Distributed Wavelength Assignment
Algorithms and the Traffic Classification and
Service (ClaServ) in Wavelength Routed All-
Optical Networks

by

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**Distributed Wavelength Assignment Algorithms
and the Traffic Classification and Service (ClaServ) in
Wavelength Routed All-Optical Networks**

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Master of Applied Science

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ABSTRACT

The wavelength-routed all-optical networks are apparently the dominant transport architecture of the future because of the high bandwidth requirement of the expanding Internet traffic. In such networks, the end-to-end lightpath must occupy the same wavelength on each link of the path in the absence of wavelength converters; this is known as the wavelength continuity constraint. This constraint deteriorates the network performance in two aspects: the network traffic blocking probability and the fairness problem. Two wavelength assignment algorithms, the Lightpath Neighborhood Weight (LNW), and the Lightpath End Nodes Neighborhood Weight (LENW) algorithms are developed in this thesis to optimize the network performance. The Traffic classification and service (ClaServ) method are proposed to optimize the fairness problem as well as reduce the average traffic blocking probability. The number of hops the traffic traverses from the source node to the destination node classifies traffic. The combination of the waveband access range method and waveband reservation method provides different services to the classified traffic. This thesis studies two types of networks, the 4x4 mesh torus network and the NSFNET, by running the simulation models using the OPNET simulation software. The simulation results show that the LNW and LENW perform better than the First-Fit and Random algorithms in allocating wavelengths in an optical network. The ClaServ method optimizes the fairness problem as well as reduces the network traffic blocking.

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LIST OF ACRONYMS AND SYMBOLS

Acronym

WDM – Wavelength division multiplexing

OEO – Optical-electronic-optical

SONET/SDH – Synchronous optical network/synchronous digital hierarchy

OXC – All optical crossconnects

OADM – All optical add-drop multipliers

RWA – Routing and wavelength assignment

LNW – Lightpath neighborhood weight

LENW – Lightpath end nodes neighborhood weight

ClaServ – Traffic classification and service

Thr – Threshold method

Rsv – Reservation method

WAR – Waveband access range method

WRsv – Waveband reservation method

CU – Control unit

Symbol

λ_i – Wavelength i

$W_i^{T_j}$ – The weight of λ_i on link j at node T

W_i^T – The weight of λ_i at node T

W_i – The weight of λ_i

W_a - The available wavelength with the heaviest weight

Y – Discrete-time data array

θ – Mean of the output data

$\hat{\theta}$ – Point estimator of θ

θ_x – Mean of the output data when the traffic load is x Erlang

$\sigma^2\left(\hat{\theta}\right)$ – True variance of the point estimator $\hat{\theta}$

$\hat{\sigma}^2\left(\hat{\theta}\right)$ – Estimator of $\sigma^2\left(\hat{\theta}\right)$

$\hat{\sigma}\left(\hat{\theta}\right)$ – Standard error of the point estimation $\hat{\theta}$

$t_{\alpha/2, f}$ – The 100(1- α /2) percentage point of a t-distribution with f degrees of freedom

Chapter 1

1 Introduction

1.1 Background and Motivation

Optical networks are those in which the dominant physical layer transport technology is operating upon the optical fiber. They can be opaque or all optical, and can be single-wavelength or multi-wavelength based on Wavelength Division Multiplexing (WDM) technology [1].

In opaque networks, the path between end users is interrupted at intermediate nodes by optical-electronic-optical (OEO) [2] conversion operations. Because this introduces dependencies on bit rate and bit pattern syntax, the expectation of communication transparency is lost. The traditional synchronous optical network/synchronous digital hierarchy (SONET/SDH) [3] is an opaque single-wavelength system.

In all optical networks, each connection (lightpath) is totally optical, or at least totally transparent, except at the end nodes. Recent technology developments in the all optical crossconnects (OXC) [4] and all optical add-drop multipliers (OADMs) [5] are now making the all optical solution quite workable. It stimulates the evolution from simply point-to-point WDM links to full wavelength-routed all-optical networks [6].

The wavelength-routed all-optical networks are apparently the dominant transport architecture of the future because of the following reasons.

First, when exploring the potential bandwidth of a single fiber, the present SONET network will migrate to the WDM network [7].

Second, the asymmetric traffic flows on the Internet will encourage the adoption of the WDM network [8].

Third, the bit rate and packet format will be transparent to the all-optical network.

Fourth, the problem determination and system maintenance of all optical network are much simpler than they are with the traditional fiber-plus-OEO systems. Each signal needs not to traverse several layers of software or firmware and back down again at each intermediate node, accumulating in the process software path length delays and exposure to the many possible failure modes intrinsic in very high-speed electronics.

Fifth, one of the most important reasons is the intrinsic robustness of an all-optical network. The all optical physical layer, which replaces the old one based on copper of fiber-plus-OEO, can provide not only basic transport, but also several other network-wide rerouting functions that allow the optical layer to exhibit extremely high service availability.

One of the challenges involved in designing wavelength routed all optical networks is to develop efficient algorithms and protocols for establishing lightpaths in the optical network. The algorithms must be able to do route and wavelength assignment (RWA) [9] to connections in a manner which efficiently utilizes network resources while maximizing the number of lightpaths that can be established.

In the absence of wavelength conversion devices, the RWA problem operates under the constraint that a lightpath must occupy the same wavelength on each link in its route. This restriction is known as the wavelength continuity constraint [10]. Although there are

all optical wavelength converters proposed recently [11], the adoption of the all optical converters is proved to be a slow, incremental process, a considerable effort has been spend focusing on optimizing the network performance under this constraint [12]. In the following part of this thesis, we consider the situation where no wavelength converters available, thus, the network must fulfill the wavelength continuity constraint.

Because of the wavelength continuity constraint, the connection request for establishing long lightpath (lightpath with larger number of hops) suffers higher blocking probability than the connection request for establishing shorter lightpath (lightpath with small number of hops). The inability of connection requests of longer lightpaths to have an equal blocking probability as connection requests of shorter lightpaths causes the *fairness* problem.

The wavelength routed all optical network is converging to a two-layer communication infrastructure [13] (Fig. 1). The all-optical islands with IP routers are attached to serve end users. The OEOs stitch those islands that are in different jurisdictions together. There is an underlying all optical data plane layer upon which either IP routers lead to higher user-oriented control plane layers or OEO intermediaries lead to the next island. The role of the control plane is to establish, tear down and control the state of a lightpath [14] [15] [16], while the role of the data plane is to carry the information from one node to another. The challenge posed by this architecture is the methodology of constructing end-to-end lightpaths by allocating the wavelengths in the control plane.

In order to setup a lightpath, a signaling protocol [17] needs to run upon the control plane to exchange control information among nodes and to reserve resources along the

path. The signaling protocol is closely integrated with the routing and wavelength assignment algorithms; it must effectively manage the distribution of control messages and network state information in order to establish a connection in a timely manner.

Figure 1. The two-layer structure of wavelength routed all optical networks

1.2 Thesis Objective

This Thesis investigates approaches for optimizing the performance of distributed RWA algorithms for all optical networks in two aspects: Reducing the network traffic

blocking probability and tackle the fairness problem introduced earlier. The traffic is comprised of a set of connection requests arriving at the network.

Many distributed wavelength assignment algorithms were proposed to solve the wavelength assignment problem [6]. They were supposed to adapt to the distributed managed network nature by using distributed global information. However, for all algorithms proposed, due to the size of networks and variability of carried traffic requests, the processing of wavelength assignment should rely on local information. One of the objectives of the thesis is to develop new distributed wavelength assignment algorithm using local information. The second objective is to develop a traffic engineering method to tackle the fairness problem. A distributed signaling control protocol is developed to support the new proposed wavelength assignment algorithm and the traffic engineering method.

For evaluating the performance of the new algorithms and methods, simulation models needed to be built. The OPNET modeler was selected for all simulations in this thesis.

1.3 Thesis Outline

This Thesis is organized as follows: Chapter II gives the introduction of the Routing and Wavelength assignment problems. The routing problem is introduced, along with the wavelength assignment problem, fairness problem, and the signaling problem in all optical networks. Chapter III gives the introduction of the Lightpath Neighborhood

Weight (LNW) and Lightpath End Node Neighborhood Weight (LENW) wavelength assignment algorithms. In Chapter IV, the Traffic Classification and Service method (ClaServ) is introduced. The ClaServ signaling protocol and simulation models are introduced in Chapter V. The simulation results analysis and performance evaluation are presented in Chapter VI. Finally, conclusion and future research are introduced in Chapter VII.

1.4 Thesis Contributions

The first contribution is the development of the Lightpath Neighborhood Weight (LNW) and Lightpath End Nodes Neighborhood Weight (LENW) algorithms to optimize the network performance with local information. For assigning wavelength to a given path, the two algorithms only consider the wavelengths' occupation information in the lightpath's neighborhood. We show that compared with the first-fit and random algorithms, the LNW algorithm reduces the blocking probability by 10 times for both the average traffic and the 4-hop traffic in the 4x4 mesh torus network when the network is required running with small blocking probability (a practical situation). The normal traffic is the traffic that has not been classified in the network. The 4-hop traffic is the traffic that traversed 4 hops from the source node to the destination node. The n-hop traffic is the traffic that traversed n hops from the source node to the destination node. The LNW and LENW algorithms only slightly complicate than the First-Fit and Random algorithms, require a little more processing time and packet overhead.

The second contribution is the development of the Traffic Classification and Service (ClaServ) Protocol to address the fairness problem as well as reduce the network blocking probability. The traffic requests are classified depending on the number of hops that are traversing from the source to the destination. The combination of the waveband access range and waveband reservation provides different level of service to the classified traffic. The simulation results show that when the small blocking probability is required (around 10^{-4}), under a 4x4 mesh-torus topology, the ClaServ method can reduce the blocking probability 100 times for 4-hop traffic, 4 times for 3-hop traffic, and 20 times for the overall network traffic; under a NSFNET topology, the ClaServ method can reduce the blocking probability 50 times for 4-hop traffic, 2 times for 3-hop traffic, and 10 times for the overall network traffic. (For complete details, the reader should refer to chapter 4 , and 6)

The third contribution was to implement the LNW, LENW algorithms and ClaServ approach into one signaling protocol. The ClaServ protocol can also support the first-fit algorithm and the random algorithm.

The Fourth contribution was to develop and build the simulation models upon the network simulator OPNET. The process models are programmed with C/C++ language.

Chapter 2

2 The Routing and Wavelength Assignment (RWA) Problem

The problem of finding a route for a lightpath and assigning a wavelength to the lightpath is often referred to as the routing and wavelength assignment problem (RWA). The objective is to route lightpaths and assign wavelengths in a manner that minimizes the amount of consumed network resources, while at the same time ensure that no two lightpaths share the same wavelength on the same fiber link. In the absence of wavelength conversion devices, the RWA problem operates under the constraint that a lightpath must occupy the same wavelength on each link in its route. This restriction is known as the wavelength-continuity constraint. Figure 2 illustrates a wavelength-routed network in which lightpaths have been set up between pairs of access nodes on different wavelengths to satisfy the wavelength-continuity constraint. Assume that wavelength λ_1 has already been assigned to the lightpath for the connection from source node A to destination node C. When a request arrives to source node B, requiring a connection to destination node D, wavelength λ_2 is assigned to the lightpath of this connection because λ_1 has already been occupied in one of the links on the path. Wavelength λ_1 can be

assigned to the lightpath for the connection from source node F to destination node E because λ_1 is idle on each link of the path.

Figure 2. Wavelength continuity constraint

The optimal formulation of the RWA problem is known to be NP-complete [18], therefore, heuristic solutions are often employed to solve this problem. The RWA problem can be considered under two different traffic assumptions. The static RWA problem applies to the case in which the set of connections is known in advance, and a lightpath must be established for each connection. In the dynamic RWA problem, connections arrive to the network dynamically and remain for some amount of time

before departing; thus, lightpath not only has to be established dynamically, but also be taken down dynamically. This thesis studies the dynamic RWA problem and finds the solutions to this problem.

When lightpaths are established and torn down dynamically, routing and wavelength assignment decisions must be made as connection requests arrive to the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. The connection may also be blocked if there is no common wavelength available on all of the links along the chosen route. Thus, the objective in the dynamic situation is to choose a route and a wavelength, which maximizes the probability of setting up a given connection, while at the same time attempts to minimize the blocking probability for future connections.

The RWA problem can be decomposed into a routing sub-problem and a corresponding wavelength assignment sub-problem. While assigning the wavelength to the lightpath, another problem has to be solved, the fairness problem. The connection requests experience different blocking probability due to the length of the lightpaths they are need to establish. The establishment of a long lightpath experiences substantial higher blocking probability than the establishment of a short lightpath, which is known as the fairness problem. A network control (signaling) mechanism is required to find the path and assign one of available wavelengths to the path. The routing problem, wavelength assignment problem, the fairness problem and signaling in all optical networks is introduced in the following sections.

2.1 Routing Problem

Approaches to solving the routing problem can be categorized as being fixed, fixed-alternate and adaptive routing. The routing approaches could utilize either global or local network state information.

2.1.1 Fixed Routing

In fixed routing, a single fixed route is predetermined for each source-destination pair. When a connection request arrives, the network will attempt to establish a lightpath along the fixed route. If no common wavelength is available on every link in the route, the connection will be blocked. A fixed routing approach is simple to implement; however, it is very limited in terms of routing options and may lead to a high level of blocking. In order to minimize the blocking in fixed routing networks, the predetermined routes need to be selected in a manner that balances the load evenly across the network links. Fixed routing schemes do not require the maintenance of global network state information.

As showed in figure 3, for establishing lightpaths in a 3x3 mesh torus network, the predetermined routes can be determined as follows. When the source node receives the connection request to a destination node, the source node will find the shortest path to the destination node, and set up the lightpath on the shortest path. For example, when node 0 receives a connection request to node 6, node 0 will find the shortest path that starts from node 0, goes through node 3, arrives at node 6. If there are wavelengths available on this path, one of them will be assigned to this path.

If node 0 receives a connection request to node 8, node 0 will find six shortest paths. One of them starts from node 0, goes through node 3, node 6 and node 7, arrives at node 8; another one starts from node 0, goes through node 1, node 2 and node 5, arrives at node 8. To make the network traffic evenly distributing on the network, the source node finds the cross-point node at first. The cross-point node is the only node that belongs to both the column of the source node and the row of the destination node. The shortest paths can be found from the source node to the cross-point node, and from the cross-point node to the destination node. As showed in figure 3, when node 0 is required to set up a connection to node 8, node 0 first finds the cross-point node 6 as well as the shortest path to node 6, then node 6 finds the shortest path to node 8, so the shortest path from node 0 to node 8 starts from node 0, goes through node 3, node 6 and node 7, arrives at node 8 as showed in the solid line. For the same reason, the shortest path from node 8 to node 0 starts from node 8, goes through node 5, node 2 and node 1, arrives node 0 as showed in the dashed line.

Figure 3. Fixed routing in the 3x3 mesh torus network

2.1.2 Fixed-Alternate Routing

Fixed-alternate routing relies on a set of predetermined fixed routes between a source node and a destination node [19] [20] [21] [22]. When a connection request arrives, a single route is chosen from the set of predetermined routes, and a lightpath is established on this route. For example, the set of routes may include the shortest-path route, the second-shortest-path route, the third-shortest-path route, etc. The primary route is defined as the first route in the list of routes to the destination node in the routing table at the source node. An alternate route is any route that does not share any links (link-disjoint) with the first route in the routing table of the source node. Figure 4 illustrates the primary shortest-path route (solid line) from node 0 to node 2, and an alternate route (dashed line) from node 0 to node 2.

Figure 4. Fixed-Alternate Routing

When a connection request arrives, the source node attempts to establish the connection on each of the routes from the routing table in sequence, until a route with a valid wavelength assignment is found. If no available route is found from the list of alternate routes, the connection request is blocked. Normally, the shortest-path route is selected as the primary route in the routing table. However, on the occasion of ties in the length of routes, one route may be selected at random.

When setting up connections in a wavelength-routed optical network, it is often desirable to provide some degree of protection to against link and node failures in the network by reserving some amount of spare capacity [23] [24]. The Fixed-alternate routing can provide fault tolerance upon link failures. By choosing the alternate routes such that they are link-disjoint from the primary route, any single-link failures can be protected by allocation one of the alternate routes as a backup route. As showed in figure 4, the route represented with the dashed line can be the protection path of the route represented with the solid line.

2.1.3 Adaptive Routing

Adaptive routing approaches increase the likelihood of establishing a connection by taking into account network state information. The network state is determined by the set of all connections that are currently in progress. One form of adaptive routing is unconstrained routing, which considers all possible paths between a source node and a destination node. In order to choose an optimal route, a cost is assigned to each link in the network based on current network state information, such as wavelength availability on links. A least-cost routing algorithm is then executed to find the least cost route [25] [26]

[27]. Whenever a connection is established or taken down, the network state information is updated. Two examples of unconstrained routing approaches are link-state routing and distance-vector routing.

In a distributed link-state routing approach, each node in the network must maintain complete network state information [26]. Each node may then find a route for a connection request in a distributed manner. Whenever the state of the network changes, all of the nodes must be informed. Therefore, the establishment or removal of a lightpath in the network may result in the broadcast of update messages to all nodes in the network. The need to broadcast update messages may result in significant control overhead. Furthermore, it is possible for a node to have outdated information, and for the node to make an incorrect routing decision based on this information.

A distance-vector routing approach is proposed in [27]. This approach doesn't require that each node maintains complete link-state information at each node as in [26]. Instead, each node maintains a routing table that indicates for each destination and on each wavelength, the next hop to the destination and the distance to the destination. The approach relies on a distributed Bellman-Ford algorithm to maintain the routing tables. Similar to [26], the scheme also requires nodes to update their routing table information whenever a connection is established or taken down. This update is accomplished by having each node send routing updates to their neighbors periodically or whenever the status of the node's outgoing links changes. Because each node maintains less information than in [26] and the updates are not broadcast to all nodes, the scheme has less control overhead to accelerate the processing time.

2.2 Wavelength Assignment Problem

If there are multiple feasible wavelengths between a source node and a destination node, a wavelength assignment algorithm is required to select a wavelength for a given lightpath. The wavelength selection may be performed either after a route has been determined, or in parallel with finding a route. Since the same wavelength must be used on all links in a lightpath, it is important that wavelengths are chosen in a way to reduce the blocking for subsequent connections. A review of wavelength assignment approaches is given in [28].

One simple but effective wavelength assignment heuristic is the first-fit algorithm. In first-fit, the wavelengths are indexed, and a lightpath will attempt to select the wavelength with the lowest index before attempting to select a wavelength with a higher index. By selecting wavelengths in this manner, existing connections will be packed into a smaller number of total wavelengths, leaving a larger number of wavelengths available for longer lightpaths.

Another approach for choosing one wavelength among different wavelengths is simply to select one of the wavelengths at random from the set of available wavelengths on the path. The random wavelength assignment algorithm usually selects wavelength according to the uniform distribution. The first-fit algorithm outperforms the random algorithm when full knowledge of the network state is available or without considering the link propagation delay and processing delay [20]. However, if the wavelength selection is done in a distributed manner, with only limited or outdated wavelength utilization information, then random wavelength assignment may outperform first-fit assignment. The reason for this behavior is that, in a first-fit approach, if multiple

connections are attempting to set up a lightpath simultaneously, then it may be more likely that they will choose the same wavelength, leading to one or more connections being blocked. Other wavelength assignment heuristics include the least-used wavelength assignment algorithm and the most-used wavelength assignment algorithm. In least-used wavelength assignment, the wavelength that is the least used in the network is selected, thereby attempting to balance the load among all the wavelengths. This approach breaks up the long wavelength paths so quickly that only connection requests that traverse a small number of links will be serviced in the network. The performance of the least-used algorithm is worse than the Random and First-Fit algorithms. The most-used algorithm selects the most used wavelength in the network assigning to the path. It outperforms least-used, random, and First-Fit algorithms [29]. Both the least-used and most-used algorithms require the global information of the network. The communication overhead, storage, and computation cost of both the least-used and the most-used algorithms are considerable higher when comparing them to those of random and first-fit algorithms. The Distributed Relative Capacity Lose (DRCL) algorithm is proposed for the distributed-controlled network [28]. It requires to calculate the possible damage of other possible Source-Destination pairs' connections when assigning one specific wavelength to a specific Source-Destination pair. DRCL compares the damages among those assignments, and picks up the one that causes the smallest damage to the possible connections of the whole network. This algorithm introduces a heavy computation load and packet overhead at each node; many outdated messages will be used to make the wavelength assignment decision. Under a dynamic traffic pattern, DRCL is difficult to estimate the damage that one assignment causes to other assignments. Many other

distributed wavelength assignment algorithms also have been proposed to fit for the distributed network nature [30], they assign wavelength to the path based on distributed global wavelength utilization information. It is expected that, as network traffic continues to grow and become more bursty in nature, a higher degree of multiplexing and flexibility will be required at the optical data layer. Thus, assigning wavelength to lightpath will become dynamic in nature, with connection requests arriving at higher rates, and lightpaths being established for shorter time durations. In such situations, maintaining distributed global information may become infeasible. The alternative is to implement wavelength assignment schemes that rely only on local information.

That two distributed wavelength assignment algorithms that implement wavelength assignment relies only on local information will be introduced in Chapter III. The two algorithms are only slightly more complicated than the first-fit and random algorithms, but their performance is much better than the first-fit and random algorithms. It is easy to implement these two algorithms into the distribute-controlled signaling protocols.

2.3 Fairness Problem

Assume that all the wavelengths have the equal possibility to be assigned to different lightpaths. The lightpaths' length (number of hops) may vary in the network topology. It has been shown in [31] that the traffic for establishing a longer lightpath with large number of hops suffers a higher blocking probability compared to the traffic establishing a shorter lightpath with small number of hops. As it was show in [31] [32] [36] [37] [38], the path length is a key parameter for networks without wavelength

converters. One simple but effective analysis model has been developed in [31] to calculate the traffic blocking probability when considering the path length issue.

Let ρ be the probability that a wavelength is in use on a link, and let H be the number of hops (links) in a path. Then W is the expected number of wavelength used on a link, which can be seen as a measure of wavelength utilization in a link. Let P_b denote the probability that a connection request experiences blocking. Assuming all the links are equally likely to be included in a path, the blocking probability without wavelength converters is expressed as [31]:

$$P_b = [1 - (1 - \rho)^H]^W$$

This equation shows that the blocking probability increases with the path length and decreases with the number of wavelengths that are accommodated by each link.

The simulation results are shown in Figure 5 for a 4x4 Mesh-Torus network with each link accommodating 240 wavelengths. Note that when the traffic load (Erlang) approaches 400 calls per unit time, the traffic for establishing the 4-hop lightpath suffers more than 95% blocking probability while the traffic for establishing the 1-hop lightpath experiences no blocking probability. While no network administrator would allow such a high blocking probability, it is still interesting to observe this situation since it can happen under worst circumstances.

Figure 5. Fairness problem

This phenomenon can be described as the Fairness Problem and can be defined as the inability of call requests of shorter lightpaths to have an equal blocking probability as call requests of longer lightpaths. The solution to this problem would be to equalize the blocking probability of call requests for both short and long lightpaths.

Two methods have been proposed to solve the Fairness Problem in [20]. In the Protecting Threshold Method (Thr), the single-hop traffic is assigned an idle wavelength only if the number of idle wavelengths on the link is equal to or above a given threshold. The Wavelength Reservation Method (Rsv) assigns a given wavelength on a link to a specified traffic arrival stream. As showed in [20], the combination of these two methods only slightly reduces the blocking probability of the multi-hop traffic but increases the

blocking probability greatly for both the single-hop traffic and the network average traffic.

The traffic classification and service (ClaServ) method is proposed in Chapter IV to solve the fairness problem. The traffic requests are classified either at the source node or the destination node, and different services are provided to classified traffic to optimize the fairness problem. In Chapter VI, the simulation results show the ClaServ method achieves very good performance.

2.4 Signaling in all-optical networks

The signaling control mechanism is used to find the path and assign wavelength to the path, therefore to perform the RWA functions. The signaling control required for establishing connection may be either centralized or distributed. The centralized signaling control based on a single entity, maintains complete network state information, and is responsible for finding routes and setting up lightpaths for connection requests [33][34][35]. Since a centralized entity manages the entire network, a high degree of coordination among nodes is not necessary; however, a centralized entity becomes a possible single point of failure. Furthermore, a centralized approach does not scale well, as the centralized entity would need to maintain a large database to manage all nodes, links, and connections in the network. Hence, the distributed signaling is preferred to control the state of lightpaths [36].

Figure 6 shows an example of network signaling architecture. Each host is attached to a router. The router is consisted with an electronic control unit and an optical switch. The control unit controls the optical switch.

Figure 6. Distributed Signaling in all-optical networks

The optical switches are interconnected through data channels drawn as bold lines, while the control units are interconnected through control channels drawn as dashed lines.

The data network, consisting of the optical switches and the data channels, is used to form lightpaths, and operates in circuit-switching mode. The control network, consisting of the control units and the control channels, is used to exchange control information and operates in packet-switching mode.

The traffic load of the control channel is much lighter than the traffic load of the data channel. Accordingly, the control channels can be implemented either by one dedicated wavelength in each fiber link or by electronic interconnects (TCP/IP network).

In addition to setting the optical switches, the control unit at a router maintains the status of every wavelength on every link emerging from that router. A wavelength λ on a given link can be in one of the following three states:

AVAIL: indicates that the wavelength λ is available on that link and can be assigned to a new lightpath.

LOCK: indicates that λ is reserved for a possible connection.

BUSY: indicate that λ is being used by a lightpath.

When a wavelength is on the state of LOCK, it may not be known whether the connection can be successfully established to use this wavelength or not. Accordingly, the LOCK and BUSY states are useful for distinguishing two phases in the reservation process, the phase that the wavelength only been reserved and the phase that the wavelength is on use. If a wavelength is in either the LOCK or the BUSY state, the control unit maintains a field, namely connection ID, which uniquely specifies the connection that is locking or is using the wavelength. By checking the connection ID, other connections can not reserve this wavelength. Instead, they can only reserve wavelengths that are in the AVAIL state.

When performing the signaling control in all optical networks, the deadlock prevention is necessary to prevent the unused wavelengths to be locked for endless time. Deadlock may occur due to one of the following reasons:

The signaling packets compete for wavelengths. Deadlock can occur if a request is allowed to lock wavelengths forever on some links while requesting wavelengths on other links. The dropping or a holding policy is used for preventing the deadlock under this situation. Under the dropping policy, the protocol immediately releases the wavelengths locked on the partially established path, while under the holding policy, the protocol keeps the wavelengths on the partial path locked for some period of time, hoping that during this period, the reservation will progress. If the reservation could not be accomplished at the end of this period, the connection request is dropped and the locked wavelength is released.

Lack of buffer space at a router can cause the signaling packet lost in the middle way. This problem can be avoided by making the buffer at each router large enough to accommodate all signaling packets that possibly arrive to each router. This situation is mostly unlikely to happen because the control packet is small (a few bytes) and the traffic load in the control channel is light.

The transmission errors or link/node failures can cause the loss of signaling information. Both cases can cause deadlock because the related wavelengths may end up in the state of LOCK or BUSY but can not be changed to AVAIL. This kind of deadlock can be avoided by associating a timer with every wavelength in the state of LOCK or BUSY. If the state of a wavelength is not changed from LOCK or BUSY to AVAIL within a certain time-out period, and no signal is detected during the entire period (heart-beat signals can be detected when the connection is active), the state of related wavelength is automatically changed to AVAIL state.

The ClaServ signaling protocol, which is proposed in Chapter V, assumes that the signaling is running upon the TCP/IP network. The ClaServ protocol is responsible for establishing the lightpath and managing the connection for each source-destination pair according to the user defined RWA algorithm and traffic engineering method.

Chapter 3

3 The LNW and LENW wavelength assignment algorithms

The LNW and LENW algorithms are proposed to minimize call blocking probabilities when assigning suitable wavelengths to a path, but it also optimizes fairness problem in all optical network. The algorithm works as follows: When a set of wavelengths is found to be available on a path, a weight is calculated for each wavelength based on its occupancy. The most-occupied wavelength in the Path Neighborhood is given the heaviest weight and is assigned to the path. The heuristic behind this algorithm is that the most occupied wavelength is the least likely to be available to other paths and therefore should be selected if it is available for the current path. In this way, the wavelengths' utilization in each Path Neighborhood is increased; therefore, the wavelengths' utilization is increased in the whole network based on the local information in a distributed manner.

In the context of a node, the 'neighborhood' refers to the links connected to this node. In the context of a path (a series of nodes), the 'neighborhood' refers to the links connected to all nodes in that path. Figure 7 shows the Node Neighborhood and Path

Neighborhood.

Figure 7. Node's and Path's Neighborhood

3.1 The LNW wavelength assignment algorithm

LNW selects wavelengths by considering the available wavelengths' occupation information on the Path Neighborhood. Starting from the source node, each node on the path weighs each wavelength based on this wavelength's occupation information on the Node Neighborhood, and passes the wavelength's weight to the next node on the path. The destination node is responsible to find the available wavelength (satisfy the wavelength continuity constraint) with the heaviest weight, and assign this wavelength to the path.

Figure 8 illustrates N nodes on a path from the source node to the destination node. We assume that there are K wavelengths available on the path; λ_i can be any one of these K wavelengths. It has been assumed that there are M_T links directly connected to node T ,

where node T can be any node on the path.

Figure 8. LNW Wavelength Assignment algorithm

If λ_i is occupied on one of the M_T links that is connected with the node T, then its weight on this link equals to one, otherwise, its weight equals to zero if λ_i is idle.

The weight of the wavelength λ_i on link j at node T can be represented as:

$$W_i^{T_j} = \begin{cases} 0 & \text{When } \lambda_i \text{ is idle on link } j \\ 1 & \text{When } \lambda_i \text{ is occupied on link } j \end{cases}, 1 \leq i \leq K, 1 \leq j \leq M_T, 1 \leq T \leq N \quad (3.1)$$

The weight of the wavelength λ_i at node T can be represented as:

$$W_i^T = \sum_{j=1}^{M_T} W_i^{T_j} \quad 1 \leq i \leq K, \quad 1 \leq T \leq N \quad (3.2)$$

This value can be obtained at the Node neighborhood. One node on the path weigh each wavelength based on the wavelength's occupation in the links connected with the node. Thus, each wavelength's weight at one node can be obtained with only the node's local information.

When node T is the source or the destination node, it has only one directly connected link on the path, λ_i is available on this link and λ_i 's weight on this link is equal to zero. The range of λ_i 's weight on node T is:

$$0 \leq W_i^T \leq M_T - 1, \quad 1 \leq i \leq K, \quad T \in \{1, N\} \quad (3.3)$$

When node T is an intermediate node on the path, it has two links on the path; λ_i is available on those two links, the range of λ_i 's weight on node T will be:

$$0 \leq W_i^T \leq M_T - 2, \quad 1 \leq i \leq K, \quad T \notin \{1, N\} \quad (3.4)$$

After weighed by each node on the path, the weight of the wavelength λ_i is:

$$W_i = \sum_{T=1}^N W_i^T \quad 1 \leq i \leq K \quad (3.5)$$

The wavelength λ_a with the heaviest weight W_a will be assigned to the lightpath.

$$W_a = \text{Max}\{W_i\}, \quad 1 \leq i \leq K \quad (3.6)$$

3.2 The LENW wavelength assignment algorithm

The passing of intermediate node information is optional. If no intermediate information is considered, then only the source and destination node information is used to select a wavelength. This is called the Lightpath End Nodes' Neighborhood Weight (LENW) algorithm. LENW introduces less computation and packet overhead at each processing node when compared to the LNW algorithm, but the overall performance is slightly worse than that of LNW.

The LENW algorithm considers only the wavelength occupation information on the neighborhood links connected with the source and destination nodes. After the source node weights each wavelength that belong to the network, it passes the weight of each wavelength to the destination node, the destination node weights each available wavelength upon the weight provided by the source node. The available wavelength with the heaviest weight will be assigned to the path.

For an s-d pair, assume K wavelengths are found available on the path, they were sorted from λ_1 to λ_k as showed in figure 9. The weight of λ_i is represented as

$$W_i, \quad 1 \leq i \leq K$$

The source node connected with M links and the destination node connected with N links. The link M at source node is the first link on the path. The link N at destination node is the last link on the path.

Figure 9. LENW wavelength assignment

On one of the M links that is connected with the source node, if λ_i is occupied (used or reserved), then its weight on this link equals to one, otherwise, its weight equals to zero. Because λ_i is available on the path, so λ_i 's weight on link M equals to zero. The weight of λ_i on link j connected with the source node is represented as:

$$W_i^{S_j} = \begin{cases} 0 & \text{When } \lambda_i \text{ is idle on link } j \\ 1 & \text{When } \lambda_i \text{ is occupied on link } j \end{cases}, 1 \leq i \leq K, 1 \leq j \leq M \quad (3.7)$$

For the same reason, λ_i 's weight on link N equals to zero. The weight of λ_i on link j connected with the destination node is represented as:

$$W_i^{D_j} = \begin{cases} 0 & \text{When } \lambda_i \text{ is idle on link } j \\ 1 & \text{When } \lambda_i \text{ is occupied on link } j \end{cases}, 1 \leq i \leq K, 1 \leq j \leq N \quad (3.8)$$

The Weight of λ_i equals the summation of its weight on each link that is connected with the source node and destination node. Which is represented as follows:

$$W_i = \sum_{j=1}^M W_i^{S_j} + \sum_{j=1}^N W_i^{D_j} \quad 1 \leq i \leq K \quad (3.8)$$

Because λ_i has zero weight on both of the link M and link N, so the range of λ_i 's weight is:

$$0 \leq W_i \leq M + N - 2 \quad (3.9)$$

The available wavelength λ_a with the heaviest weight W_a is assigned to the path.

$$W_a = \text{Max}\{W_i\}, \quad 1 \leq i \leq K \quad (3.10)$$

3.3 The implementation of the two algorithms into the signaling protocol

The LNW and LENW algorithms can be implemented by a distributed signaling protocol, like one proposed in [35]. Assuming that a path is found and assigned to the connection request of one specific s-d pair, the source node will send a PROB packet towards the destination node along the path, as depicted in Figure 10 (a) and (b). This PROB packet contains several fields: Field 1 is responsible for recording the weight of

each wavelength and Field 2 is used to store the availability information of each wavelength in the path. As the PROB packet propagates to the destination, each node will weigh each wavelength depending on the wavelength's availability in the neighborhood of this node and adds the new weight in Field 1. At each node on the path, Field 2 will be updated by eliminating any uncommon wavelengths to satisfy the wavelength continuity constraint. At the destination node, Field 2 will indicate all common and available wavelengths along the path. The destination node checks Field 1 and 2 to find the available wavelengths with the heaviest weight and assigns it to the path. Figure 10 (c) shows that at the destination node, Field 1 and Field 2 have been modified. The destination node checks Field 2 and finds that λ_2 and λ_3 satisfy the wavelength continuity constraint on the path. Field 1 shows that λ_3 has a heavier weight than λ_2 , so the destination chooses λ_3 as the best suitable wavelength for the lightpath.

Figure 10. The implementation of the LNW algorithm into the signaling protocol

Chapter 4

4 The traffic Classification and Service Method

The traffic classification and service (ClaServ) method is proposed to optimize the Fairness Problem. The traffic requests are to be classified depending on the number of hops that are traversed from the source to the destination. These classified traffic requests are offered different levels of service to guarantee low blocking probability in order to optimize the fairness problem. To do so, all wavelengths on the link are equally separated into a set of wavebands, which are sorted and contain the same number of indexed wavelengths. Separating the wavelengths into wavebands can benefit the hierarchical searching of the available wavelengths by speeding up the processing for the establishment of lightpaths in Dense Wavelength Division Multiplexing (DWDM) Networks. The combination of the Waveband Access Range Method (WAR) and the Waveband Reservation Method (WRsv) is used to serve the classified traffic. Both WAR and WRsv assume that the shortest-path routing has been completed through a distributed routing protocol.

4.1 Traffic Classification

The traffic requests are classified by the number of hops they going to traverse. The number of hops is also called the *type*, which is the classifier of the traffic. The traffic requests can be classified either at the source node or at the destination node. In the first method, upon traffic requests arrived, the source node checks the routing table to find the path to the destination and count the number of hops along this path. This number determines the *type* of the traffic. This first method is called *Source Traffic Classification*. For the second method, the traffic request maintains a counter that is incremented as the packet is sent from the source to the destination, along the predetermined path. Each intermediate node increments the counter upon a request reception. The value of the counter at the destination node determines the *type* of the traffic. This method is called *Destination Traffic Classification*. Destination Traffic Classification can be implemented into distributed signaling protocols, such as the ones presented in [35]. Figure 11 shows the process of classifying traffic as it arrives at the source node. Destination Traffic Classification is illustrated here. Figure 11 (a) shows a request arriving at the source node. A path is found for the s-d pair. The source node generates a PROB packet and sends it toward the destination node along the path to collect wavelength availability information on the path. As shown in Figure 11 (b), the PROB packet contains a counter field that is initialized to zero at the source node. Figure 11 (c), shows the counter being incremented at each intermediate node and the

destination node. Assuming that the value of the counter equals to N at the destination node, this traffic request's *type* is N -hop traffic.

Figure 11. The implementation of the traffic classification into the signaling protocol

4.2 Waveband Access Range and Waveband Reservation Methods

The Waveband Access Range (WAR) and the Waveband Reservation (WRsv) methods are two methods that reduce the interference of the establishment of shorter lightpaths to longer lightpaths. A short lightpath may be considered a lightpath of 1-hop or 2-hops, whereas a long lightpath can be 3-hop, 4-hop or more. The following two sub-

Chapters describe WAR and WRsv and show that both methods can improve the performance of the blocking probability and also optimize the fairness problem.

4.2.1 Waveband Access Range Method

The Waveband Access Range Method (WAR) is a method of assigning wavelengths to lightpath requests. This method involves the division of the set of wavelengths on a link into waveband access ranges. When requests arrive at the source or destination, the node will select a wavelength to be assigned to the lightpath. This wavelength will be selected from its respective waveband, based on the request's *type*. Normally, the traffic with small number of hops has a smaller waveband access range than the traffic with large number of hops. For example, Figure 12 shows K wavebands on each link. The 1-hop traffic requests can only access the first X wavebands. The 2-hop traffic can access the first Y wavebands. All the other type traffic can access all the K wavebands.

Figure 12. Waveband assess range method

4.2.2 Waveband Reservation Method

The Waveband Reservation Method (WRsv) reserves wavebands to reduce the blocking probability of the establishment of longer lightpaths. Thus, one or more wavebands can be reserved for requests of large number of hops. The reserved wavebands are normally reserved for the traffic requests with longer lightpaths, and the shorter lightpaths are granted unreserved wavebands. The wavebands are organized as illustrated in Figure 13. Wavebands 1 to K-2 are unreserved, whereas waveband K-1 is reserved for 3-hop and 4-hop lightpaths and waveband K is reserved for 4-hop lightpaths only. A request for longer lightpaths search unreserved wavebands first and are forced to compete with requests for shorter lightpaths. If no available wavelengths are found, then a search for wavelengths in the reserved wavebands is made. This allows the reserved waveband to be kept relatively free, if the need arises to use them when the other wavebands are used up by shorter lightpaths.

Figure 13. Waveband reservation method

4.2.3 The combination of the WAR and WRsv methods

Both of the WAR and WRsv methods can be used the same time to achieve the low blocking probability for all type of traffic. For the traffic with small number of hops, the WAR method limits their interference to other type of traffic. For the traffic with large number of hops, the WRsv method guarantees the low interference from other type of traffic. The combination of the WAR and WRsv methods serves the classified traffic to guarantee the degree of the interference one type of traffic received from other type of traffic or the degree of interference one type of traffic contributes to other type of traffic. In this way, the interference among the traffic is under control, the fairness can be achieved for all type of traffic.

Chapter 5

5 The ClaServ Signaling Protocol and The Simulation models

5.1 The ClaServ Signaling protocol

The ClaServ signaling protocol is built upon the distributed control signaling protocol [35]. Distributed control improves the scalability as well as the reliability and reduces the cost of establishing a lightpath. The ClaServ signaling protocol supports the Random, First-Fit, LNW and LENW wavelength assignment algorithms; it also supports the traffic classification and service (ClaServ) method for all optical networks.

As showed in figure 14, when using the ClaServ protocol with the connection request arrives to the network, the source node sends a PROB packet to the destination node for searching the available wavelengths along the path and assigns one of the available wavelengths to the path. There are three kinds of possibilities.

The first possibility, as showed in figure 14 (a), at one of the intermediate nodes, by checking the information contained by the PROB packet, the signaling protocol knows there is no available wavelength on the links that traversed by the PROB packet, so this intermediate node sends a Negative Acknowledgement (NAK) packet to the source node.

When the source node receives this NAK packet, the node either resends a PROB packet after some waiting time or cancels the connection request.

The second possibility, as showed in figure 14 (b), the PROB packet arrives to the destination node and finds there are available wavelengths on the path. The destination node assigns one of the available wavelengths to the path according the ClaServ method and one of the wavelength assignment algorithms. The selected wavelength's information will be stored in a Reservation (RES) packet. The destination node sends the RES packet to the source node along the path that was traversed by the corresponding PROB packet to reserve the selected wavelength on each link of the path. At one of the intermediate nodes, the signaling protocol finds that the selected wavelength is occupied by another connection on one of the links on the path, so this intermediate node has to generate an NAK packet to notify the source node that this connection request is fail and send a FAIL packet to release the wavelength that was reserved by the RES packet on the links that were traversed by the RES packet.

The Third possibility, as showed in figure 14 (c), the PROB packet arrives to the destination node and finds there are available wavelengths on the path, then the destination node generate and send a RES packet to the source node. The RES packet arrives to the source and the selected wavelength is reserved on each link of the path for establishing the lightpath. The source-destination pair begins their communication on the lightpath. After the communication is complete, the lightpath should be tired down. The source node generates and sends a release (REL) packet to the destination node along the path to release the selected wavelength on each link of the path.

Figure 14. Distributed control signaling protocol

5.2 The Simulation models

The Simulation models were built upon the OPNET Modeler. Five kinds of models were built up: the Network model, the Node model, the Process model, the Link model and the Packet model. There are described as follows.

5.2.1 The Network model

The Network model can represent any arbitrary network topology, such as the Ring network, Mesh-torus network and the NSFNET network. The nodes are connected with each other through links. Each node and link have their own identity in the network and

can be distinguished from other nodes and links. Each node has the indexed ports to connect with different links. As showed in Figure 15, each node of 0, 1, 2 and 3 has three ports, and node 4 has four ports. Through port 0, node 4 connected with node 0 through link 4. When a connection request arrives to the network, the routing algorithms are responsible to find a path for the specific source-destination pair. For example, in figure15, when the shortest path algorithm is used, for the connection from node 0 to node 2, three possible shortest paths can be found as follows: from node 0 through node 1, connected with node 2; from node 0 through node 4, connected with node 2; from node 0 through node 3, connected with node 2. One of them should be selected for the connection as the shortest path.

Figure 15. A five-node network model

5.2.2 The Node model

The node model is responsible for directing the connection through different ports of the same node. As showed in figure 16, each port of the node supports bi-directional transmission, which can be represented as one receiver plus one transmitter. As one of the receivers receives a packet, the receiver will forward this packet to the processor. After the processing of the received packet, the processor will either forward this packet to one of the transmitters or generate new packets and send to different nodes through different transmitters. Each node contains a routing table, which can be dynamic or fixed. When the node receives or generates a packet, by checking the packet header, the node will know the packet's destination; by checking the corresponding part of the routing table, the node will know through which port to forward this packet toward its destination. For example, the node 0's routing table is showed in table 5.1. If node 0 has a packet send to node 2, by checking the third row of its routing table, node 0 finds the packet should be forward through transmitter port 1, through link 4 to next node. If node 0 has received a packet with source address 2, by checking the third row of its routing table, node 0 finds the packet come from the receiver port 0, through the link 0. If the node 0 generates a packet with the destination address 2, by checking the routing table, node 0 finds the number of hops is 2 for this travel, so node 0 knows it generates a 2-hop traffic.

Figure 16. Node Model

Destination	transmitter-port	Out-link	Source	In-link	receiver-port	number of hops
1	0	0	1	0	0	1
2	1	4	2	0	0	2
3	2	3	3	3	2	1
4	1	4	4	4	1	1

Table 1. Routing table of node 0

5.2.3 The Process model

The process model processes the received packets and generates packets depends on the signaling protocols. As showed in figure 17, in this thesis, the process model comprised eight states: the Initial state (init), the state of waiting the arrival packet and other interruptions (WAIT), the Generating PROB packet (GENE PROB) state, the state of receiving the PROB packet (PROB), the state of receiving the RES packet (RES), the

state of receiving the REL packet (REL), the state of receiving the FAIL packet (FAIL), the state of receiving the NAK packet (NAK).

Figure 17. Process State model

- The Initial State

All the user determined parameters are read from the Initial state, such as the number of the nodes and links in the network, the number of the wavelengths accommodated by each link, the traffic pattern (the traffic distribution, the traffic load, and the mean of the service time of traffic), the RWA algorithms (shortest path routing and one of the wavelength assignment algorithms), the waveband access range and reserved wavebands of the classified traffic, the set of specific source-destination pair for collecting statistics, etc.

The initialization of variables is performed in this state, such as the representation of each wavelength, the utilization of each link, the initialization of the routing table on each node, and the scheduled event for generating the first PROB packet.

- The WAIT State

After the Initial State performs all its functions, the process model directly steps into the WAIT State without any condition. By monitoring the status of the host node, the migration of WAIT State to other states is conditional. When a PROB traffic generation interruption arrives, the WAIT State will transfer to the GENE PROB State. When a receiving packet interruption arrives, the WAIT State will check what type of packet has been captured, according to the packet's type, the WAIT State transfers to the corresponding state. When the simulation is finished, a statistics collection interruption will be generated to stimulate a function to record the simulation results.

- The GENE PROB State

The PROB packets are generated at this state, and their destinations are set by the traffic pattern obtained from the initial state. If the user set the traffic distribution in the scenario that for each source node, the destination node is uniformly distributed among all other nodes in the network, then each PROB packet's destination is randomly select one from all the other nodes' addresses. The PROB packet's destination can also be set to generate asymmetric traffic for the network.

The PROB packet's format is showed in figure 18. This format contains the source_address field, the destination_address field, the wave_set field, the packet_format

field, the hops_counter field, the PROB_begin_time field, the fields from wave_band_0 to wave_band_7, and the fields from the b0w0 to b7w29. The source_address field represents the source node's address. The destination_address field represents the destination node's address. The wave_set field represents the specified user defined wavelengths. The packet_format field indicates the type of the packet. The hops_counter field calculates the number of links traversed by the PROB packet. The PROB_begin_time field records the time that the PROB packet was generated. The PROB packet can support up to 8 wavebands, each waveband contains up to 30 wavelengths. The fields from the wave_band_0 to wave_band_7 are used to represent each wavelength's availability in each waveband. The fields from the b0w0 to b7w29 are used to record the weight for up to 240 wavelengths.

Figure 18. PROB Packet Format

- The PROB State

When one node receives a packet and this packet's `packet_format` field indicates that is a PROB packet, the node's process model processes this packet in the PROB State. The process follows the procedures as showed in figure 19.

The PROB packet's `wave_band_#` fields contain each wavelength's availability information on the route that traversed by the PROB packet. By combining this information with each wavelength's availability information on the incoming link of the PROB packet, the wavelengths that satisfy the wavelength continuity constraint can be found. If PROB packet couldn't find available wavelengths at one node on the path, a negative acknowledgement (NAK) will be generated at this node to notify the source node. If PROB packet finds available wavelengths on the traversed route, the host node will check if it is the destination of the PROB packet. If the host node is not the PROB packet's destination, the host node passes the packet to its destination by sending it to the corresponding transmission port. If the host node is the PROB packet's destination, the host node will check if the ClaServ method is used to provide different service to the classified traffic. If the signaling protocol does not require to perform the ClaServ method, according to one of the wavelength assignment algorithms, the host node going to generate a RES packet. The RES packet is send to the source node along the same path traversed by the PROB packet to reserve the selected wavelength on each link of the path. If the signaling protocol requires performing the ClaServ method, the traffic will be classified by reading the information from the RES packet, and according to the attribute obtained from the initial state, different service will be provided to the classified traffic.

For the traffic with available wavelengths among the accessible wavebands, the wavelength assignment algorithm will assign one of the available wavelengths to this traffic. The NAK packet format and RES packet format are showed in figure 20 and figure 21 respectively.

Figure 19. Flow Chart of the PROB State

source_address (32 bits)
dest_address (32 bits)
PROB_begin_time(32 bits)
packet_format (4 bits)
traffic_type (32 bits)

Figure 20. NAK packet format

source_address (32 bits)
dest_address (32 bits)
PROB_begin_time(32 bits)
packet_format (4 bits)
wave_band_number (32 bits)
reserved_wavelength (32 bits)

Figure 21. RES packet format

- The RES State

When one node receives the RES packet, the node's process model enters the RES state. If the RES packet arrives to its destination, the source node will generate a REL packet after user-defined service time and send it to the destination node along the path traversed by the corresponding RES packet. The reserved wavelength will be released on each link of the path. If the RES packet arrives a intermediate node, the packet will check if the selected wavelength still available on the outgoing link on the path. If the selected wavelength still available, the intermediate node will pass the RES packet to the next node on the path; if the selected wavelength not available, the intermediate node will generate two packets, the NAK packet and the FAIL packet. The NAK packet will be

send to the source node to notify the failure of the connection request, and the FAIL packet will be send to the destination packet along the path to release the reserved wavelength. The RES State's flow chat is showed in figure 22. The REL and the FAIL packet's format are showed in figure 23 and figure 24 respectively.

Figure 22. Flow Chart of the RES State

Figure 23. REL packet format

source_address (32 bits)
dest_address (32 bits)
packet_format (4 bits)
wave_band_number (32 bits)
released_wavelength (32 bits)

Figure 24. Fail packet format

- The NAK State

When one node receives the NAK packet, the node's process model enters the NAK state. If the NAK packet is still on the way to its destination, the host node passes the NAK packet toward its destination. If the NAK packet arrives to its destination, the host node records the statistics of the failure of the connection request. The flow chat is showed in figure 25.

- The FAIL State

When one node receives the FAIL packet, the node's process model enters the FAIL state. When the host node receives the FAIL packet, the reserved wavelength on the incoming link will be released. The host node will check if the FAIL packet arrives its destination. If the FAIL packet is still on the way to its destination, the host node passes the FAIL packet toward its destination, otherwise, the host node destroys the FAIL packet. The flow chat is showed in figure 26.

- The REL State

When one node receives the REL packet, the node's process model enters the REL state. When the host node receives the REL packet, the reserved wavelength on the incoming link will be released. The host node will check if the REL packet arrives its destination. If the REL packet is still on its way, the host node passes REL toward its destination, otherwise, the host node destroys the REL packet. The REL State has the same flow chat as the FAIL State.

Figure 25. Flow Chart of the NAK state

Figure 26. Flow Chart of the REL and Fail state

Chapter 6

6 Simulation Results and Performance Evaluation

Simulation experiments are used to evaluate the LNW, LENW wavelength assignment algorithms as well as the ClaServ method. All the simulation models are built upon the OPNET network simulator. The 4x4 mesh torus network topology (figure 27) is used to study the performance of LNW and LENW algorithms. Both the 4x4 mesh torus network topology and the NSFNET network topology (figure 28) are used to study the performance of the ClaServ method.

Both of the network topologies have the following parameters: (i) Each link has 240 bi-directional wavelengths available when no lightpaths exist; (ii) The destinations of the lightpaths are equally distributed; (iii) The requests are random and follow a Poisson Distribution; (iv) The call holding time (lightpath duration) is exponentially distributed with a mean of one time unit; (v) The shortest path routing algorithm is used to allocate the path for the s-d pair; (vi) It is assumed that there is no delay between nodes; (vii) There are no wavelength converters in the network, so the Wavelength Continuity Constraint is valid.

The networks' performance is studied with two metrics: (i) The average Call (traffic) blocking probability and (ii) The Fairness Achievement.

Figure 27. 4x4 Mesh Torus Network

Figure 28. NSF Network

6.1 Simulation results and performance evaluation of the LNW and LENW

For the 4x4 mesh torus network, a set of traffic load (Erlang) is given to test the performance of the LNW, LENW, First-Fit and Random wavelength assignment algorithms. The set of traffic load is given as 165, 170, 175, 180, 195, 210 Erlang at each node of the network. The time unit can be defined from one second to one year. For example, for a network with high frequency connection requests, the time unit can be one second, the traffic load can be 160 calls per second at each node; for a network with relative static connection request, the time unit can be one year, the traffic load can be 160 calls per year at each node.

Figure 29 shows the average call (traffic) blocking probability of the four wavelength assignment algorithms. LNW achieves a lower blocking probability than both the First-Fit and Random assignment algorithms. At 165 requests rate per node, there is a 10 times improvement from First-Fit to LNW, and a 12 times improvement from Random to First-Fit. From 165 to 210 requests, LNW follows the blocking probability curves of both Random and First-Fit, but improves on both of them. The LENW's average call blocking probability is higher than the LNW algorithm, but lower than those of the first-fit and random algorithms.

Figure 29. Average traffic blocking probability of different algorithms

Figures 30, 31, 32 and 33 show the performance of the Random, First-Fit, LENW and LNW algorithms for connection requests of 1, 2, 3 and 4-hop lightpaths respectively. From figure 4, 5, 6, and 7, we can see that the LNW algorithm has the best achievement in minimizing the mismatch of the blocking probability of 1-hop, 2-hop, 3-hop and 4-hop traffic when given the traffic load 165 Erlang, therefore, the LNW algorithm has the best fairness achievement when the network is required running under small traffic blocking probability (around 10^{-4}). The figures also show that 1 hop lightpaths experience no blocking probability and the 2 hop lightpaths experience relatively much lower blocking probability than the 3 and 4 hop lightpaths.

Figure 30. Performance of Random algorithm in establishing lightpaths

Figure 31. Performance of first-fit algorithm in establishing lightpaths

Figure 32. Performance of LENW algorithm in establishing lightpaths

Figure 33. Performance of LNW algorithm in establishing lightpaths

Figure 34, and 35 compare the traffic blocking probability of different algorithms in establishing 4-hop, 3-hop lightpaths respectively. At 165 calls per unit time, for the establishment of the 4-hop lightpaths, the LNW's blocking probability is 4 times lower than the LENW's, 12 times lower than the First-Fit's, and the First-Fit's blocking probability is 10 times lower than the Random's; for the establishment of the 3 hop lightpaths, LNW's blocking probability is 1.5 times lower than the LENW's, 8 times lower than the First-Fit's, and the First-Fit's blocking probability is 7 times lower than the Random's. The LNW and LENW algorithms achieve the lowest blocking probability in establishing 3 and 4-hop lightpaths when compare with First-Fit and Random algorithms. Therefore, the LNW algorithm achieves the best performance in both the average call blocking probability and the fairness problem when compared with the First-Fit and Random algorithms.

Figure 34. Blocking Probability in establishing 4-hop lightpaths

Figure 35. Blocking probability in establishing 3-hop lightpaths

6.2 Simulation results and performance

evaluation of the ClaServ Method

For the 4x4 mesh-torus network, one set of traffic load is given to test the performance of the ClaServ method. The set of traffic load is 150, 160, 170, 180, 200, 220 Erlang at each node of the network. For the NSFNET network, another set of traffic load is given to test the performance of the ClaServ method; the set of traffic load is 95, 100, 110, 120, 130, 140 Erlang per time unit at each node of the network.

Figure 36 shows that the 240 wavelengths on each link are separated into 8 wavebands with 30 wavelengths in each waveband. To perform the ClaServ method,

each one of waveband 1, 2, 3, and 4 can be accessed by all type of traffic, waveband 5 and 6 can be accessed by 2-hop, 3-hop and 4-hop traffic, waveband 7 and 8 are reserved for 3-hop and 4-hop traffic. The Random wavelength assignment algorithm is used to assign wavelength to the path when a set of available wavelengths are found on the path within the traffic's accessible wavebands.

Figure 36. Waveband access range and reservation for the classified traffic

Figure 37 shows the blocking probability of the 4x4 Mesh-Torus network without the ClaServ method for traffic of four different types. Figure 38 shows the same scenario with the ClaServ method implemented. It can be observed that by using the ClaServ method, with the wavebands divided as in Figure 36, the blocking probability for 4-hop traffic requests was reduced 100 times and the blocking probability for 3-hop traffic was reduced by a factor of 4 times, when the traffic load was 150 calls per unit time. Notice that 2-hop traffic gets blocked more often when ClaServ is implemented. This follows the Fairness Problem and the solution, in that the blocking probability is equalized for all

types of traffic. 1-hop traffic suffers a very low blocking probability and is almost too small to collect valid data.

Figure 37. Performance of different type of traffic without using ClaServ method in the mesh-torus network

Figure 38. Performance of different type of traffic with ClaServ method in the mesh-torus network

Figure 39 and 40 shows the NSFNET network's performance for all types of traffic without and with the use of the ClaServ methods respectively. It can be seen that in this asymmetric network, ClaServ improves the blocking probability for 4-hop traffic requests by a factor of 50 and by a factor of 2 for 3-hop traffic requests, when the traffic load was 95 calls per time unit. Note that 2-hop traffic requests have also increased when ClaServ is introduced, but is closer to the blocking probabilities of 3-hop and 4-hop traffic. 1-hop traffic suffers a very low blocking probability in this scenario and is too small to collect valid data.

Figure 39. Performance of different type of traffic without using ClaServ method in the NSFNET

Figure 40. Performance of different type of traffic with ClaServ method in the NSFNET

Figure 41 and 42 shows the comparison of the average traffic blocking probability with and without using the ClaServ method in the 4x4 Mesh-Torus network and NSFNET network respectively. Figure 41 illustrates that when the traffic load is 150 calls per unit time in the 4x4 Mesh-Torus network, the ClaServ method can reduce the average traffic blocking probability by a factor of 20. Figure 42 shows that when the traffic load is 95 calls per unit time in the NSFNET network, the ClaServ method reduces the average traffic blocking probability by 10 times. Notice that under larger traffic load such as 220 calls per time unit, both ClaServ and non-ClaServ graphs converge to the same blocking probability.

Figure 41. Average Traffic blocking probability in 4x4 mesh-torus network with and without using ClaServ method

Figure 42. Average Traffic blocking probability in NSFNET network with and without using ClaServ method

From these graphs it can be observed that the ClaServ method optimizes the Fairness Problem by equalizing the blocking probabilities of 2-hop, 3-hop and 4-hop traffic. It also reduces the average blocking probability greatly when the networks are required to run under a small blocking probability for requests of varying number of hops.

6.3 Output analysis of the simulation results

Output analysis is the examination of data generated by the simulations. If the performance of the system is measured by a parameter θ , the result of a set of simulation experiments will be an estimator of θ . The precision of the estimator can be measured by the variance (or standard error) of the estimator. The purpose of the statistical analysis is to estimate this variance.

The simulation results in this thesis are all discrete-time data, they are in the form $\{Y_1, Y_2, \dots, Y_n\}$, n is the number of independent replications. The parameter θ is defined as the mean of the output data. The point estimator of θ based on the data $\{Y_1, Y_2, \dots, Y_n\}$ is defined by

$$\hat{\theta} = \frac{1}{n} \sum_{i=1}^n Y_i \quad (6.1)$$

Let $\sigma^2(\hat{\theta}) = \text{var}(\hat{\theta})$ represent the true variance of the point estimator $\hat{\theta}$, and let $\hat{\sigma}^2(\hat{\theta})$ represent the estimator of $\sigma^2(\hat{\theta})$ based on the data $\{Y_1, Y_2, \dots, Y_n\}$. The estimator of the variance is defined by

$$\hat{\sigma}^2(\hat{\theta}) = \frac{1}{(n-1)n} \sum_{r=1}^n (Y_r - \hat{\theta})^2 \quad (6.2)$$

Therefore, the standard error of the point estimation $\hat{\theta}$ is defined by

$$\hat{\sigma}(\hat{\theta}) = \left[\frac{1}{(n-1)n} \sum_{r=1}^n (Y_r - \hat{\theta})^2 \right]^{1/2} \quad (6.3)$$

If $\hat{\sigma}^2(\hat{\theta})$ is approximately unbiased, then the statistic $t = \frac{\hat{\theta} - \theta}{\hat{\sigma}(\hat{\theta})}$ is approximately t-

distributed with some number of degrees of freedom f. Therefore, an approximate 100(1- α)% confidence interval for θ is given by

$$\hat{\theta} - t_{\alpha/2, f} \hat{\sigma}(\hat{\theta}) \leq \theta \leq \hat{\theta} + t_{\alpha/2, f} \hat{\sigma}(\hat{\theta}) \quad (6.4)$$

$t_{\alpha/2, f}$ is defined as the 100(1- $\alpha/2$) percentage point of a t-distribution with f degrees of freedom. Assume in the simulation n independent replications are made; the degrees of freedom f is defined by $f = n - 1$. When calculates the 99% percent of confidence interval with 29 degrees of freedom in this thesis, the t-distribution statistic

$$t_{0.01/2, 29} = 2.76 \quad (6.5)$$

6.3.1 Confidence interval of the simulation results of the Wavelength Assignment algorithms

The simulation results in the average traffic blocking probability of the Random algorithm and the LENW algorithm are collected for analysis. Let θ_x represents the mean

of the output data when the traffic load is x calls per unit time. The LENW algorithm is a special case of the LNW algorithm but introduces less packet overhead than the LNW algorithm. Given the same traffic load and the same number of scheduled events, the LENW only consume $1/24$ time of the time spend by LNW in each simulation. Table 6.1 shows the simulation results of the Random algorithm when given a set of traffic load of 165, 180 and 195 calls per time unit. The point estimator (mean) of the average traffic blocking probability, the standard error and the confidence interval are also given in table 1 according equation (6.1), equation (6. 3) and equation (6. 4) respectively.

Simulation Sequence number	Traffic blocking probability under different traffic load		
	165 calls/unit time	180 calls/unit time	195 calls/unit time
1	0.011409992	0.030518449	0.056918982
2	0.011363927	0.031052116	0.055915555
3	0.011643434	0.030767864	0.056249166
4	0.011726625	0.03088776	0.056264343
5	0.011249508	0.031233491	0.056025451
6	0.011276644	0.030549664	0.056806478
7	0.01158529	0.031074305	0.056656124
8	0.0115957	0.030893145	0.056293142
9	0.011471525	0.030501039	0.05604529
10	0.01106122	0.030713366	0.056129328
11	0.011666695	0.03103221	0.05619452
12	0.011511516	0.030373349	0.056301384
13	0.011518003	0.030427996	0.056663659
14	0.011582557	0.030727201	0.056384104
15	0.011492142	0.030585649	0.056057172
16	0.011219879	0.031081661	0.056282073
17	0.01148485	0.030574029	0.056350354
18	0.011433708	0.030725666	0.056079649
19	0.011618595	0.031029422	0.056131517
20	0.011085233	0.030736264	0.056094414
21	0.011470818	0.030586451	0.056151269
22	0.011524144	0.030693065	0.05637257
23	0.011466819	0.031030778	0.05607671
24	0.011088931	0.03058268	0.055876871
25	0.011361108	0.030774206	0.056793568
26	0.011364401	0.031003608	0.056303976
27	0.011423104	0.030794267	0.056077635
28	0.011360509	0.03091052	0.056393921
29	0.011390713	0.031196023	0.056704025
30	0.011426951	0.030858624	0.055908187
mean	0.011429151	0.030797162	0.056283381
standard error	3.13503E-05	4.32505E-05	5.21343E-05
confidence interval	8.6527E-05	0.000119371	0.000143891

Table 2. Simulation results and output analysis of the Random algorithm

The simulation result analysis of the random algorithm can be represented as follows:

When the traffic load is 165 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$1.1429\text{E-}02 - 8.6527\text{E-}05 \leq \theta_{165} \leq 1.1429\text{E-}02 + 8.6527\text{E-}05$$

When the traffic load is 180 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$3.0797\text{E-}02 - 1.1937\text{E-}04 \leq \theta_{180} \leq 3.0797\text{E-}02 + 1.1937\text{E-}04$$

When the traffic load is 195 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$5.6283\text{E-}02 - 1.4389\text{E-}04 \leq \theta_{195} \leq 5.6283\text{E-}02 + 1.4389\text{E-}04$$

Table 6.2 shows the simulation results of average blocking probability of the LENW algorithm when given a set of traffic load of 165, 180 and 195 calls per time unit. The point estimator (mean) of the simulation results, the standard error and the confidence interval are also given in table 6.2 according equation (6.1), equation (6. 3) and equation (6. 4) respectively.

Simulation Sequence number	Traffic blocking probability under different traffic load		
	165 calls/unit time	180 calls/unit time	195 calls/unit time
1	0.000242631	0.006246656	0.026738353
2	0.000236215	0.006190825	0.02660237
3	0.000217815	0.006257381	0.026888511
4	0.000232122	0.006214032	0.026717321
5	0.000236101	0.006234867	0.026696866
6	0.000221782	0.006257381	0.026888511
7	0.000224322	0.006207827	0.026692599
8	0.000226073	0.006121345	0.026603583
9	0.000241378	0.006258351	0.026655894
10	0.000209394	0.006237271	0.027001418
11	0.000250206	0.006287922	0.02711621
12	0.000232211	0.006136968	0.026524099
13	0.000238015	0.006392997	0.02656875
14	0.000227852	0.006119789	0.026813234
15	0.000208818	0.006133065	0.026746421
16	0.000221255	0.006148619	0.026639508
17	0.000228252	0.006283816	0.026874725
18	0.000228286	0.006262003	0.026802679
19	0.000236271	0.006168462	0.026496533
20	0.000239823	0.006146579	0.027192359
21	0.000238455	0.006335716	0.026927005
22	0.000229762	0.006331394	0.026419491
23	0.000229976	0.006224135	0.026803689
24	0.000237705	0.006202764	0.026820256
25	2.08883E-05	0.006320263	0.026867539
26	0.000242291	0.006358698	0.026807667
27	0.000227591	0.006255039	0.026862045
28	0.000229292	0.006237036	0.026728698
29	0.000229652	0.00622461	0.026813244
30	0.000207891	0.006133785	0.027001011
mean	0.000223077	0.006230986	0.02677702
standard error	7.33735E-06	1.35777E-05	3.26615E-05
confidence interval	2.02511E-05	3.74744E-05	9.01457E-05

Table 3. Simulation results and output analysis of the LENW algorithm

The simulation result analysis of the LENW algorithm can be represented as follows:

When the traffic load is 165 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$2.2308E-04 - 2.0251E-05 \leq \theta_{165} \leq 2.2308E-04 + 2.0251E-05$$

When the traffic load is 180 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$6.2309\text{E-}03 - 3.7474\text{E-}05 \leq \theta_{180} \leq 6.2309\text{E-}03 + 3.7474\text{E-}05$$

When the traffic load is 195 calls per time unit, the 99% confidence interval of the average traffic blocking probability is represented as:

$$2.6777\text{E-}02 - 9.0145\text{E-}05 \leq \theta_{195} \leq 2.6777\text{E-}02 + 9.0145\text{E-}05$$

Figure 43 shows the confidence interval of the simulation results of the Random and LENW wavelength assignment algorithms.

Figure 43. Confidence Interval of the Random and LENW algorithms

From figure 43 we can see, the estimator of the traffic blocking probability based on the simulation results is approximately unbiased.

6.3.2 Confidence interval of the simulation results of the ClaServ method

Table 6.3 gives the simulation results of the 4-hop traffic's blocking probability and output analysis of the mesh torus network without using ClaServ method. Table 6.4 gives the simulation results of the 4-hop traffic's blocking probability and the output analysis of the mesh torus network running with the ClaServ method.

Simulation Sequence number	Traffic blocking probability under different traffic load		
	150 calls/unit time	180 calls/unit time	195 calls/unit time
1	0.026935254	0.302332544	0.470292616
2	0.027128172	0.306662999	0.465305465
3	0.026261255	0.304987901	0.466951225
4	0.027091629	0.305751452	0.465724594
5	0.027706788	0.307593491	0.466447231
6	0.027533979	0.303545799	0.468120805
7	0.026556681	0.307206878	0.469272692
8	0.027804371	0.303932451	0.465143332
9	0.027135532	0.304509993	0.467316741
10	0.025937695	0.304509612	0.467784947
11	0.025357238	0.304375048	0.465696749
12	0.025862607	0.302177733	0.467014011
13	0.025908437	0.301321149	0.469902765
14	0.026930775	0.304532468	0.467461747
15	0.026971386	0.303971468	0.465900859
16	0.026724978	0.306017123	0.467647259
17	0.026567127	0.303844203	0.46834589
18	0.027829984	0.303431694	0.464471283
19	0.027636213	0.306723557	0.465518277
20	0.026904292	0.303747721	0.466038846
21	0.027715267	0.302668784	0.466665061
22	0.027703084	0.30396639	0.468823226
23	0.027471754	0.305522173	0.465628312
24	0.027004246	0.302852855	0.464344756
25	0.025813534	0.303339242	0.469739444
26	0.027923856	0.305371711	0.467516877
27	0.026384099	0.305650131	0.467074597
28	0.026256149	0.30616984	0.467321664
29	0.026191721	0.308503004	0.469319535
30	0.026941964	0.304973115	0.462102963
mean	0.026873002	0.304673084	0.466963126
standard error	0.000131308	0.000315015	0.000343269
confidence interval	0.00036241	0.000869441	0.000947422

Table 4. Simulation results and output analysis without the ClaServ method

The simulation output analysis without the ClaServ method can be represented as follows:

When the traffic load is 150 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$2.6873\text{E-}02 - 3.6241\text{E-}04 \leq \theta_{150} \leq 2.6873\text{E-}02 + 3.6241\text{E-}04$$

When the traffic load is 180 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$3.0467\text{E-}01 - 8.6944\text{E-}04 \leq \theta_{180} \leq 3.0467\text{E-}01 + 8.6944\text{E-}04$$

When the traffic load is 195 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$4.6696\text{E-}01 - 9.4742\text{E-}04 \leq \theta_{195} \leq 4.6696\text{E-}01 + 9.4742\text{E-}04$$

Simulation Sequence number	Traffic blocking probability under different traffic load		
	150 calls/unit time	180 calls/unit time	195 calls/unit time
1	0.000303278	0.14981238	0.31393701
2	0.000344162	0.148342489	0.312113911
3	0.000272261	0.147137804	0.311578236
4	0.000349802	0.148153405	0.312103592
5	0.000322782	0.151796523	0.314914484
6	0.000291286	0.153262055	0.314843806
7	0.000355742	0.151536717	0.309874418
8	0.000301881	0.14631765	0.312946481
9	0.00029696	0.149678097	0.314233251
10	0.000375444	0.148792108	0.313684632
11	0.000297214	0.147507349	0.308689223
12	0.000302839	0.148745205	0.314935803
13	0.000370666	0.14909634	0.314608685
14	0.000378951	0.149621399	0.313449747
15	0.000354856	0.149926229	0.315263697
16	0.000255093	0.147586688	0.314528952
17	0.000287398	0.148631186	0.311718929
18	0.000359188	0.152032751	0.31375476
19	0.000238921	0.148663309	0.314353276
20	0.00034551	0.147182608	0.310047102
21	0.000340145	0.148755365	0.310280927
22	0.000323811	0.149278033	0.313732791
23	0.000276158	0.149477526	0.317284742
24	0.000353981	0.151142643	0.312732045
25	0.000322955	0.149681037	0.314532604
26	0.000224545	0.151036891	0.310109454
27	0.00029619	0.149756871	0.311118993
28	0.000296279	0.148505466	0.310846397
29	0.000327961	0.150153279	0.314517676
30	0.000348686	0.147965364	0.312372223
mean	0.000317165	0.149319159	0.312970261
standard error	7.44184E-06	0.000295476	0.000372315
confidence interval	2.05395E-05	0.000815514	0.00102759

Table 5. Simulation results and output analysis with the ClaServ method

The simulation output analysis with the ClaServ method can be represented as follows:

When the traffic load is 150 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$3.1717\text{E-}04 - 2.054\text{E-}05 \leq \theta_{150} \leq 3.1717\text{E-}04 + 2.054\text{E-}05$$

When the traffic load is 180 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$1.4932\text{E-}01 - 8.1551\text{E-}04 \leq \theta_{180} \leq 1.4932\text{E-}01 + 8.1551\text{E-}04$$

When the traffic load is 195 calls per time unit, the 99% confidence interval of the 4-hop traffic's blocking probability is represented as:

$$3.1297\text{E-}01 - 3.7232\text{E-}04 \leq \theta_{195} \leq 3.1297\text{E-}01 + 3.7232\text{E-}04$$

Figure 44 shows the confidence interval of the 4-hop traffic's blocking probability of the simulation results in the mesh torus network running with and without ClaServ method.

Figure 44. Confidence interval with and without ClaServ method

From figure 44, we can see, the estimator of the traffic blocking probability based on the simulation results is approximately unbiased.

Chapter 7

7 Conclusion

7.1 Conclusion

As networks migrate to all-optical networks, novel methods of selecting end-to-end lightpaths are needed. The First-Fit and Random algorithms are subject to a problem of high blocking probability and low utilization. Many distributed wavelength assignment algorithms are proposed to solve this problem with distributed global information. But the dynamic nature of network traffic requires assign wavelength to lightpath with local information.

We have proposed two new distributed wavelength assignment algorithms, the LNW and the LENW, which assign wavelength to the lightpath relying only on local information in a distributed manner. By considering the occupation information of wavelengths in the neighborhood of a path, LNW finds one of the most occupied available wavelengths represented by the heaviest weight and assigns it to the path. The LENW is a special case of the LNW algorithm with only considering the wavelengths occupation information on the neighborhoods of the lightpath's source node and destination node. The two algorithms are only slightly complicated than the First-Fit and Random algorithms and easily to be implemented into the distribute-controlled signaling

protocol as showed in Chapter 3. Under a 4x4 mesh torus network topology as showed by simulation, the LNW algorithm produces a 10 times lower average traffic blocking probability than Random and First-Fit algorithms, the simulation results also show the LNW optimize the fairness problem by 10 times when comparing with the First-Fit and Random algorithms in the condition of the network is required running under small blocking probability. The LENW's performance is slightly worse than the LNW algorithm but it introduces less computation and packet overhead to the network.

As carriers and ISPs deploy all optical networks, a growing concern will arise by customers that they will not get the same level of service for their lightpath establishment requests, due to the Fairness Problem. As the number of peers in an optical network grows in size, the difficulty to establish longer lightpaths to those peers will also increase. The traffic classification and service (ClaServ) method has been proposed to reduce and optimize the Fairness Problem, maximizing the usage of the wavelengths through the classification of traffic and the division of wavelengths into wavebands. The network running with the ClaServ optimizes the traffic distribution to reduce the blocking probability of the connection requests of the long lightpath (3, or 4 hop in a 4x4 mesh torus network or NSFNET) with only slight affection of the establishment of the short lightpaths (1, or 2 hop in a 4x4 mesh torus network or NSFNET). Carriers and ISPs can benefit from using ClaServ to bring added value to their customers, by guaranteeing a more reliable method of establishing lightpaths to peers.

The simulation results show that when the small blocking probability is required, under a symmetric 4x4 mesh-torus topology, the ClaServ method can reduce the blocking probability 100 times for 4-hop traffic, 4 times for 3-hop traffic, and 20 times for the

overall network traffic; under a asymmetric NSFNET topology, the ClaServ method can reduce the blocking probability 50 times for 4-hop traffic, 2 times for 3-hop traffic, and 10 times for the overall network traffic. The ClaServ method helps the symmetric 4x4 Mesh-Torus network and an asymmetric NSFNET network achieving the fairness for four different types of traffic as well as reducing the average traffic blocking probability when both networks are required to run under small traffic blocking probability.

The ClaServ method can be easily implemented into a distributed managed signaling protocol. The traffic can be classified either at the source node or at the destination node; different service for different traffic can be provided at the destination node with the combination of the waveband access range method and the waveband reservation method.

7.2 Future Research topics

- Further study on the performance of the LNW and LENW algorithms in the asymmetric network such as the NSFNET in two aspects: the network overall traffic blocking probability and the fairness problem.
- The LNW and LENW algorithms can be first-fit oriented or random oriented. For a network being established without existing lightpaths, the weight of each wavelength is zero, which means all the wavelengths are available to any path. When using the LNW or LENW, the first-fit oriented scenario means to set up the first lightpath with the first available wavelength (the wavelength with the lowest index number); the random oriented scenario means to set up the first

lightpath by randomly select one from the available wavelengths. This thesis use the two algorithms based on the first-fit oriented scenario. Compare the performance of the two scenarios.

- One heuristic that why LNW and LENW could reduce the traffic blocking probability when compared with first-fit and random algorithms is that they increase the interference length (the expected number of hops shared by two sessions which share at least one hop) [31]. Verify this heuristic, and develop the mathematic models for the two algorithms based on this heuristic.
- Assume the number of wavelengths on each link are fixed, separating wavelengths into wavebands play an important role in providing services to classified traffics when network runs with ClaServ method. The hierarchy search of available wavelengths from the accessible wavebands determines how the network runs in a timely manner. Given the number of wavelengths accommodated by each link, research the way for separating the wavelengths into wavebands, find the best scenario to optimize the network performance. For example, 240 wavelength can either be separated into 8 wavebands with each waveband accommodates 30 wavelengths or can be separated into 16 wavebands with each waveband accommodates 15 wavelengths, find one of the two scenarios or other scenarios which can benefit the network most.
- The ClaServ method is independent of the wavelength assignment algorithms. The ClaServ method assigns classified traffic the accessible wavebands. When wavelengths are find available from the accessible wavebands in the traffic, one of the wavelength assignment algorithms has to be used to assign the wavelength

to the traffic. This thesis studies the network performance in the scenario of combining the ClaServ method and Random wavelength assignment algorithm at the same time. Compare this scenario with other combinations, such as using the ClaServ method with either First-Fit or LNW at the same time.

- The accessible wavebands are fixed and predetermined for each type of traffic in this thesis. Study the performance of dynamic wavebands access range for the classified traffic according the variable traffic load. For example, in a mesh torus network, when the traffic requests are uniformly distributed among all the nodes, the percentage of traffic load for different type of traffic is fixed, 12.5% of the traffic is 1-hop traffic, 37.5% of the traffic is 2-hop traffic, 37.5% of the traffic is the 3-hop traffic, the rest is the 4-hop traffic. The percentage of traffic load for different type of traffic can be dynamic when other traffic request distributions are introduced to the networks. Study the approach to automatically change the accessible wavebands for each type of traffic according the dynamic traffic load. This approach has to consider the network topology and traffic load prediction.
- The ClaServ method obtains great improvement in optimizing the fairness problem for both the symmetric and asymmetric networks in the heuristic that the ClaServ method optimizes the traffic distribution. Verify and validate this heuristic with mathematic models.

Bibliography

- [1] Rajiv Ramaswami, Kumar Sivarajan, "Optical Networks: A Practical Perspective (Second Edition)," Morgan Kaufmann Publishers, October 2001.
- [2] Sharma, R.; MacDonald, R.I. "A signal transparent 10/spl times/10 space-division optoelectronic switch core for virtual-transparent path-based multiwavelength networks", Lightwave Technology, Journal of , Volume: 15 Issue: 8 , Page(s): 1522 – 1529, Aug. 1997
- [3] Luss, H.; Rosenwein, M.B.; Wong, R.T. "Topological network design for SONET ring architecture Systems", Man and Cybernetics, Part A, IEEE Transactions on , Volume: 28 Issue: 6 , Page(s): 780 –790, Nov. 1998 .
- [4] Chu, P.B.; Shi-Sheng Lee; Sangtae Park, "MEMS: the path to large optical crossconnects" IEEE Communications Magazine , Volume: 40 Issue: 3 , Page(s): 80 –87, March, 2002
- [5] Keyao Zhu; Mukherjee, B. "Traffic grooming in an optical WDM mesh network " Selected Areas in Communications, IEEE Journal on , Volume: 20 Issue: 1 , Page(s): 122–133, Jan. 2002
- [6] B. Mukherjee, Optical Communication networks. New York: McGraw-hill, 1997.
- [7] Circuits and Systems, "Dense Wavelength Division Multiplexing", Tutorial Guide, The IEEE International Symposium, 2001, pages: 9.3.1-9.3.10

- [8] Ting Wo Chung, John Coulter, Jeff Fitchett, Sam Mokebel, Bill St. Arnaud, “ Architectural and Engineering Issues for building an Optical Internet”
<http://www.canet2.net>
- [9] Nagatsu, N. “Photonic network design issues and applications to the IP backbone”
Lightwave Technology, Journal of , Volume: 18 Issue: 12 , Page(s): 2010 –2018,
Dec.2000
- [10] Banerjee, D.; Mukherjee, B. “Wavelength-routed optical networks: linear
formulation, resource budgeting tradeoffs, and a reconfiguration study”,
Networking, IEEE/ACM Transactions on , Volume: 8 Issue: 5 , Page(s): 598 –607,
Oct.2000
- [11] Perlin, V.E.; Winful, H.G.,”All Fiber Wavelength Conversion Using Cross-Phase
Modulation and Bragg Gratings”,IEEE Photonic Technology Letters, Volume: 14,
Issue:2, Feb, 2002, Page(s): 176-178
- [12] John Strand, Robert Doverspike, Guangzhi Li,” Importance of Wavelength
Conversion in an Optical Network”, Optical Networks Magazine, Issue: 6, Page(s):
33-44, June, 2001,
- [13] Bala Rajagopalan, Dimitrios Pendarakis, “ Ip over optical networks: Architectural
Aspects”, IEEE Communication Magazine, Volume: 23, Issue: 9, Sep. 2000, page(s):
94-102
- [14] Guang Zhi Li, Yates, J., Dongmei Wang, “ Control Plane Design For Reliable
Optical Networks”, IEEE Communication Magazine, Volume: 40, Issue: 2, Feb.
2002, page(s): 90-96

- [15] Strand, J.; Chiu, A.L.; Tkach, R. "Issues for routing in the optical layer", IEEE Communications Magazine , Volume: 39 Issue: 2 , Page(s): 81 –87, Feb. 2001
- [16] Grover, W.; Doucette, J.; Clouqueur, M.; Leung, D.; Stamatelakis, D. "New options and insights for survivable transport networks", IEEE Communications Magazine , Volume: 40 Issue: 1 , Page(s): 34 –41, Jan. 2002
- [17] Banerjee, A.; Drake, L.; Lang, L.; Turner, B.; Awduche, D.; Berger, L.; Kompella, K.; Rekhter, Y. "Generalized multiprotocol label switching: an overview of signaling enhancements and recovery techniques", IEEE Communications Magazine , Volume: 39 Issue: 7 , Page(s): 144 –151, July 2001
- [18] I. Chlamtac, A. Ganz, and G. Karmi. "Lightpath Communications: An Approach to High-Bandwidth Optical WAN ", IEEE Transactions on Communications, vol. 40, no. 7, pp. 1171-1182, July 1992.
- [19] K. Bala and T.E.Stern, "Algorithms for Routing in a Linear Lightwave Network", Proceedings, IEEE Inforcom'91, Miami, FL, Apr. 1991.
- [20] A. Birman and A. Kershenbaum, "Routing and Wavelength Assignment Methods in Single-Hop All-Optical Networks with Blocking", Proceedings, IEEE Infocom'95, Boston, MA, Vol.2, Apr. 1995, pp. 431-438
- [21] H. Harai, M. Murata, and H. Miyahara, "Performance of Alternate Routing Methods in All-Optical Switching Networks", Proceedings, IEEE Infocom'97, Kobe, Japan, Apr. 1997, pp. 516-524
- [22] S. Ramamurthy and B. Mukherjee, "Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks", Proceedings, IEEE Globecom'98, Australia, Nov. 1998, pp. 2295-2302.

- [23] S. Ramamurthy, "Optical Design of WDM Network Architectures", Ph.D. Dissertation, University of California, Davis, 1998.
- [24] S. Ramamurthy and B. Mukherjee, "Survivable WDM Mesh Networks, Part I – Protection", Proceedings, IEEE Inforcom'99, New York, NY, vol. 2, pp. 744-751, March, 1999.
- [25] A. Mokhtar and M. Azizoglu, "Adaptive Wavelength Routing in All-Optical Networks", IEEE/AGM Transactions on Networking, vol. 6, No. 2, 1998, pp. 197-206
- [26] R. Ramaswami and A. Segall, "Distributed Network Control for Wavelength Routed Optical Networks", Proceedings, IEEE Infocom'96, San Francisco, CA, Mar. 1996, pp. 138-147
- [27] H. Zang, L. Sahasrabudhe, J.P.Jue, S. Ramamurthy, and B. Mukherjee, "Connection Management for Wavelength-Routed WDM Networks", Proceedings, IEEE Globecom'99, Rio de Janeiro, Brazil, Dec. 1999, pp. 1428-1432
- [28] H. Zang, J.P. Jue, and B. Mukherjee, "Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks", Optical Network Magazine vol.1, No.1, Jan. 2000, pp. 47-60
- [29] S.Subramaniam and R. A. Barry, "Wavelength Assignment in Fixed Routing WDM Networks", Proceedings, ICC'97, Montreal, Canada, vol. 1, pp. 406-410, June,1997
- [30] Yongbing Zhang; Taira, K.; Takagi, H.; Das, S.K. "An efficient heuristic for routing and wavelength assignment in optical WDM networks", Communications, 2002. ICC 2002. IEEE International Conference, Volume: 5 , 2002 Page(s): 2734 –2739

- [31] Bary and P. Humblet, "Models of Blocking Probability in All-Optical Networks with and without Wavelength Changers", Proceedings, IEEE Infocom'95, pp. 402-412, Boston, April 1995.
- [32] A. Aggarwal et al. "Efficient routing and scheduling in optical networks", Proceeding of the ACM-SIAM Symp. On discrete algorithms (SODA'93), 1993, pp. 412-423.
- [33] I. Chlamtac, A. Ganz, and G. Karmi. "Lightpath communications: an approach to high bandwidth optical WANs", IEEE Trans. On Communications, vol. 40, July 1992, pp. 1171-1182.
- [34] R. Ramaswami and K.N. Sivarajan. "Optimal routing and wavelength assignment in all optical networks", Proceedings of IEEE, infocom, June 1994, pp. 970-979.
- [35] X. Yuan, R. Melhem, R. Gupta, Y. Mei, C. Qiao, Distributed Control Protocols For Wavelength Reservation And Their Performance Evaluation, in Photonic Networks and Communications, Vol. 1, No. 3, 1999. pp. 207-218.
- [36] M. Kovacevic and A. Acampora, "On wavelength translation in all optical networks", IEEE infocom'1995, Boston, MA. Apr. 1995, pp. 651-657.
- [37] A. Birman, "Computing approximate blocking probabilities for a class of all-optical networks", IEEE infocom'1995, Boston, MA. Apr. 1995, pp. 651-657.
- [38] K. Sivarajan and R. Ramaswami, "Lightwave networks based on debruijn graphs," IEEE Trans. Networking, vol. 2, Feb. 1994.

Appendix

A number of publications were produced in this thesis and are listed below:

- Y. Li, M. Francisco, I. Lambadaris, C. Huang, “*Traffic Classification and Service in all optical networks*”, to appear in proceedings SPIE APOC 2002, ShangHai, China, Oct. 2002, paper number: 4910-49
- Y. Li, M. Francisco, I. Lambadaris, C. Huang, “*The distributed wavelength assignment algorithm with neighborhood wavelength utilization information*”, to be submitted to IEEE/ICC 2003, Anchorage, Alaska, May 2003
- Y. Li, M. Francisco, I. Lambadaris, C. Huang, “*Traffic Classification and Service in wavelength-routed all optical networks*”, to be submitted to IEEE/ ICC 2003, Anchorage, Alaska, May 2003
- X. Sun, Y. Li, I. Lambadaris, Y. Zhao, “*Performance Analysis of First-Fit wavelength Assignment Algorithm*”, to be submitted to IEEE/ ICC 2003, Anchorage, Alaska, May 2003