	0.5 0.5	0.5 0.5		0.5 0.5	0.5 0.5 0.5			0.5 0.5 0.5	0.5 0.5

Node 4

Destination Node	Available Paths	Weight of each path	Path Selected
1	i. $L_{43-L32-L21}$ ii L_{45} – L56 –L61	i) 4.5 ii) 5	L43-L32-L21
2	i)L43-L42 ii) L45-L52	i)3.5 ii)2	L_{45} – L52
3	i) L43 ii) L45-L53	i)1.5 ii)3	L43
5	i)L45	i)1.5	L45
6	L45- L56	i)2.5	L45-L56

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5	0.5 0.5	0.5	0.5 0.5	0.5 0.5 0.5		0.5 0.5 0.5	0.5 0.5	0.5 0.5 0.5	0.5 0.5	0.5 0.5	0.5 0.5 0.5	0.5		0.5 0.5 0.5	0.5 0.5

Node 5:

Destination Node	Available Paths	Weight of each path	Path Selected
1	2 i. $L_{52\text{-}L21}$ ii L56 –L61	i) 4 ii) 3.5	L52-L21
2	i)L52	i)3.5	L52
3	i) L53 ii) L54-L43	i)2 ii)4	L53
4	i)L54	i)1.5	L54
6	L56	i) 2.5	L56

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5	0.5 0.5	0.5	0.5 0.5	0.5 0.5 0.5 0.5		0.5 0.5 0.5 0.5	0.5 0.5	0.5 0.5 0.5 0.5	0.5 0.5	0.5 0.5	0.5 0.5 0.5	0.5 0.5		0.5 0.5 0.5	0.5 0.5

Node 6:

Destination Node	Available Paths	Weight of each path	Path Selected
1	L61	I1	L61
2	i)L56-L52 ii) L61-L12	i)5.5 ii)4	L61-L12
3	i) L65 -L53 ii) L61-L12-L23	i)4 ii)7	i) L65 -L53
4	i)L65-L54 ii)L65-L53-L34	i)5.5 ii)6.5	L65- L54
5	i)L65 iii)l61-L12-L25	i)1	L61-L12-L25

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
0.5 0.5 0.5 0.5	0.5 0.5	0.5	0.5 0.5	0.5 0.5 0.5 0.5	0.5 0.5 0.5	0.5 0.5 0.5 0.5	0.5 0.5 0.5	0.5 0.5 0.5 0.5	0.5 0.5	0.5 0.5 0.5 0.5	0.5 0.5 0.5	0.5 0.5	0.5	0.5 0.5 0.5 0.5	0.5 0.5

Thus with this scheme the maximum wavelength needed is as low as 4. When combined with the proposed wavelength-allocation scheme even higher saving in number of wavelength channel was observed. Effect of using a load balanced scheme become more prominent in large scale networks, as seen with the simulation result. As load is distributed across tall links, this scheme strategically minimizes the number of wavelength used on each link, as a result minimizing total channel we would need to allocate for static path allocation. Unlike the wavelength –allocation scheme described above, the scheme we study takes into account the channel allocation on all the other links, irrespective of their direct involvement in the selected path. With a little price of slightly more complex selection algorithm our scheme provides tremendous saving in resources. As this scheme focuses on finding static paths, we can assume that a central machine would have been the controlling entity of the network and this machine would be capable of storing information about all the links. At the end of this chapter we show compare results obtained by a load-balanced and shortest path routing scheme, with proposed longest continuous path and first-available allocation scheme respectively. The efficiency of this scheme would be more appearing after this comparison.

4.2 Proposed Wavelength Allocation Scheme:

(Longest continuous wavelength scheme)

Once the route has been chosen for each lightpath, the number of lightpaths going through a physical fiber link defines the congestion on that particular link .We need to assign wavelength to each lichgate such that any two lightpaths passing through the same physical link are assigned different wavelength. .A multi-step wavelength allocation scheme has been proposed in this study. As a comprehensive definition of problem we can divide it onto two parts, search and selection. Search is simple since any wavelength can be assigned on a link the bigger and more challenging problem is the selection among available wavelength, which can minimize the wavelength utilization.

This novel strategy that we introduce strategically minimizes the number of wavelength used on each link, thereby minimizing total channel we would need to allocate for static path allocation. Unlike the wavelength –allocation scheme described above, the scheme we study takes into account the channel allocation on all the other links, irrespective of their direct involvement in the selected path. With a little price of slightly more complex selection algorithm our scheme provides tremendous saving in resources. As this scheme focuses on finding static paths, we can assume that a central machine would have been the controlling entity of the network and this machine would be capable of storing information about all the links.

The aim of our wavelength selection algorithm is to find out the most efficient path. As by optimizing selected route we have already minimized upper bound on number of wavelength channel, we can now choose to concentrate on optimizing number of converters. For a hypothetical network having all nodes equipped with optical –converters, we can choose to optimize number of wavelength channels for static paths.
In such cases proposed wavelength allocation algorithm can branch out to "optimize-wavelength" part as shown in the flow chart.

Given that wavelength converters nowadays remain very expensive, making optimum use and limiting the number of wavelength converters becomes an important issue. In real networks wavelength converters are scarce resource. Moreover, the introduction of wavelength converters into WDM cross-connects increases the hardware cost and complexity. A wavelength converter can be defined as a which takes as its input a data channel modulated onto an optical carrier with a wavelength λ_{in}, and produces at its output the same data channel modulated onto an optical carrier with a different wavelength λ_{out}. Wavelength conversion is currently performed using optoelectronic (OE) regenerators. Optoelectronic regenerators convert the modulated optical carrier into a base band electrical signal using a photo detector, regenerate and amplify this electrical signal, and then use it to re-modulate an output laser with the desired frequency (wavelength). If the frequency to which the output laser is tuned is different to the frequency of the input signal, then wavelength conversion is also performed.

From above discussion we can conclude that minimizing number of wavelength converters provide two fold saving. We not only reduce the cost and the complexity of the network, but also reduce the latency by minimizing the O-E-O conversion.

The wavelength allocation proposed significantly save the number of wavelength converters, yet achieves excellent blocking performance.

Proposed algorithm can be explained as sequence of following steps

1. First searches for wavelengths which are available on all links of path calculated by load-balanced routing.
   a) From this set of wavelength channels, select a channel which is being used by maximum number of disjoint links on the network
2. If a wavelength continuous lightpath can not be established on the network, Look for channel available on all the links
3. If wavelength converters is the resource we want to conserve, select longest wavelength continuous sub-path
4. If wavelength channel are scarce resource, select most-used wavelength on disjoint links.

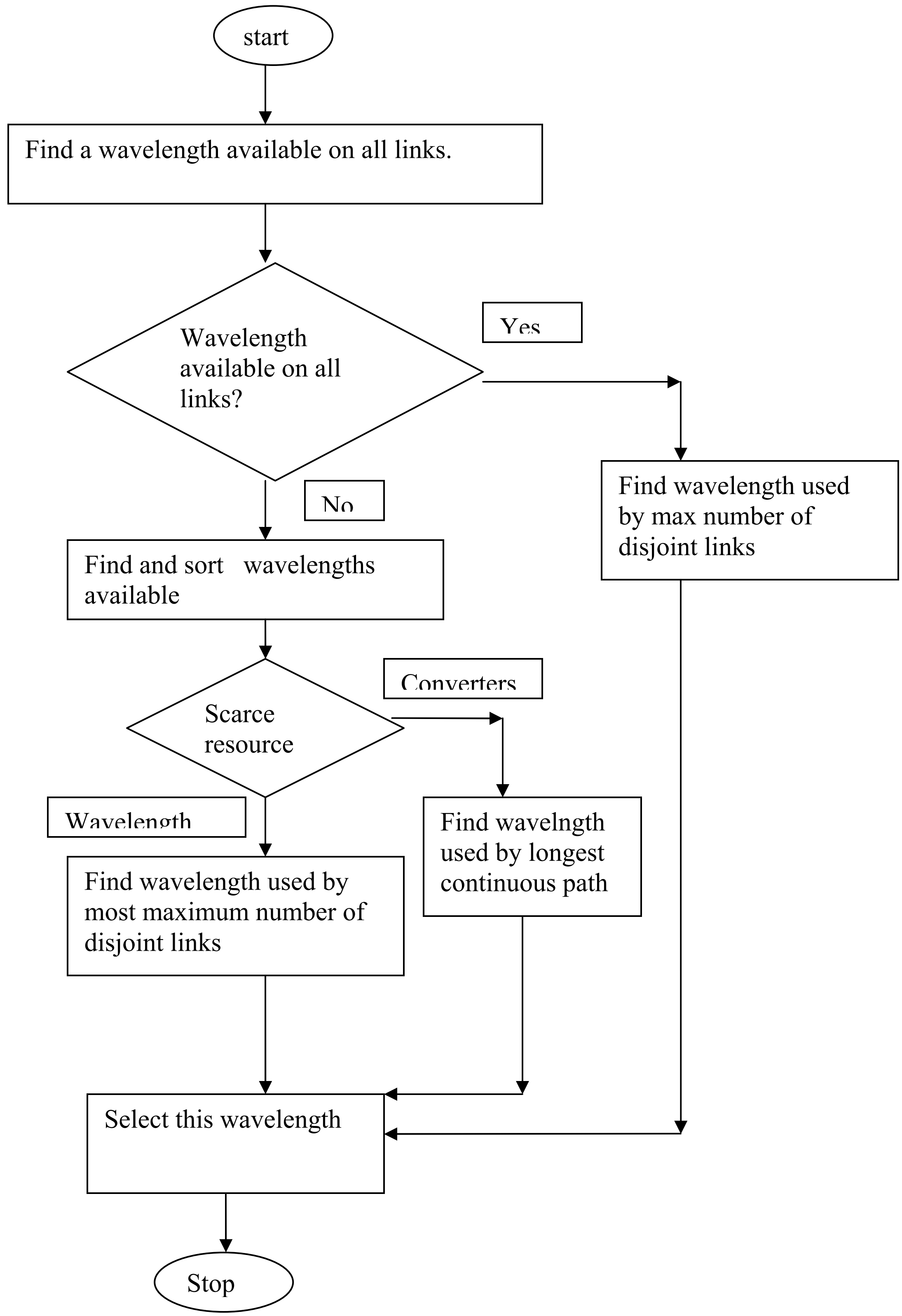
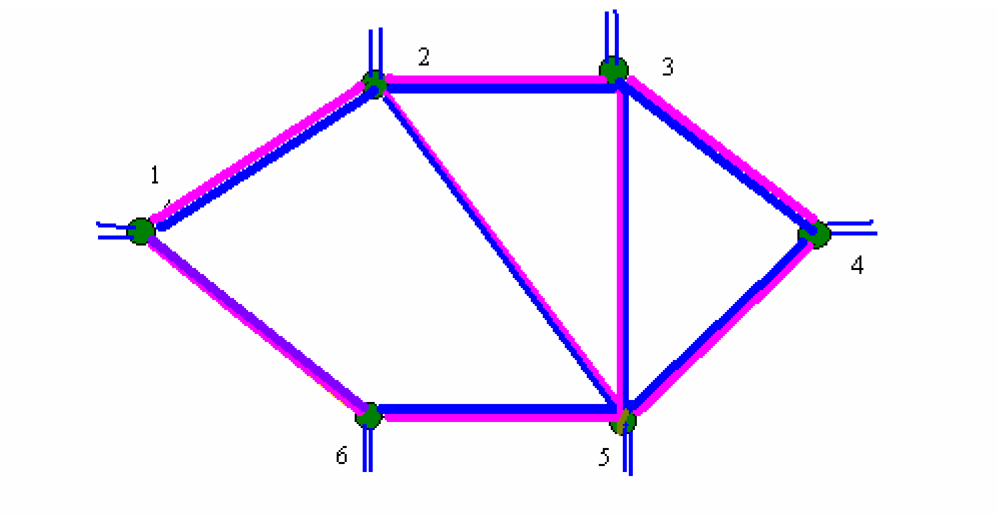


Figure 4: Flowchart of wavelength allocation scheme

4.2.1 Comparison of wavelength allocation schemes:

To compare saving in resources using the proposed scheme, and the first fit scheme, We would again take up our 6 node network.



Assumption taken here are we have a set of 6 available wavelengths (λ1, λ2 λ3, λ4, λ5, λ6). Using the paths selected by Routing algorithm we will apply proposed allocation scheme for routes selected previously by proposed routing scheme. Hand crafted routes using the above allocation scheme is tabulated below for each source and destination pair for the 6 node asymmetrical example network. While calculating this path, our goal for first section is to minimize number of wavelength channels and in second section, to minimize number of wavelength conversions

Source Node 1:

Destination Node	Path Selected	Wavelength channel Selected
2	L_{12}	Λ1
3	L_{12}- L_{23}	λ 2 – λ1
4	L16-L65-L54	- λ1- λ1- λ1
5	L16-L65	- λ2- λ2
6	L16	- λ3

Source Node: 2

Destination Node	Path Selected	Wavelength channel Selected
1	L_{21}	Λ 1
3	L_{23}	Λ2
4	L25-L54	Λ1- Λ2
5	L25	Λ2
6	L25-L56	Λ3- Λ1

Source Node 3

Destination Node	Path Selected	Wavelength channel Selected
1	L_{32}- L_{21}	Λ1- Λ2
2	L_{32}	Λ1
4	L34	Λ1
5	L35	Λ1
6	L35-L56	Λ1- Λ2

Source Node 4

Destination Node	Path Selected	Wavelength channel Selected
1	L43-L32-L21	Λ1- Λ2- Λ2
2	L_{45} – L52	Λ1
3	L43	Λ2
5	L45	Λ3
6	L45-L56	Λ2 –Λ3

Source Node 5:

Destination Node	Path Selected	
1	L52-L21	Λ1- Λ2
2	L52	Λ2
3	L53	Λ1
4	L54	Λ3
6	L56	Λ4

Source Node 6:

Destination Node	Path Selected	
1	L61	Λ1
2	L61-L12- L23	Λ2- Λ3- Λ3
3	L65 –L53	Λ3- Λ2
4	L65- L54	Λ4- Λ2
5	L56	Λ4

As explained above a variant of the proposed least resource wavelength allocation algorithm concentrates on minimizing the number of conversion. This comprehensive scheme searches for longest wavelength continuous path. To achieve the dual purpose of minimizing number of wavelength, we would start our selection with the wavelength already used by links not involved in this path.

For a comparative study we would again take our 6 node network to study this algorithm father:

Source Node: 1

Destination Node	Path Selected	
2	L_{12}	Λ1
3	L_{12}- L_{23}	λ 2 – λ2
4	L16-L65-L54	λ1- λ1- λ1
5	L16-L65	- λ2- λ2
6	L16	- λ3

Source Node: 2

Destination Node	Path Selected	
1	(L_{21})	Λ 1
3	(L_{23})	Λ1
4	L25-L54	Λ2- Λ2
5	L25	Λ1
6	L25-L56	Λ3- Λ3

Source Node: 3

Destination Node	Path Selected	
1	L_{32}- L_{21}	λ 3- Λ3
2	L_{32}	Λ1
4	L34	Λ1
5	L35	Λ1
6	L35-L56	Λ2- Λ2

Source Node 4:

Destination Node	Path Selected	
1	L43-L32-L21	Λ4- Λ4- Λ4
2	L_{45} – L52	Λ1- Λ1
3	L43	Λ1
5	L45	Λ2
6	L45-L56	Λ4 –Λ4

Source Node: 5

Destination Node	Path Selected	
1	L52-L21	Λ2- Λ2
2	L52	Λ3
3	L53	Λ1
4	L54	Λ2
6	L56	Λ1

Source Node: 6

Destination Node	Path Selected	
1	L61	Λ1
2	L61-L12- L23	Λ3- Λ3- Λ3
3	L65 –L53	Λ3- Λ3
4	L65- L54	Λ4- Λ4
5	L56	Λ1

Next section compares this result with widely studied and standard shorts-path/First available RWA scheme

4.3 Shortest path/First available RWA analysis

The shortest path is the most popular algorithm for finding routes from a given source to destination in a network graph. The shortest path algorithm detects and is independent of other selection. An analysis of routes provided by shortest-path (Dijkastra) and number of wavelength used is provided to demonstrate the efficiency of proposed algorithm. The table below shows the result obtained by applying shortest-path algorithm to the 6 node network used in this study.

Destination / Source	1	2	3	4	5	6
1	X	L12	L12-L23	L16-L65-L54	L16-L65	L16
2	L21	X	L23	L23-L34	L25	L25-L56
3	L32-L21	L32	X	L34	L35	L35-L56
4	L43-L32-L21	L43-L32	L43	X	L45	L45-L56
5	L52-L21	L52	L53	L54	X	L56
6	L61	L61-L12	L65-L53	L65-L54	L65	X

Number of times each link is used for the above selection of routes is presented in the table below:-

L_{12}	L_{23}	L_{34}	L_{45}	L_{56}	L_{61}	L_{21}	L_{54}	L_{32}	L_{43}	L_{65}	L_{16}	L_{52}	L_{53}	L_{25}	L_{35}
5	5	4	4	5	3	2	2	4	3	5	1	1	1	2	2

As shown by comparison result, a significant saving is number of channel, number of converters and number of converting node.

Routing and Wavelength allocation Scheme	Number of Wavelength Used	Number of wavelength conversion	Number of converting node
Shortest path/ First available	5	11	4
Proposed Least Resource scheme	**4**	**0**	**0**

Above result obtained for an asymmetrical 6 node network give an indication of how much saving in resources can be obtained using the proposed routing and wavelength allocation scheme. This saving increase exponentially as we increase number of nodes and complexity of the network, as presented in the performance analysis, of a 24 node network.

Chapter 5

Integer Linear Programming Model

One of the most effective ways to analyze, evaluate and optimize a problem is to build computer models of the decision problems. A computer model is a set of mathematical relationships and logical assumptions implemented as a real world optimization problem. The mathematical model of optimization problem involves three elements decision variables, constraints and objective. In our optimization model we have used linear programming (LP), which involves creating and solving optimization problem with linear objective functions and linear constraints.

Network flow models are formulated normally as Integer linear programming problems as if we use the simplex method to solve any minimal cost network flow model having integer constraint RHS value ,then the optimal solution assumes integer value A few ILP formations were studied in [10] ,however the complexity of these approaches have been shown to be NP-complete. In computational complexity theory, NP or Non-deterministic Polynomial time is the set of decision problems solvable in polynomial time on a non-deterministic Turing machine.

This increased complexity limit their applicability to only very small networks .By giving a simple objective function and by segmenting the problem in two parts, our objective is to minimize the time and solve large network problems in acceptable time.

Unlike any other work, we use a spreadsheet modeler for our ILP model. Spreadsheet modeler provides inbuilt optimization tools called solvers that work with constraint and objective to find out an optimized result. For solving an optimization problem using spreadsheet solver, we need to specify the LP constraint and the give it the cell corresponding to the objective function. ILP solvers provide three different algorithms for solving optimization problem, standard nonlinear, Standard Simplex LP and standard evolutionary. As the problem we are solving ,is an LP problem ,solver can use special class of algorithms called as simplex methods .The simplex method provides an efficient was of solving LP problems and therefore requires less solution time .

In this given problem we need to find least expensive path optimizing the number of link used. For our example network our these objective function can be expressed as

MIN: $\sum w_{ij}L_{ij}$, MIN : $\sum nLij$

Using the balance-of-flow rule on each node, for a source and destination pair (1,4) we get following linear relation

-L12 –L13 = -1

L12 –L23-L25 = 0

L23 – L34 –L35 =0

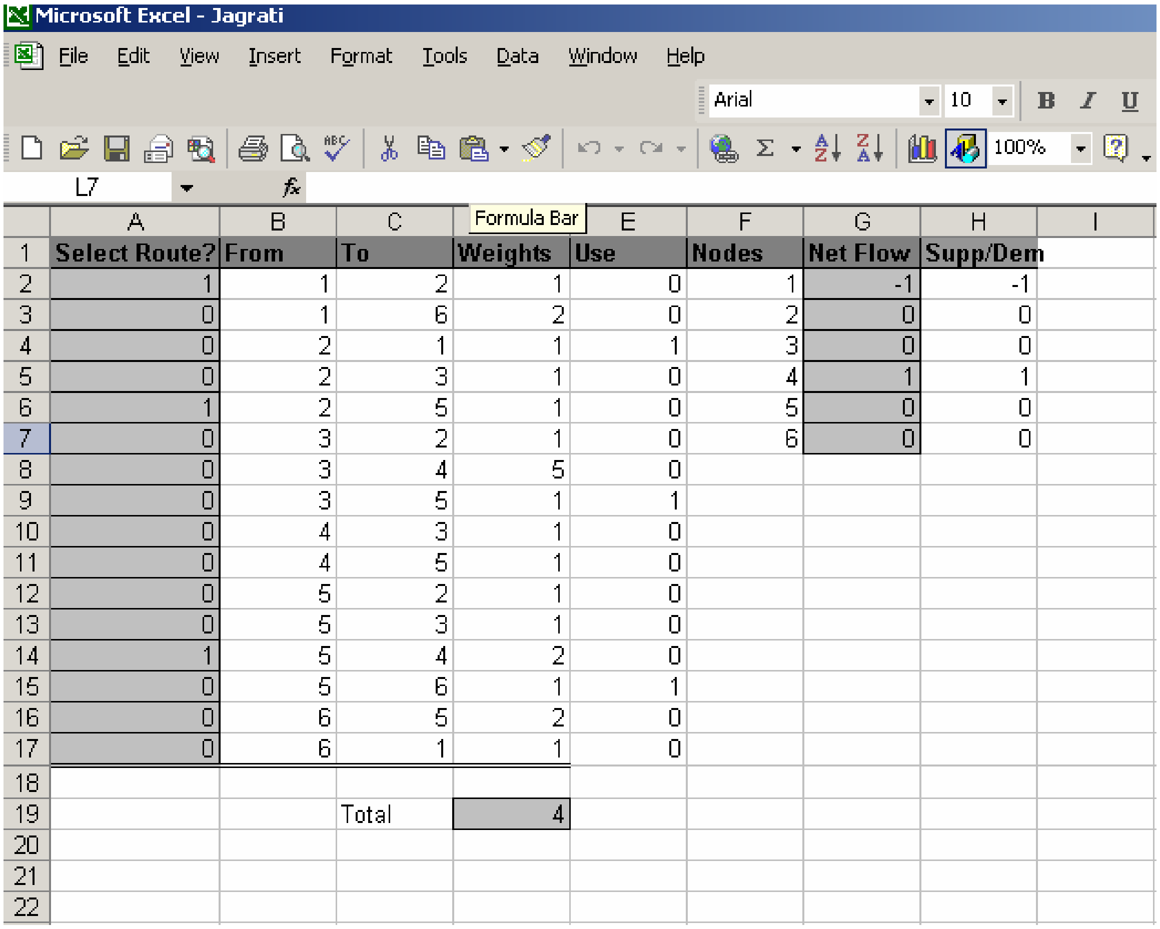
L35+L25+L64- L51 = 0

L16-L65 = 0

L34 +L54 = 1

As the total supply equals the total demand in this problem ,the above constraints are stated as equalities . The first constraint of the model ensures that the 1 unit of supply available to node 2 or 6. The next 4 constraint indicate that anything flowing to nodes 2 ,3,5 and 6 must also flow out of these nodes because each has a demand of). The last constraint indicates that the unit must ultimately flow to node 4. Thus the solution of the problem indicates the least expensive route from node 1 to node 4.

The optimal solution to this problem is shown in figure 5 was obtained using the solver parameters and options shown in figure 6 This model constraints given by both equations and can be used for calculating path for any given source anode destination pair of any topology.



Select Route?	From	To	Weights	Use	Nodes	Net Flow	Supp/Dem
1	1	2	1	0	1	-1	-1
0	1	6	2	0	2	0	0
0	2	1	1	1	3	0	0
0	2	3	1	0	4	1	1
1	2	5	1	0	5	0	0
0	3	2	1	0	6	0	0
0	3	4	5	0			
0	3	5	1	1			
0	4	3	1	0			
0	4	5	1	0			
0	5	2	1	0			
0	5	3	1	0			
1	5	4	2	0			
0	5	6	1	1			
0	6	5	2	0			
0	6	1	1	0			
		Total	4				

Figure 5: Result obtained by ILP formulation

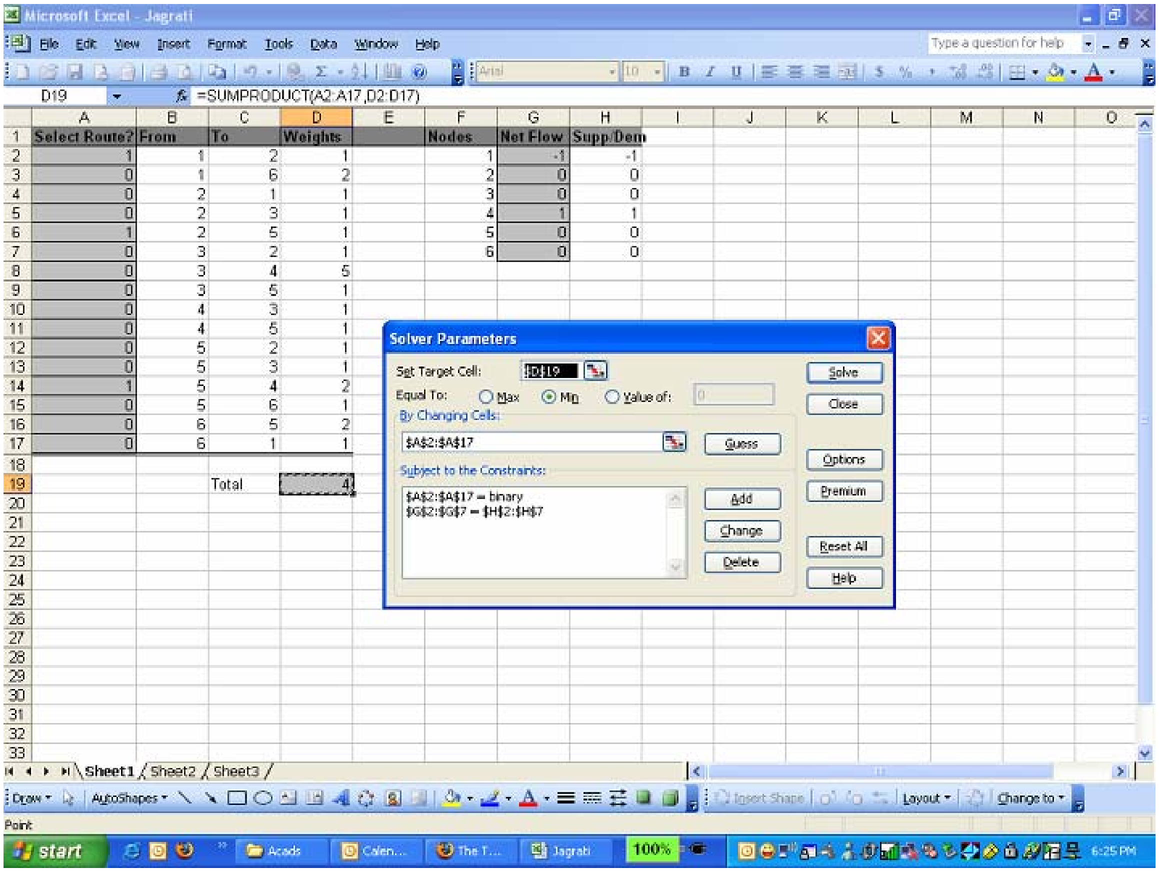


Figure 6: Solver parameter used for ILP formulation

Chapter 6

Performance Analysis

Simulation plays a vital role in network protocol design, providing researchers with inexpensive methods to analyze and study the behavior of proposed protocol models. Network simulators provide a rich opportunity for efficient experimentation. Some advantages of using simulation tools for new and existing protocols are

1 .Improved validation of the behavior of existing protocols

2 Provides a rich infrastructure for developing new protocols.

3 The opportunity to study large-scale protocol interaction in a controlled environment.

4 Easier comparisons of results across research effort

For the sake of comparison with existing protocol, for this study we have selected WDM simulation tool, called optical WDM network simulator based on the ns framework. This simulator reuses existing ns-2 components and provides infrastructure for accommodating new protocol and characteristics. This simulator extends network simulator to incorporate all the characteristics of WDM network Including optical switching nodes, multi-wavelength links, and routing and wavelength assignment algorithms.

This design uses components of ns-2 to include following extensions:

1. Optical switching node – An extension of ns node object, with port classifier and a light path classifier.

2. Multi-wavelength link – This link of the simulator derives from ns-duplex link, with configurable number of wavelength channels...

3. Wavelength Assignment module – This module is responsible for computing wavelength assignment and constructing virtual topologies.

4. Routing Module – Routing modules computes the routes to establish lightpath using specified routing algorithm. New algorithms can be defined by extending this object.

For performance analysis of the proposed wavelength scheme we compare the results of simulation model with shortest path and first-available wavelength allocation scheme.

6.1 Simulation Model:

This section evaluates the effectiveness of the proposed network architecture and the heuristic algorithm by simulation results. In the simulation, the network topology is the ARPANET-like network topology (24 nodes, 50 links, 16 wavelength channel/ Link) which is a standard network for the performance evaluation in the wavelength-routed networks.

We consider an incremental load of L erlangs per node. The load unit erlangs is defined as average connection time/ average connection inter- arrival time. Each connection requests requires uses $n\lambda$, where n ranges from 0.1 – 1. In other words we use variable load connection requests ranging from one-tenth of a wavelength to a complete wavelength channel. All links are allocated equal number of wavelengths. Based on the assumption that 60 % of the wavelength channels would be dedicated for static routes, for this network we have 10 channels. For our simulator network we have assumed that each node is conversion capable. The parameters used varied to compare result is blocking probability of this network against Load and number of conversions. Blocking probability is defined as the fraction of the total connection request that is rejected. The goal is to minimize number of conversion for a given blocking probability. Mean arrival rate and mean session holding time. Traffic session arrival is modeled by a poisson distribution to simulate static traffic, larger holding time has been used. Simulation script included in appendix was used for the network shown below. The first parts defines simulation variable and the second part conducts simulation configuration based on simulation variables.

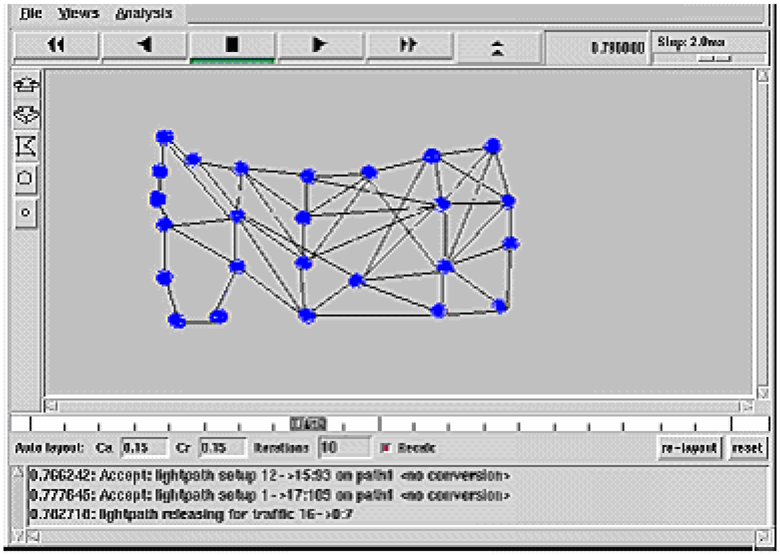


Fig 7: Network used for simulation

6.2 Simulation results

In order to validate proposed RWA scheme, we ran many simulations comparing proposed algorithm to shortest-path/first fit algorithm. Typical results obtained from Simulations are presented below. The result from proposed algorithm are shown by a Solid line while results from shortest-path/first fit algorithm are shown by broken line.

Figure 8 presents blocking probability given by two algorithms keeping number of conversion constant at 10. This figure depicts that proposed routing and wavelength allocation scheme performs significantly better than widely used scheme. With number of conversion restricted to 10, proposed scheme provide an improvement by factor of almost 10 in blocking probability. The two curves see a smoothing effect as traffic increases, as we start approaching the maximum available channels on links. Even for higher loads, a ratio of 7.5 -8 times is maintained.

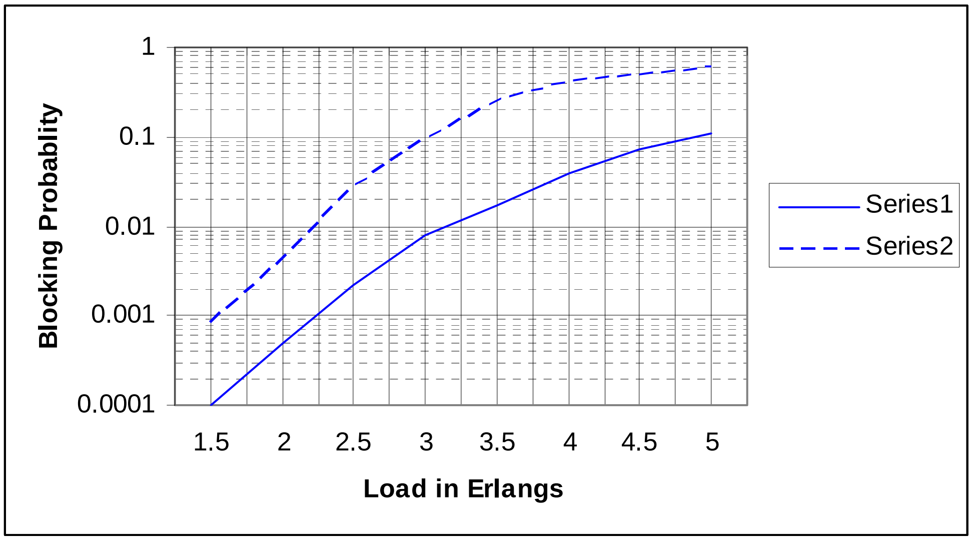


Figure 8: Blocking probability

Figure 9 shows blocking probability for a given number of conversions for a fixed load of 5 erlangs. For an assumed load of 5 erlangs we can also see the saving in number of conversion for same blocking probability. For 2 converters the proposed algorithm at 5 erlangs load gives 0.14 probability of blocking as compared to 0.54 offered by shortest-path/first-fit This further reinforces the reduction in number of converters. The new technique offers same performance for significantly lower number of converters .Also having more than 10 converters does not reduced the blocking probability any further.

Average hop count

Average hop count is plotted for a load range for which the probability of blocking is lower. The average hop count for proposed algorithm starts with a slightly higher, but sees a steeper slope for increasing loads, as the routing algorithm balances number of wavelength channel across the network. The same trend follows for heavier load, for network with a limited number of wavelength converters, longer paths get dropped because of unavailability of wavelength channel for the path, and only shorter paths get serviced. Proposed algorithm continues to serve longer paths and thus the average hop count keeps on increasing. (Fig 9)

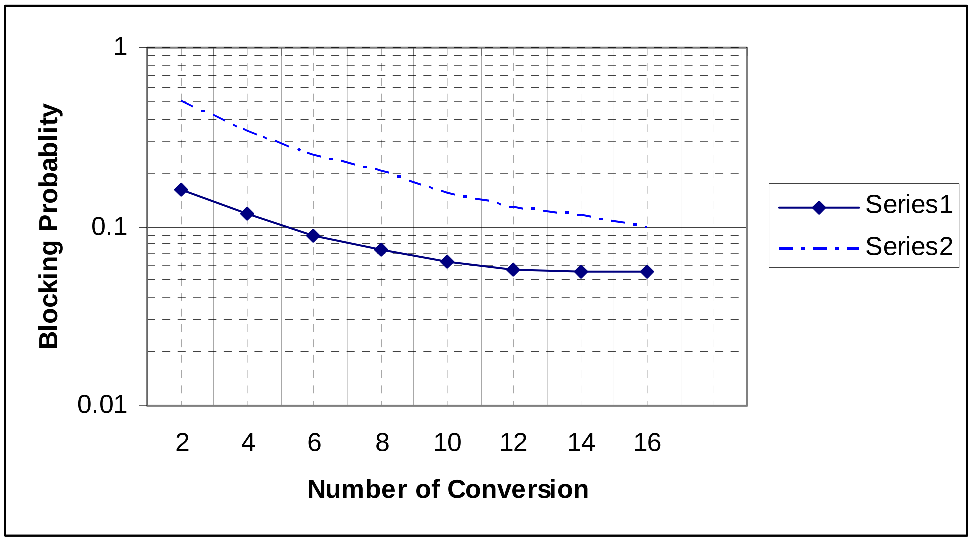


Figure 9: Blocking probability

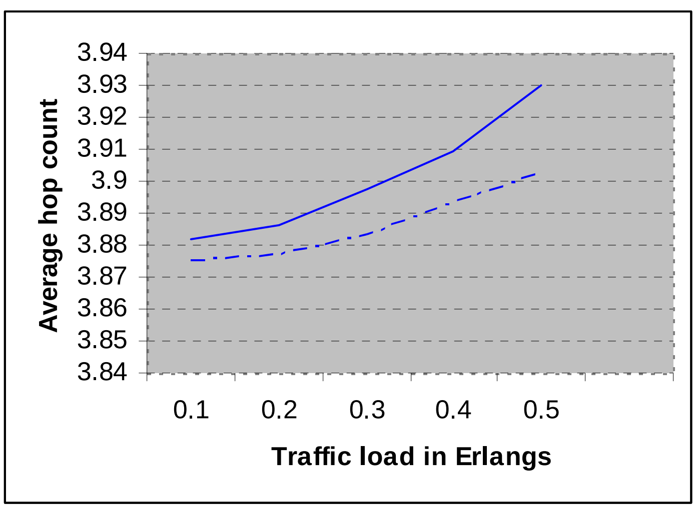


Figure 10: Average hop count

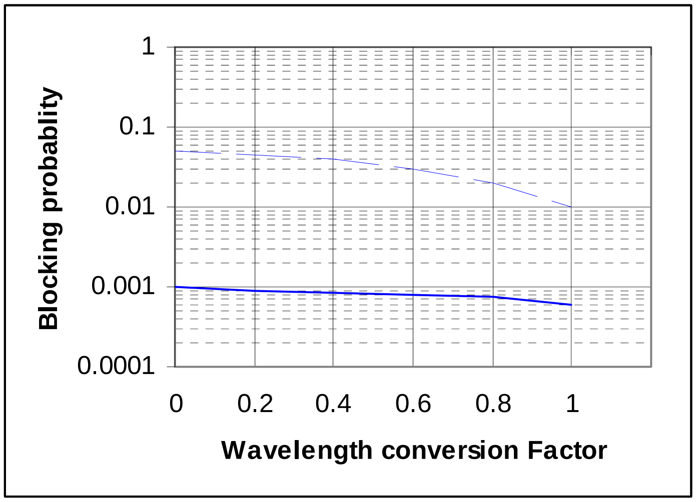


Figure 11: Blocking probability

Wavelength Conversion Factor

Wavelength conversion factor for our simulation is defined as the ration of conversion capable and total node in a given network. As expected increasing number of conversion does not improve the blocking probability for the proposed algorithm by the same factor as it does for shortest-path/first-fit RWA algorithm. Increasing conversion capable node

Does affect performance and increasing wavelength conversion factor, result in a non-linear increase in performance. (Fig10)

6.3 Result Analysis

This performance analysis shows that the combination of the proposed algorithm results in substantial reduction in blocking probability compared to shortest-path/first-fit wavelength allocation scheme, which studies have proved, provides best performance compared to other proposed RWA scheme. Also lower number of converters is required for a targeted probability of blocking. The proposed algorithm also accepts more connection without additional wavelength converters. This would have twofold affect on revenue. Less number of wavelength converters make core network more inexpensive, more number of connection increase the revenue generated.

Chapter 7

Future Work

There are many possible future research directions within this framework. A natural and very efficient extension of the algorithm would be to minimize and conserve channels in a space-time-wavelength router. In this kind of transport network, a connection is established by constructing a time-slot based lightpath between two STW routers. Figure 12 shows a conceptual space time wavelength transport network.

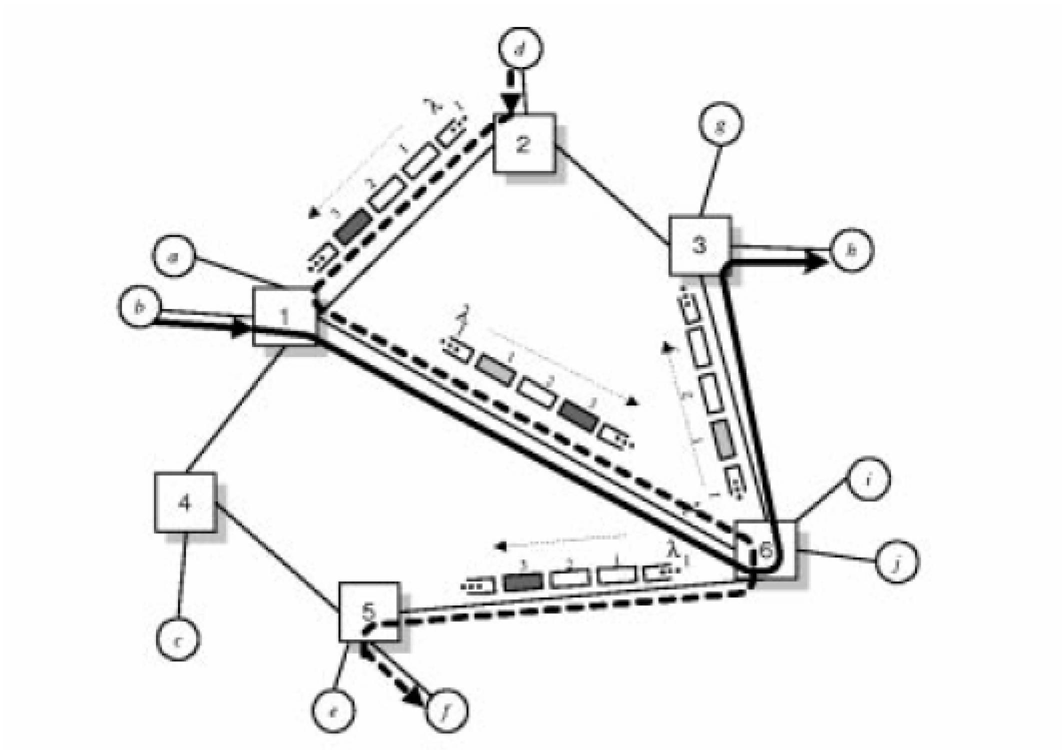


Figure 12 A Space-Time-Wavelength networks

Three dimensions of switching in this network would increase the complexity of RTW allocation problem by manifold; the model presented in this thesis could be extended for preserving resources in this network.

Lightpaths are high-capacity all-optical channels. Hence, when there is a link failure, e.g., an optical fiber cable cut, the data loss may be very large if the traffic is not re-routed quickly. ITU specifies an upper bound of 50 ms on the complete restoration process. In a mesh network, end-to-end path-protection schemes should be employed to achieve efficient resource utilization. The goal is to protect each connection from single-link failures, as well as to minimize the overall blocking probability and end-to-end delays. To focus on the basic problem of path allocation we have omitted establishment of protection path for each connection. This RWA scheme could be extended to include configuration of protection path.

Wavelength converters increase the traffic-carrying capacity of circuit-switched optical networks by relaxing the wavelength continuity constraints. Optimal placement a given number of wavelength converters on a path, to minimize the call-blocking probability, could be studied in conjunction with this algorithm. Affects of this scheme should be studied on dynamic traffic connection from a pair of access point in the core.

Chapter 8

Conclusion

Optical networks using wavelength division multiplexing (WDM) technology have emerged as an attractive solution for meeting rapidly growing demands for bandwidth. WDM allows the same fiber to carry many signals independently as long as each uses a different wavelength. Connections must therefore be routed and assigned to wavelengths such that no two calls use the same wavelength on the same link. This is known as the *routing and wavelength assignment* (RWA) problem. If full conversion is available at all nodes, the WDM network is equivalent to a circuit-switched
network; however, the high cost of wavelength converters often makes it desirable to keep the amount of conversion used in the network to a minimum.

The next generated optical network is predicated to have a “inner core" or the highest hierarchal level of the network, which would predominantly serve quasi static
High capacity traffic. RWA problem becomes even more challenging as network resources should be used to there maximum efficiency to provide least probability of blocking to dynamic traffic burst, typical of data traffic . This core is also expected to be highly interconnected, calling for a very efficient routing scheme. The path established between a source and destination pair is called light-path

Through the introduction of the lightpath concept, the proposed optical core architecture makes use of emerging transmission and switching capabilities in the photonic domain to overcome the inherent limitations of electronics based networks. Since the performance of this architecture is tightly linked to the efficient establishment of light paths, a detailed investigation of the lightpath establishment problem was conducted.

This study addresses an important problem in wavelength routed all-optical WDM networks: how to efficiently utilize a limited number of resources on statically routed optical core. We first formulated a routing scheme to balance channels across the network and then introduce a wavelength allocation scheme to reduce number of wavelength channel and wavelength conversion. Both theoretical and simulation results are presented. By using the proposed routing scheme and wavelength assignment algorithm, only a very small number of wavelength converters are needed to achieve same performance as that of the full-Complete Wavelength conversion. This objective is achieved in the study by evolving the routing and wavelength assignment scheme using very simple and intuitive steps.

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Appendix A
Simulator Script

```
set val(link bw) 16Mb ;# bandwidth of link
set val(result_file) "simulator.res" ;# result file
set val(wvlen_routing) WDMStatic ;# wvlen routing protocol
set val(wvlen_assign) FirstFit ;# wvlen assignment protocol
set val(node_num) 24 ;# total nodes number in network
set val(conn_prob) 0.11 ;# nodes connection prob.
set val(wvlen_routing2) WDMLB ;# wvlen routing protocol2
setval (wvlen_assign2)LongestContinousPath; # wvlen assignment protocol2
set val(link bw) 16Mb ;# bandwidth of link
set val(link wvlen num) 16 ;# wavelengths number on each link
set val(wvlen conv factor) 0.5 ;# wvlen conversion factor, between 0 and 1
set val(wvlen conv time) 0.024 ;# wvlen conversion time (relative time)
set val(traf density) 0.6 ;# generated traffic density in networks
set val(traf arrival rate) 0.5 ;# mean of each session arrival rate
set val(traf holding time) 1.0 ;# mean of each session holdingtime
set val(traf pkt size) 1000 ;# session-traffic packet size
set val(traf pkt rate) 1Mb ;# session-traffic packet arrival rate
set val(traf type) Exponential ;# session-traffic type in network
set val(traf exp burst time) 0.7 ;# expoo traffic average burst time
set val(traf exp idle time) 0.1 ;# expoo traffic average idle time
set val(traf max req) 1000 ;# max traffic requests number
set val(traf start time) 0.0 ;# session-traffic starting time
set val(traf stop time) 0.0 ;# session-traffic stoping time
......


# Create a simulator object
set ns [new Simulator]

# Wvlen routing protocol and assigning mechanism
$ns wrouting-proto $val(wvlen routing)
$ns wassign-proto $val(wvlen assign)

# Generate the topology creation script
topology -outfile $val(topofile) -nodes $val(node num)
-connection prob $val(conn prob) -seed $val(topo seed)
# Generate the traffic creation script
traffic $val(traf type) $val(node num) $val(traf num) $val(traffile)
......


create-traffic ns traffic WDMNode SessionTrafficRcvr $val(node num) $val(traf num)
$val(traf pkt size) $val(traf pkt rate) $val(traf arrival rate) $val(traf holding time)
$val(traf exp burst time) $val(traf exp idle time)

# Schedule session traffics
for set i 0 $i < $val(traf num) incr i
$ns schedule-sessiontraffic $traffic($i) $val(traf start time) $val(traf stop time)

# Schedule ns stop
if $val(traf stop time) > 0
$ns at [expr $val(traf stop time) + 1.0] "finish"
$ns run
set ns [new Simulator]
# Wvlen routing protocol and assigning mechanism
$ns wassign-proto $val(wvlen assign)
$ns wrouting-proto $val(wvlen routing)
$ns run
```

Appendix B
Psuedo Code

Routing Algorithm

```
// Initialization

// Routing
        do d[v] := infinity
           previous[v] := undefined
     d[s] := 0
     S := empty set
     Q := set of all vertices
    while Q is not an empty set
        do u := Extract-Min(Q)
         S := S union {u}
          for each edge (u,v) outgoing from u
              do if (d[v] < d[u] + w(u,v)) && ({ d[v]link < d[u]link))
                 then d[v] := d[u] + w(u,v), w(u,v) += increment
                    previous[v] := u
                    Q := Update(Q)

// Wavelength Allocation Algorithm

      While d[v]
             do if( OR (d[v] linkbitmap )
                   then find λmax in Q not in d[v]
                     break
                   else for d[v]= 0, d[v]->null,d[v]++
                     OR (d[v] linkbitmap, N[i] = number of links ;
                     Get Nmax->λ
                   end if
      end while
```