ABSTRACT

Title of Thesis: Routing in SONET/VCAT based Optical WDM Networks

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In this thesis, we investigate problems related to optical wavelength division multiplexing (WDM) networks that use the virtual concatenation (VCAT) mechanism of synchronous optical network (SONET) technology. SONET has been a successful standard for communicating digital information over optical fiber. The VCAT technique, which was proposed as a part of the next-generation SONET, can support the increasing bandwidth demands economically. VCAT allows SONET based optical WDM networks to carry traffic via multiple paths, which leads to efficient utilization of link capacity and implicit partial link failure protection if paths are link-disjoint. However, multi-path routing causes differential delay among constituent paths and requires high-speed buffer capacity at receiving nodes. Thus, we propose two route selection methods to study the tradeoffs of VCAT's multi-path routing feature. The performance analysis is conducted using a discrete-event simulation model. Optical WDM grooming networks under dynamic traffic demand, with and without wavelength conversion, are considered. Our simulation results quantify the costs and benefits of using VCAT's multi-path routing instead of the traditional single-path routing.

Routing in SONET/VCAT based Optical WDM Networks

by

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To my mother, Lan Fang Yang

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Chapter 1

INTRODUCTION

Wavelength division multiplexing (WDM) has significantly expanded the capacity of optical networks by allowing different wavelengths to be combined and transmitted simultaneously over the same optical fiber [6]. Synchronous optical network (SONET) is a successful standard for communicating digital information over optical fiber and it forms the basis of current high-speed backbone networks [4]. The increasing bandwidth demands are placing a heavier load on the current network infrastructure. Deploying additional hardware equipment and laying extra optical fibers are expensive. Therefore, improving upon current technologies is a more feasible solution.

Virtual concatenation (VCAT) addressed the bandwidth inefficiency of the traditional SONET concatenation mechanism [10]. This technique can split requested connection bandwidth into a set of traffic sub-streams and route them across the network via multiple paths. The benefits of VCAT's multi-path routing feature include efficient utilization of link capacity, more evenly distributed traffic load, and implicit partial link failure protection if paths are link-disjoint [2]. However, the cost is the requirement of high-speed buffer capacity at receiving nodes. When multiple paths are used to route a connection, the difference between its longest and shortest path delay is known as the differential delay. The existence of differential delay requires the receiving node to store information until data from all constituent paths reach the destination. The buffer capacity increases as transmission rate and differential delay increase. In an optical WDM network that has 16 wavelengths per link and a wavelength capacity of OC-48 (2.5 gigabits per second), an average differential delay of 10 milliseconds requires 50 megabytes of buffer capacity per link.

This thesis aims to quantify the costs and benefits of using VCAT's multi-path routing instead of the traditional single-path routing. We propose two route selection methods to study the tradeoffs: single-path and multi-path. The *single-path* method routes a connection's traffic sub-streams using the same wavelength on a single path and the *multi-path* method routes a connection's traffic sub-streams using as many link-disjoint paths as possible. While the single-path method avoids the differential delay problem by using only one path, it also forgoes the potential benefits of routing with multiple paths mentioned earlier.

A discrete-event simulator is used for performance analysis. We consider optical WDM grooming networks under dynamic traffic demand, with and without wavelength conversion. Performance evaluation metrics include blocking probability, link utilization, connection setup time, differential delay, and implicit link failure protection ratio.

The simulation results confirm the benefits of using VCAT's multi-path routing feature. Despite higher link capacity usage, the multi-path method consistently outperforms the single-path method by 50 percent or more in blocking performance. In the event of a link failure, the implicit protection ratio increases as connections use more link-disjoint paths. The results also show that differential delay, which is the cost of using VCAT's multi-path routing feature, increases as the number of link-disjoint paths increases.

The rest of this thesis is organized as follows. In chapter 2, we provide a brief description of optical WDM networks, SONET, VCAT, routing and wavelength assignment, wavelength conversion, traffic grooming, and survival techniques in optical WDM networks. In chapter 3, we explain the route selection methods used to study the tradeoffs of VCAT's multi-path routing feature. In chapter 4, we explain the simulation model used for performance analysis and compare the performance of the route selection methods. In chapter 5, we state our conclusions and scope for future work in this area.

Chapter 2

BACKGROUND AND RELATED WORK

This chapter provides a brief description of the following topics: optical WDM networks, SONET, VCAT, routing and wavelength assignment, wavelength conversion, traffic grooming, and survival techniques in optical WDM networks.

2.1 Optical WDM Networks

Optical fiber has an extremely high theoretical bandwidth, approximately 25 terahertz in the 1.55 low-attenuation band, which is equivalent to 1,000 times the total radio bandwidth on the Earth [6]. However, only transmission rates of a few gigabits per second (Gbps) are achieved in optical networks due to the limited electronic speed in which users can access the network. Thus, it is difficult to fully utilize the bandwidth offered by optical fiber using only a single wavelength channel.

Wavelength division multiplexing (WDM) is a technology which can send multiple light beams of different wavelengths simultaneously through an optical fiber [6]. A WDM system uses a multiplexer to combine signals at the transmitter end. Once signals arrive at the receiver end, a demultiplexer is used to split them apart. In Fig 2.1, four optical signals with different wavelengths are combined and transmitted simultaneously over the same optical fiber. This technique can increase optical fiber's usable bandwidth and expand network capacity without laying more optical fibers. Modern systems can support up to 160 signals per optical fiber [8]. With a basic transmission rate of 10 Gbps, WDM systems can theoretically have a capacity of 1.6 terabits per second per optical fiber.

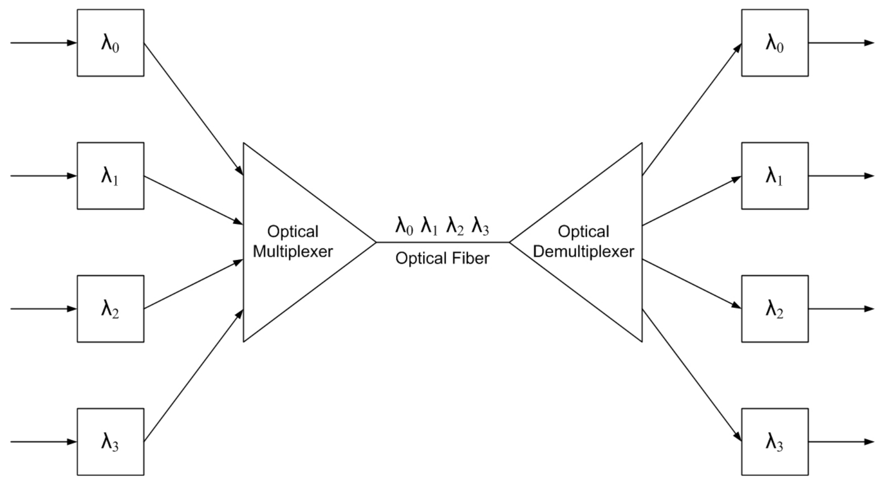


FIG. 2.1. Wavelength division multiplexing

Wavelength routing in optical WDM networks allows network nodes to communicate with each other via all-optical lightpaths [8]. Figure 2.2 shows a typical wavelength-routed optical WDM network where optical routing nodes are interconnected by fiber links. When a message is sent from the source node to the destination node using a lightpath, optical-electronic-optical conversion and buffering at the intermediate nodes are not required. Thus, a lightpath between two nodes is an all-optical communication path [6]. In wavelength-routed networks, two lightpaths can use the same wavelength if their underlying physical paths are link-disjoint. This wavelength reuse feature can increase the number of lightpaths established given a limited number of wavelengths.

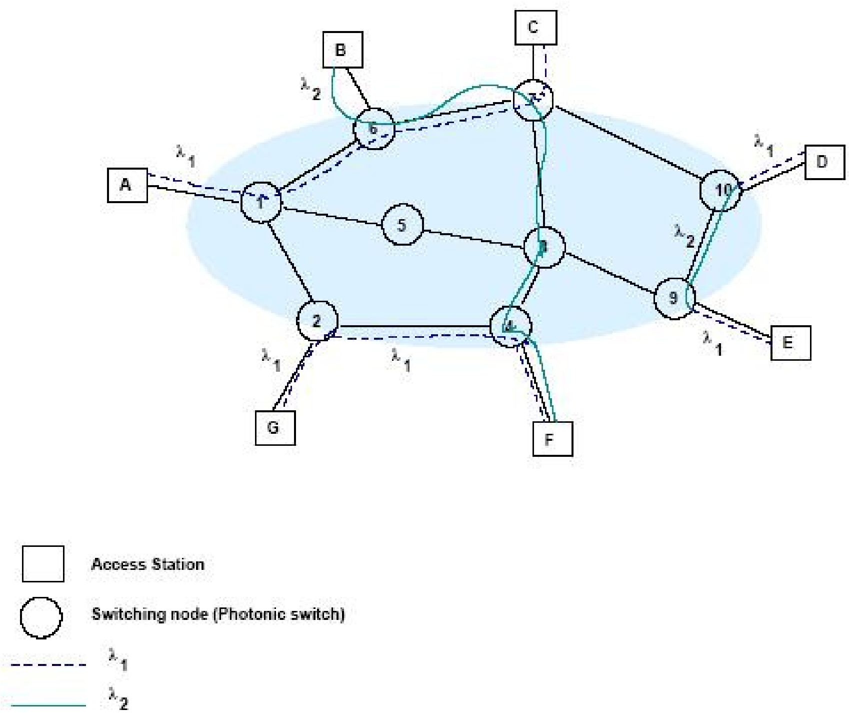


FIG. 2.2. A wavelength-routed optical WDM network

2.2 SONET

Synchronous optical network (SONET) is a successful standard for communicating digital information over optical fiber [4]. It forms the basis of current high-speed backbone networks and allows transmission of data and voice up to 40 gigabits per second (Gbps).

A standard frame consists of a header and a payload where the payload follows the header during the transmission process. A SONET frame also has two components: overhead and payload. The overhead in a SONET frame is the same as the header in a standard frame. However, overhead is not completely transmitted before the payload. The transmission of overhead and payload is interleaved, which implies part of the overhead is followed by part of the payload, then the next part of the overhead and next part of the payload, until the whole frame has been transmitted. SONET frames are 810 bytes in size and are transmitted in exactly 125 microseconds [4].

The bandwidth in SONET is represented by OC-n (Optical Carrier-n) where n typically starts at 3 and increases by multiples of 4. The basic unit is OC-1 and it specifies an approximate transmission rate of 51.84 megabits per second (Mbps) [4]. Thus, OC-192 and OC-768 correspond to approximate transmission rates of 10 Gbps and 40 Gbps respectively.

2.3 VCAT

Virtual concatenation (VCAT) is an inverse multiplexing technique [7] used to split SONET bandwidth into a set of traffic sub-streams, which can be routed independently across the network. It was proposed as a part of the next-generation SONET to address the inefficiency of the traditional concatenation method - contiguous concatenation (CCAT) [2]. In CCAT, concatenation functionality is required at source, destination, and all intermediate nodes, which could be expensive to implement. However, in VCAT, only the source and the destination requires concatenation functionality. Since the sizes of concatenated payload containers in CCAT are fixed, a large amount of bandwidth could be wasted. For example, routing a Gigabit Ethernet connection within a concatenated OC-48 (2.5 Gbps) channel leads to a 60 percent bandwidth waste. VCAT solves this problem by allowing concatenated payload containers of arbitrary sizes.

VCAT enables SONET based optical WDM networks to carry traffic in finer granularity and to efficiently utilize link capacity [10]. When the network is congested, the ability to split the bandwidth over multiple paths can significantly increase the number of connection requests admitted. In addition, multi-path routing allows traffic load to be more evenly distributed in the network and provides implicit partial link failure protection if paths are link-disjoint. However, VCAT is subjected to the problem of differential delay. For a connection that uses multiple paths, the difference between its longest and shortest path delay is known as the differential delay. For example, assume that connection N uses two paths and their delays are 10 milliseconds and 15 milliseconds respectively, then N's differential delay is 5 milliseconds. The disadvantage of differential delay is the requirement of installing high-speed buffer capacity at the receiving node to store information until data from all constituent paths reach the destination. The size of buffer required could be substantial as transmission rate and differential delay increase.

2.4 Routing and Wavelength Assignment

Connections in wavelength-routed optical WDM networks are realized by lightpaths. The routing and wavelength assignment (RWA) problem involves selecting a suitable route and assigning a wavelength to the selected route in order to establish a lightpath between any source-destination pair [6]. RWA is a critical problem in wavelength-routed optical WDM networks and an efficient RWA algorithm can significantly improve network performance.

Network traffic demand can be either static or dynamic. In the case of a static traffic demand, connection requests are known in advance and lightpaths can be predetermined. The goals of static RWA algorithms are to maximize the number of connection requests admitted and to minimize the number of wavelengths used. These two problems are known as the static lightpath establishment (SLE) problem, which has been shown to be NP-complete (no known algorithm can find the optimal solution within a polynomial time constraint) [6]. In the case of a dynamic traffic demand, connection requests arrive in a random manner and lightpaths are established on a demand basis. A dynamic RWA algorithm should assign routes and wavelengths to new requests with the goal of maximizing the number of connection requests admitted. Since requests are processed at the time of arrival, solutions to the dynamic RWA problem must be computationally simple.

2.5 Wavelength Conversion

The usage of wavelength converters at routing nodes can overcome the bandwidth loss caused by the wavelength continuity constraint [6]. A wavelength converter is an optical device that can shift wavelengths used by connections to other wavelengths and its capability is characterized by the degree of conversion. A converter with a conversion degree (D) of C can shift a wavelength to any one of C wavelengths. If the conversion degree is equal the number of wavelengths per optical fiber (W), then the converter has full degree of conversion. Otherwise, it has partial or limited degree of conversion. Optimal network performance can be reached by deploying F x W full-degree converters at each node, where F is equal to the number of incoming optical fibers at each node. However, this approach may be economically infeasible because converters are expensive and their cost increases with the conversion degree.

2.6 Traffic Grooming

Traffic grooming is a technique which allows multiple connections to share a wavelength [3]. Since the majority of traffic streams use only a fraction of the wavelength capacity, the ability to carry multiple connections on a single wavelength can greatly reduce bandwidth waste and significantly increase the number of connection requests admitted to a network. In WDM networks with optical traffic grooming, a single wavelength is organized as a time-division multiplexed frame with time slots. Traffic streams on the same wavelength have their own time slots and they can be dropped by a single optical add-drop multiplexer.

2.7 Survival Techniques in Optical WDM Networks

The failure of network components can cause traffic disruption in optical WDM networks. Commonly studied failures and their potential causes [8] are listed below. Since link failures occur most frequently, they are the focus of this study.

- **Link failures**: fiber cuts, failure of link components such as signal amplifiers and regenerators.
- **Node failures**: operator errors, power outages.
- **Channel failures**: failure of transceiver equipment.

Due to optical fiber's ultra-high bandwidth, network component failures can cause an enormous amount of data loss. Thus, optical WDM networks must be designed to respond gracefully to these failures. Survival techniques are classified as either protection or restoration [8].

2.7.1 Protection

Protection is a proactive mechanism that requires the reservation of backup resources at the connection setup time. For each connection request, link-disjoint primary and backup paths are established. A connection can either have its own backup path or share a backup path with other connections. In the event of a link failure, the traffic on the primary path will be switched to the backup path. The protection approach guarantees fast recovery in case of a failure. However, it causes inefficient utilization of resources since backup paths are unused if no failure occurs.

2.7.2 Restoration

Restoration is a reactive mechanism that handles a failure after its occurrence. In the event of a link failure, the RWA algorithm finds backup paths to reroute all traffic on the failed link. The restoration approach can efficiently utilize backup resources by using them only in case of a failure. However, it does not guarantee to find a backup path for all affected connections. In addition, its recovery time could be much longer than the protection approach since additional computation and signaling are required.

2.8 Related Work

In [3] and [9], the authors considered an explicit partial link failure protection mechanism where each connection has a primary path and a backup path. The backup bandwidth is a fraction of the primary bandwidth. In case of a link failure, the connection is carried on the backup path with reduced capacity and the system will try to identify additional capacity on the same backup path. In this thesis, we only consider the implicit partial link failure protection provided by VCAT's multi-path routing feature and we do not attempt to find additional capacity when link failure occurs.

The benefits of SONET VCAT on optical WDM grooming networks were explored in [10]. The authors have quantitatively demonstrated that VCAT can improve bandwidth efficiency, simplify network control, and balance network load. In this thesis, we investigate VCAT's effect on link capacity utilization and link failure protection in great detail.

There are heuristic based algorithms that attempt to minimize the differential delay, which is directly proportional to the buffer capacity required. In [1], the authors considered the problem of minimizing the differential delay in a virtually concatenated Ethernet over SONET system by suitable path selection. In order to keep our heuristic simple, we do not attempt to minimize differential delay during the path selection process.

Chapter 3

PROPOSED MECHANISM

This chapter explains the route selection methods used to study the tradeoffs of SONET VCAT's multi-path routing feature.

3.1 Route Selection Methods

The virtual concatenation (VCAT) technique in the next-generation synchronous optical network (SONET) can split requested connection bandwidth into a set of traffic substreams, which can be independently routed across the network via multiple paths. The benefits of routing traffic with multiple paths include efficient link capacity utilization, more evenly distributed traffic load, and implicit partial link failure protection if paths are link-disjoint. However, these benefits come at the cost of differential delay and additional buffer capacity. We want to study the tradeoffs of SONET VCAT's multi-path routing feature in optical WDM grooming networks under dynamic traffic demand, with and without wavelength conversion. Thus, we propose two route selection methods: single-path and multi-path. In the following subsections, s = source, d = destination, b = requested connection bandwidth, and p = maximum number of link-disjoint paths between s and d.

3.1.1 Single-Path

VCAT can route a connection across the network using either a single path or multiple paths. The usage of multiple paths would result in differential delay since paths are likely to have different delays. The simplest way to eliminate differential delay is to route the connection using only one path. We define *single-path* as a method that routes all SONET VCAT traffic sub-streams of a connection using the same wavelength on a single path. The heuristic for this approach works as follows:

- **Step 1**: find the shortest path between s and d such that each link on the path has one or more wavelengths with free capacity of at least b. If no such path exists, then the connection request is blocked and the algorithm ends.

- **Step 2**: select appropriate wavelengths for the lightpath. Without wavelength conversion, the establishment of a lightpath requires the usage of the same wavelength on all links. With wavelength conversion, different wavelengths can be used. If a lightpath can not be established, then the connection request is blocked and the algorithm ends.

- **Step 3**: update the available capacity of links along the path.

3.1.2 Multi-Path

Routing traffic across the network via multiple paths allows efficient utilization of link capacity and more evenly distributed traffic load. In addition, connections receive implicit partial link failure protection if paths are link-disjoint. We *multi-path* as a method that routes SONET VCAT traffic sub-streams of a connection using as many link-disjoint paths as possible where the requested bandwidth is divided equally among all paths. The single-path method provides no protection in the event of a link failure. However, in this multi-path approach, the implicit protection ratio increases as the number of link-disjoint paths increases. The heuristic works as follows:

- **Step 1**: find *p*, which is the minimum of two values: the number of outgoing links at *s* and the number of incoming links at *d*.
- **Step 2**: evenly divide *b* into *p* pieces with OC-1 as the basic unit. Examples are listed in Table 3.1.

Requested Bandwidth	**# Link-Disjoint Paths**	**Traffic Sub-Streams**
OC-1	3	OC-1
OC-2	3	OC-1, OC-1
OC-9	3	OC-3, OC-3, OC-3
OC-10	3	OC-4, OC-3, OC-3
OC-11	3	OC-4, OC-4, OC-3

Table 3.1. Bandwidth splitting examples

- **Step 3**: find a path for each traffic sub-stream using the single-path route selection heuristic described earlier such that all paths are link-disjoint.
- **Step 4**: if the number of paths found is less than the number of traffic sub-streams and *p* is greater than 1, then decrement *p* by 1 and repeat Step 2 and 3.
- **Step 5**: if the number of paths found is equal to the number of traffic sub-streams, then calculate the differential delay and update the available capacity of links along all paths. Otherwise, the connection request is blocked.

The single-path method avoids the differential delay problem. However, it forgoes the potential benefits of routing with multiple paths. The complexity of these route selection methods are dominated by the running time of Dijkstra's algorithm, which is a part of routing and wavelength assignment (RWA). With a linear storage implementation, Dijkstra's algorithm has a complexity of $O(n^2 + m)$ where n is the number of nodes and m is the number of links. The single-path method is simple and it only has to perform RWA once in all cases. The multi-path method is more computationally expensive compared to the single-path method because it has to perform RWA p times in the best case and $p(p + 1) / 2$ times in the worst case.

Chapter 4

PERFORMANCE ANALYSIS

The chapter explains the simulation model used for performance analysis and compares the performance of the route selection methods.

4.1 Simulation Model

We created a discrete-event simulator using the YACSIM library [5] and made the following assumptions in our model:

1. A network with dynamic traffic demand where connections arrive and leave the network, one at a time, following a Poisson arrival process and negative-exponential-distribution duration.

2. The selection of source and destination for each connection request is based on a uniform distribution. The source is first selected from the set of all possible nodes, and then the destination is selected from the set of all other nodes.

3. Routing paths are determined at the time of connection request arrival.

4. The Erlang load offered was adjusted for each simulation experiment to keep the blocking probability between 0 and 0.1.

5. There are 16 wavelengths per link and the first-fit algorithm is used for wavelength assignment.

6. All wavelengths have the same capacity of T = OC-48 (2.5 Gbps) and the bandwidth requested by each connection (d_m) is uniformly distributed with a mean of G_{av} [9].

   - For $1 \leq G_{av} \leq T/2$, $d_m \sim$ uniform(1, $2G_{av}$ - 1)
   - For $T/2 < G_{av} \leq T$, $d_m \sim$ uniform($2G_{av}$ - T, T)

   For example, a G_{av} of 18 implies that $d_m \sim$ uniform(1, 35), a G_{av} of 24 implies that $d_m \sim$ uniform(1, 47), and a G_{av} of 30 implies that $d_m \sim$ uniform(12, 48).

7. Link failures are introduced, one at a time, after 10,000 connection requests are made. The arrival process is modeled as a Poisson process with a rate of 0.015λ, which guarantees at least 1 link failure per 100 connection requests. However, we limit the total number of link failures to 1 per 100 connection requests.

8. All nodes in a wavelength-converting network have a converter with a conversion degree (D) of 8 for each wavelength. Such a converter can shift an input signal with wavelength W to an output signal with wavelength W minus 4 (D/2) to W plus 4 (D/2). For example, assume there are 16 wavelengths per link and they are labeled as 0 to 15, a converter with D = 8 at wavelength 7 can output a signal with wavelength 3 to 11. The first-fit algorithm is used for the selection of a different wavelength.

Simulation parameters and their possible values are listed in Table 4.1.

Simulation Parameters	**Values**
# requests per simulation	1,000,000
# wavelengths per link	16
wavelength capacity	OC-48 (2.5 Gbps)
average connection bandwidth (G_{av})	OC-12, 18, 24, 30
connection arrival rate (λ)	10 - 30
mean connection duration ($1/\mu$)	10
link failure arrival rate	0.015λ
mean link failure duration	1
propagation delay per kilometer	5 μs
processing delay per node	100 μs
degree of wavelength conversion (D)	0, 8
network topology	NSFNET, USANET

Table 4.1. Simulation parameters and values

4.2 Performance Metrics

We compare the route selection methods with respect to five performance metrics.

- **Blocking Probability**: we measure *blocking probability* as the number of connection requests rejected over the number of connection requests made.
- **Link Utilization**: we measure *link utilization* as the percentage of total link capacity used at specific points of a simulation experiment. A measurement is taken every 10,000 connection requests and the average is considered.
- **Setup Time**: we measure *setup time* as the amount of time needed to establish a connection, which includes computing routing paths and updating the available capacity of links along all paths.

- **Differential Delay**: given a connection, we measure its *differential delay* as the difference between its longest and shortest path delay. Path delay is measured in seconds and it is defined as the sum of the path length times propagation delay per kilometer and the number of intermediate nodes times processing delay per node.

- **Protection Ratio**: in case of a link failure, we measure *protection ratio* as the residual connection bandwidth over the requested connection bandwidth.

4.3 Performance Results

We considered the 14-node 21-link NSFNET topology and the 46-node 61-link USANET topology in our simulation experiments. Each link is bi-directional and is implemented as two uni-directional links. Three variable parameters are average connection bandwidth (G_{av}), connection arrival rate (λ), and degree of wavelength conversion (D). The values of G_{av} are OC-12, OC-18, OC-24, and OC-30. For each G_{av}, λ is varied to keep the blocking probability between 0 and 0.1. The simulation results for G_{av} = OC-12 are not shown due to extremely low blocking probabilities. We considered optical WDM grooming networks with and without wavelength conversion. Unless specified, results presented in this section exclude wavelength conversion. For each set of parameter values, simulations were run with different random seeds. Since similar outcomes were observed, only one set of results is presented.

4.3.1 NSFNET

We first considered the 14-node 21-link NSFNET topology in Fig 4.1. There are 42 uni-directional links in the network and every node has an equal number of incoming and outgoing links. The number of nodes with 2, 3, and 4 incoming/outgoing links are 2, 10, and 2 respectively.

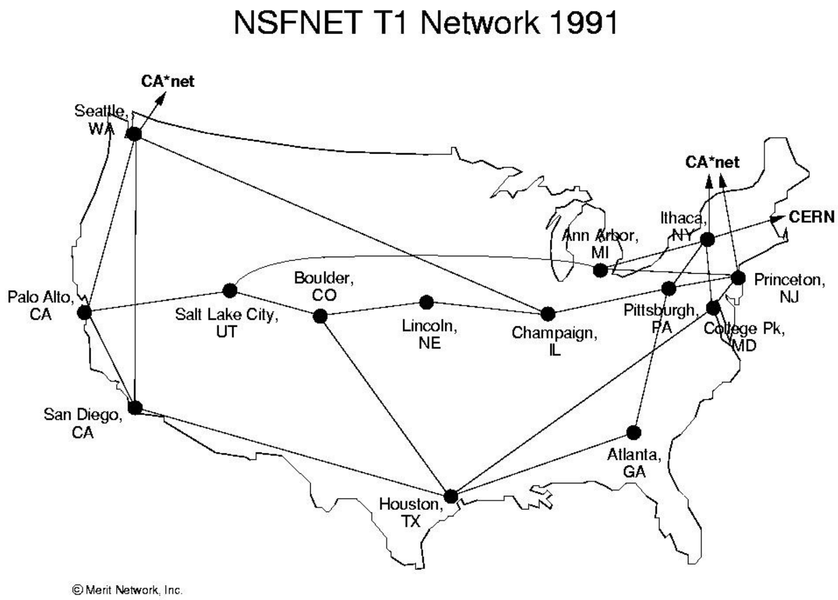


FIG. 4.1. 14-node 21-link NSFNET topology

- Fig 4.2 and Fig 4.3 show that the multi-path method utilizes link capacity more efficiently than the single-path method. For all combinations of G_{av} and λ, the single-path method has more link capacity available on average, but admitted less connection requests compared to the multi-path method. For λ = 20 and G_{av} = OC-24, the multi-path method outperformed the single-path method by 84% despite 44% higher link capacity usage. For G_{av} = OC-24, the improvement ranges from 61% to 93% and it decreases as the traffic load increases.

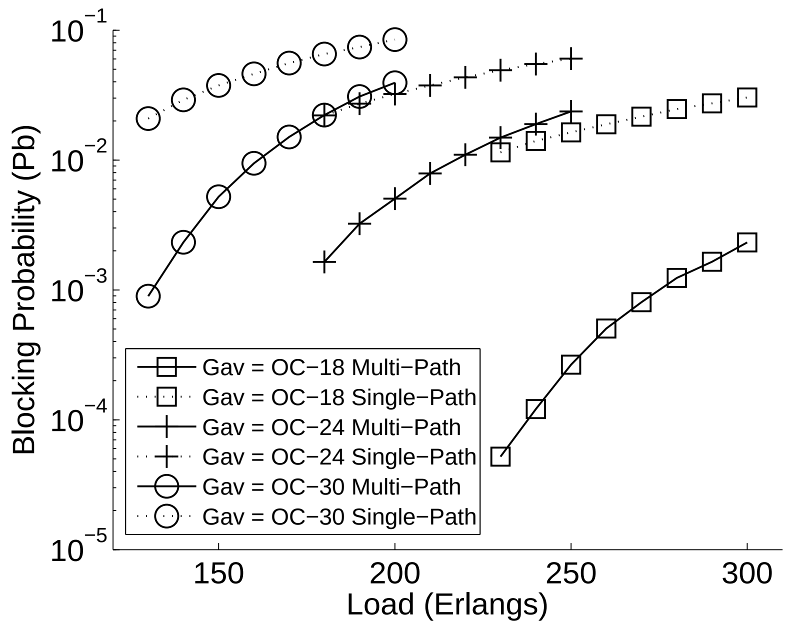


FIG. 4.2. NSFNET - Effect of variation in traffic load on blocking performance

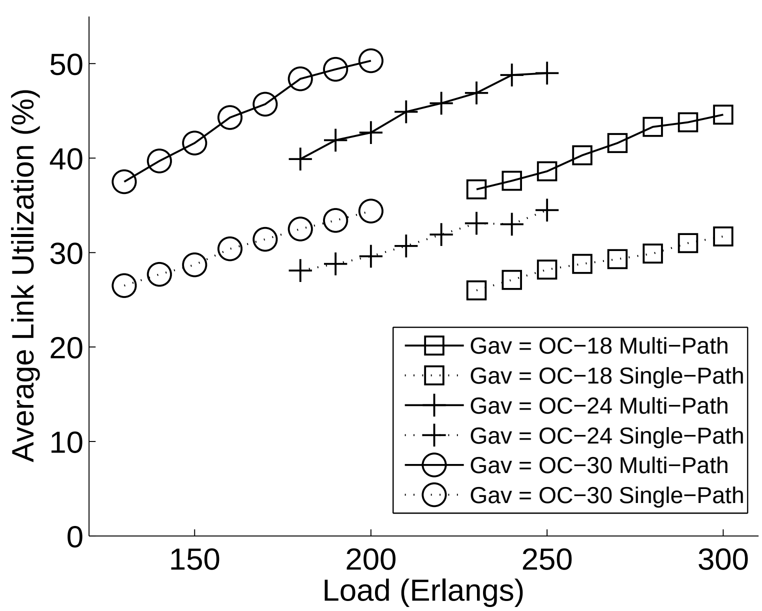


FIG. 4.3. NSFNET - Effect of variation in traffic load on average link utilization

- Fig 4.4 shows that the majority of connections use 3 link-disjoint paths to route their traffic. This is not surprising because 10 out of 14 nodes have 3 incoming/outgoing links. When λ = 20, the percentages of connections requested resulting in multi-path routing are 97%, 96%, and 92% for G_{av} = 18, G_{av} = 24, G_{av} = 30 respectively. Similar outcomes were observed with different values of λ.

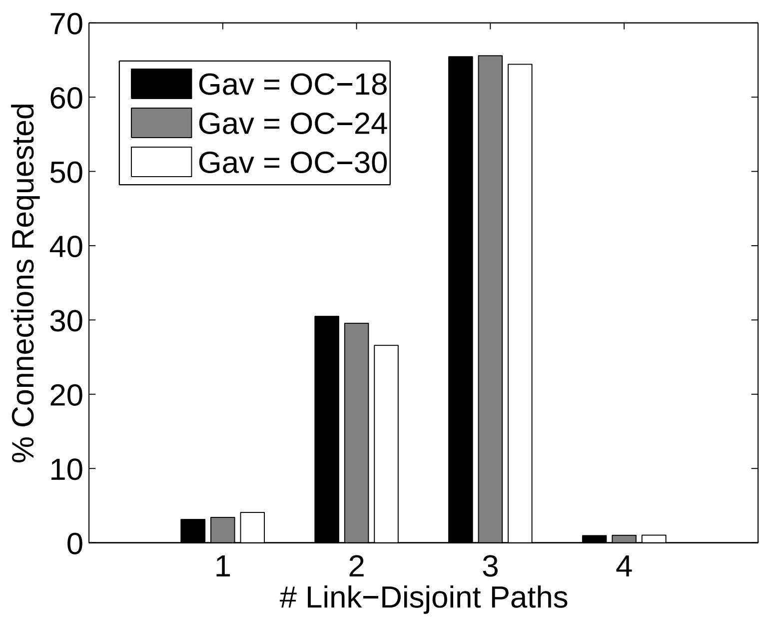


FIG. 4.4. NSFNET - Usage of different number of link-disjoint paths

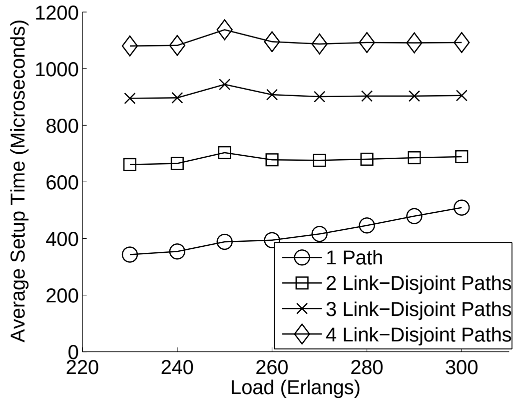
- In a dynamic-traffic network where routing paths are computed on a demand basis, the amount of time needed to establish a connection heavily depends on its number of link-disjoint paths and the network condition. Fig 4.5 shows that the average setup time increases as the number of link-disjoint paths increases. For connections that result in one routing path, their setup time increases with traffic load because less paths are available when the network is congested. For example, assume that the maximum number of link-disjoint paths between *s* and *d* of a connection request is

3. When the network is congested, there is a higher probability that only 1 path is available between *s* and *d*. Since the multi-path method aims to utilize all link-disjoint paths, it will first try to establish the connection using 3 paths. If that fails, then it will try using 2 paths. This method will also try using 1 path if the multi-path approach fails. Thus, the average setup time increases with traffic load for single-path connections.

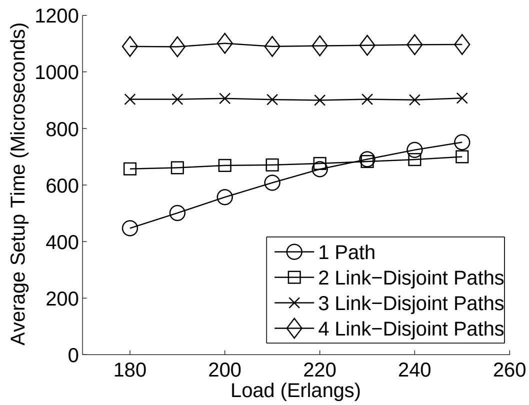
- The benefits of routing traffic with multiple link-disjoint paths include efficient link capacity utilization, more evenly distributed traffic load, and implicit partial protection in case of a link failure. However, these benefits come at the cost of differential delay and additional buffer capacity. Average differential delays and their corresponding buffer requirement per link are shown in Table 4.2. This table also shows that a higher implicit link failure protection ratio implies a longer differential delay. In the worst case where four link-disjoint paths are used, an average differential delay of 26 milliseconds requires 130 megabytes of buffer per uni-directional link. The buffer capacity is calculated as link capacity times differential delay.

# Link-Disjoint Paths	**Protection Ratio (%)**	**Average Differential Delay (ms)**	**Buffer Requirement per Link (MB)**
2	50.0	10.1	50.0
3	66.7	18.4	92.0
4	75.0	26.0	130.0

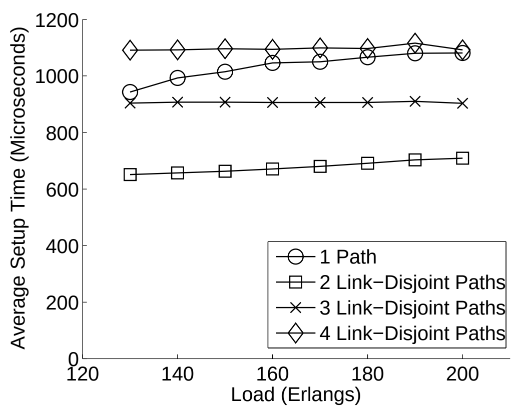
Table 4.2. NSFNET - Effect of variation in number of link-disjoint paths on implicit protection ratio and average differential delay



(a) G_{av} = *OC-18*



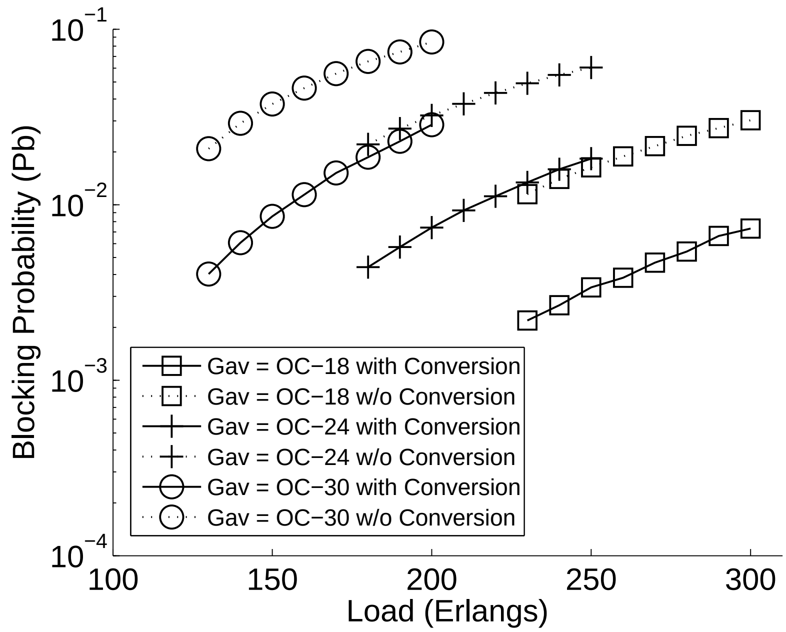
(b) G_{av} = *OC-24*



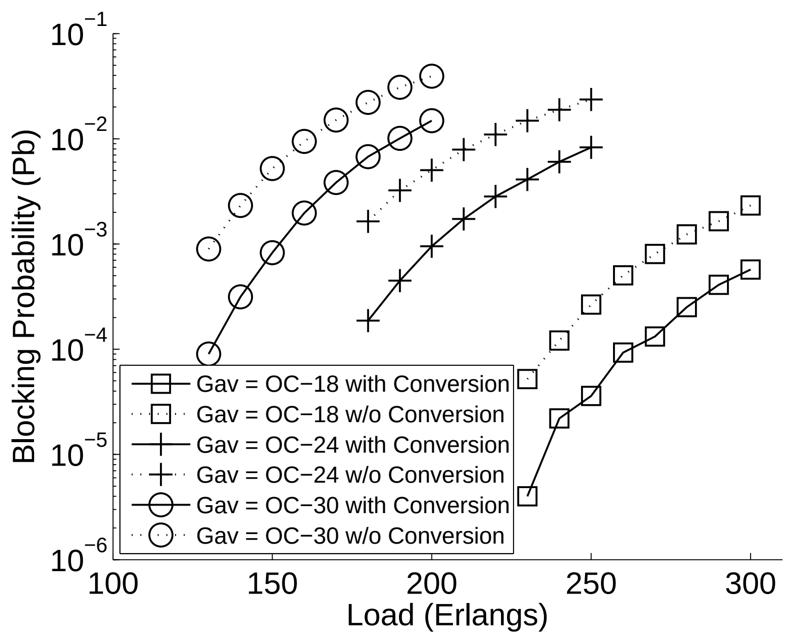
(c) G_{av} = *OC-30*

FIG. 4.5. NSFNET - Effect of variation in number of link-disjoint paths on average setup time

- Wavelength conversion allows the use of different wavelengths on a lightpath and reduces the blocking caused by the wavelength continuity constraint. Thus, results shown in Fig 4.6 are expected. For both methods, single-path and multi-path, a significant reduction in blocking probability was observed. The improvement for G_{av} = OC-24 ranges from 70% to 80% with the single-path method and 65% to 89% with the multi-path method.



(a) *Single-Path*



(b) *Multi-Path*

FIG. 4.6. NSFNET - Effect of wavelength conversion on blocking performance

4.3.2 USANET

We also considered the 46-node 61-link USANET topology in Fig 4.7. There are 122 uni-directional links in the network and every node has an equal number of incoming and outgoing links. The number of nodes with 2, 3, 4, and 5 incoming/outgoing links are 23, 17, 5 and 1 respectively. The trends in NSFNET and USANET simulation results are very similar. Thus, explanations for USANET simulation results are not provided.

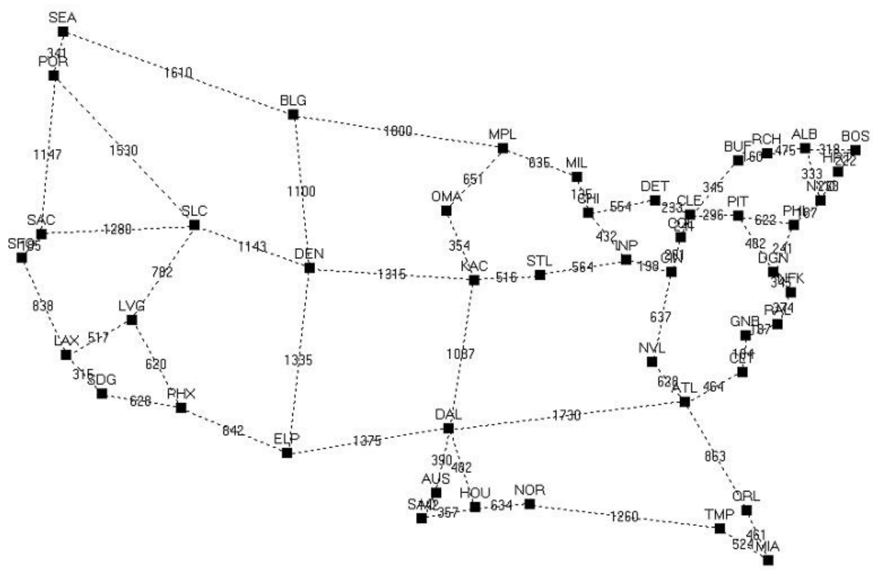


FIG. 4.7. 46-node 61-link USANET topology

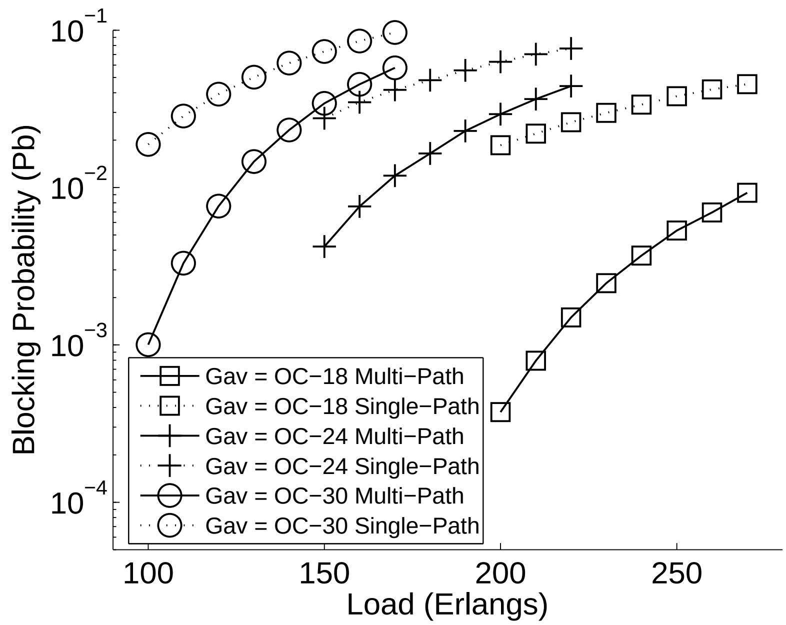


FIG. 4.8. USANET - Effect of variation in traffic load on blocking performance

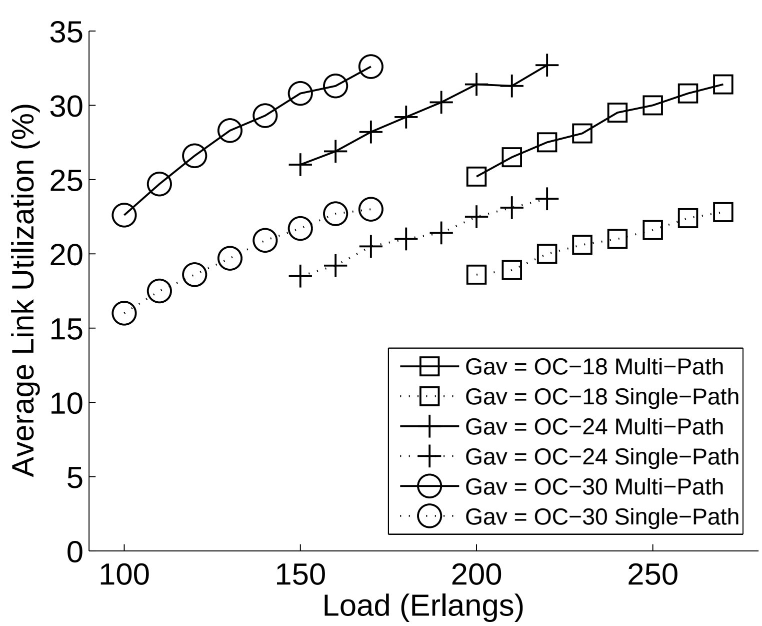


FIG. 4.9. USANET - Effect of variation in traffic load on average link utilization

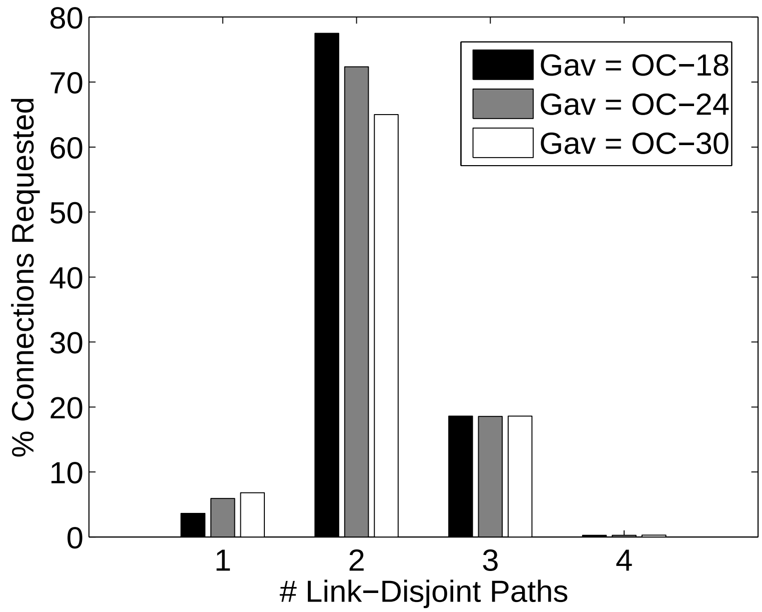
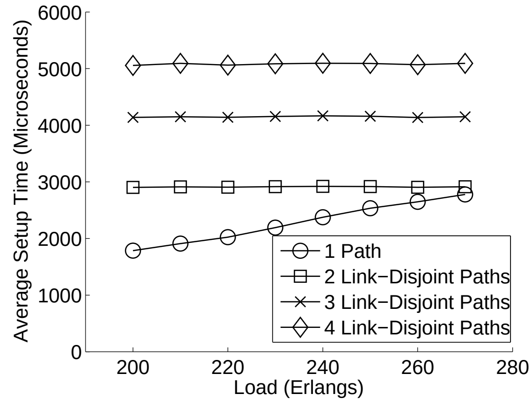


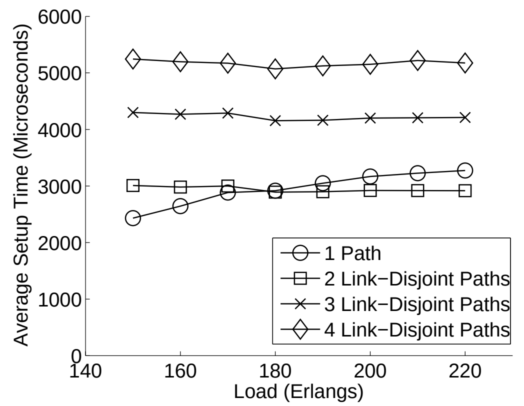
FIG. 4.10. USANET - Usage of different number of link-disjoint paths

# Link-Disjoint Paths	Protection Ratio (%)	Average Differential Delay (ms)	Buffer Requirement per Link (MB)
2	50.0	9.7	48.5
3	66.7	24.1	120.5
4	75.0	35.8	179.0

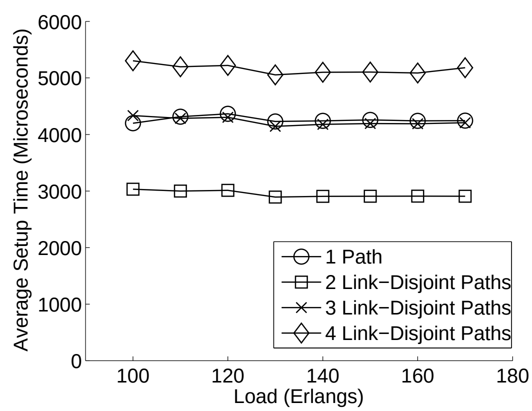
Table 4.3. USANET - Effect of variation in number of link-disjoint paths on implicit protection ratio and average differential delay



(a) G_{av} = *OC-18*

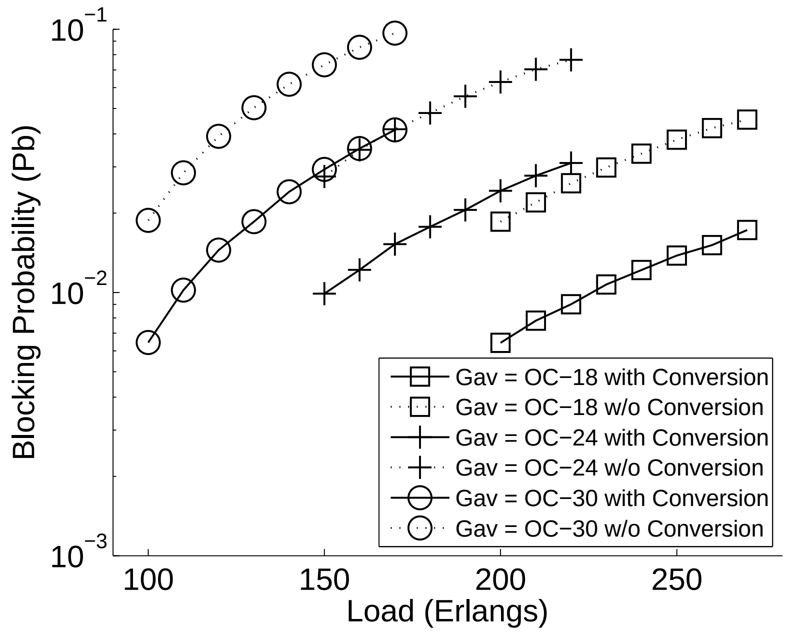


(b) G_{av} = *OC-24*

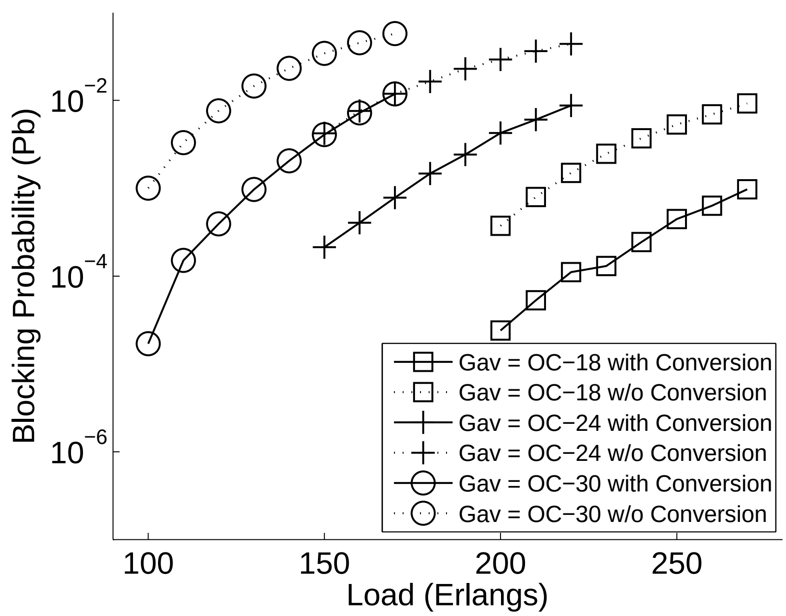


(c) G_{av} = *OC-30*

FIG. 4.11. USANET - Effect of variation in number of link-disjoint paths on average setup time



(a) *Single-Path*



(b) *Multi-Path*

FIG. 4.12. USANET - Effect of wavelength conversion on blocking performance

Chapter 5

CONCLUSIONS AND FUTURE WORK

In this thesis, we investigated problems related to using the virtual concatenation (VCAT) mechanism of synchronous optical network (SONET) technology in optical wavelength division multiplexing (WDM) grooming networks with dynamic traffic demand. We proposed two route selection methods to compare the performance of VCAT's multi-path routing and the traditional single-path routing. The simulation results confirmed VCAT's benefits of efficient utilization of link capacity and implicit partial link failure protection. Our study showed that differential delay caused by VCAT's multi-path routing increases with the number of link-disjoint paths used for routing. However, with the current cost of memory, it is feasible to provide a sufficient amount of buffer at all receiving nodes to solve the differential delay problem. Lastly, we observed that the existence of wavelength converters at routing nodes can significantly increase the number of connection requests admitted to a network.

5.1 Scope for Future Research

- **Single-Path-Multiple-Wavelength** - traffic sub-streams of a connection can be routed either using the same wavelength or multiple wavelengths on a single path. The former case was studied in this thesis and we should examine the effect of the latter case.

- **Protection and Restoration** - the establishment of a backup path along with the primary path would provide an explicit protection against link failures. In addition, it is possible to recover lost bandwidth on other paths in the event of a link failure. Thus, we should examine the effect of survival techniques.

- **Other Route Selection Methods** - the heuristic used for multi-path routing did not attempt to minimize differential delay. We should examine the effect of heuristics that attempt to minimize differential delay.

- **Wavelength Converter Distribution** - the assumption of one converter per wavelength is expensive and careful distribution of wavelength converters can lead to more efficient allocation of resources. We should examine the effect of different distributions of converters.

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