A TABU SEARCH ALGORITHM FOR SPARSE PLACEMENT OF WAVELENGTH CONVERTING NODES IN OPTICAL NETWORKS

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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All-optical Wavelength Division Multiplexing networks, providing extremely large bandwidths, are among the most promising solutions for the increasing need for high-speed data transport. In all-optical networks, data is transmitted solely in the optical domain along lightpaths from source to destination without being converted into the electronic form, and each lightpath is restricted to use the same wavelength on all the links along its path. This restriction is known as the wavelength continuity constraint. Optical wavelength conversion can increase the performance and capacity of optical networks by removing this restriction and relaxing the wavelength continuity constraint. However, optical wavelength conversion is a difficult and expensive technology. In this study, we analyze the problem of placing limited number of wavelength converting nodes in a multi-fiber network with static traffic demands. Optimum placement of wavelength converting nodes is an NP-complete problem. We propose a tabu search based heuristic algorithm for this problem. The objective of the algorithm is to achieve the performance of full wavelength conversion in terms of minimizing the total number of fibers used in the network by placing minimum number of wavelength converting nodes. Numerical results comparing the performance of the algorithm with the optimum solutions are presented. The proposed algorithm gives quite satisfactory results, it also has a relatively low computational complexity making it applicable to large scale networks.

Keywords: Wavelength Division Multiplexing Networks, Wavelength Converters, Converter Placement, Tabu Search

ÖZET

OPTİK AĞLARDA DALGABOYU DÖNÜŞTÜREN DÜĞÜMLERİN SEYREK KONUŞLANDIRILMASI İÇİN BİR TABU ARAŞTIRMA ALGORİTMASI

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Dalga Boyu Bölüşümlü Çoğullama kullanılan bütünüyle optik ağlar, çok yüksek bant genişliği sağlamalarıyla artan yüksek hızda veri taşıma ihtiyacı için en ümit verici çözümler arasındadır. Bütünüyle optik ağlarda veri kaynaktan hedefe yalnızca optik alanda, elektronik forma dönüştürülmeden iletilir ve her ışık yolu, yolu üzerindeki bütün linklerde aynı dalga boyunu kullanmak zorundadır. Bu kısıtlama, dalga boyu süreklilik kısıtı olarak bilinir. Optik dalga boyu dönüşümü, bu kısıtlamayı kaldırarak ve dalga boyu süreklilik kısıtını gevşeterek optik ağların başarım ve kapasitesini arttırabilir. Ancak, optik dalga boyu dönüşümü zor ve pahalı bir teknolojidir. Bu çalışmada, kısıtlı sayıda dalga boyu dönüştüren düğümün durağan trafikli çok fiberli bir ağda konuşlandırılması problemini inceledik. Dalga boyu dönüştüren düğümlerin en iyi konuşlandırılması, polinom zamanda çözülemeyen tam bir problemdir. Bu problem için tabu araştırma tabanlı buluşsal bir algoritma önerdik. Algoritmanın amacı en az sayıda dalga boyu dönüştüren düğüm konuşlandırarak ağda kullanılan toplam fiber sayısı açısından tüm dalga boyu dönüşümünün başarımını elde etmektir. Algoritmanın başarımını en iyi çözümlerle karşılaştıran sayısal sonuçlar sunulmuştur. Önerilen algoritma oldukça tatmin edici sonuçlar vermektedir ve göreceli olarak düşük hesaplama karmaşıklığı ile büyük ölçekli ağlara da uygulanabilir.

Anahtar kelimeler: Dalga Boyu Bölüşümlü Çoğullama Kullanılan Ağlar, Dalga Boyu Dönüştürücüler, Dönüştürücü Konuşlandırılması, Tabu Araştırma

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To My Family And My Only One . . .

Chapter 1

Introduction

In the last decades, the tremendous growth of the Internet and the new developing telecommunication services increased the need for high-speed data transport. Providing much higher bandwidth and being less affected with electromagnetic interference are some advantages of fiber optic communication enabling fiber optic cables replace copper wires in lots of areas in telecommunication networks. With the use of Wavelength Division Multiplexing (WDM) technique, in which data is transmitted at multiple carrier wavelengths, the capacity of the fiber cables is further increased. By using WDM, the fiber is decomposed into virtual fibers each carrying a different data stream. One of the most critical components of optical networks is the optical amplifiers. A single optical fiber amplifier can simultaneously amplify several WDM signals, which reduces the cost of optical networks.

The development of optical networks can be classified into two generations. In the first-generation optical networks, the fiber cables were used solely for transmission with higher capacity and all the other network functions are done in electronics domain. However, as data rates get higher, processing the data electronically becomes more difficult since the electronic components cannot catch up with the transmission speed. This fact gave rise the second-generation optical networks where some of the switching and routing functions are done in the optical domain. The most extreme example of second-generation networks are all-optical networks, where data is carried from its source to its destination completely in the optical domain without any optical-to-electrical conversion. In addition to fast switching times another advantage of these type of networks is transparency, which means that there is no dependency on the bit rate or the protocol format of the transmission [1].

Besides these advantages, WDM all-optical networks have a main drawback limiting their efficiency. Transmissions between nodes are done by establishing lightpaths that are direct optical connections between their source and destination nodes. On all the links along a lightpath, the same wavelength must be used unless wavelength conversion in the optical domain is utilized. This is called the wavelength continuity constraint. Due to this constraint, a request can be blocked if there is no wavelength which is free on every link along its lightpath, even if the capacities of the links are not exceeded. Hence, besides capacity blocking, wavelength mismatch blockings may also occur in all-optical networks [2].

The problem of establishing a lightpath for each connection request and assigning a wavelength to that lightpath is called the Routing and Wavelength Assignment (RWA) problem. The wavelength mismatch blockings can be reduced by using appropriate RWA algorithms. The RWA problem can be either static or dynamic according to the traffic type. If the set of connection requests are known beforehand, the traffic is static. Otherwise, if the connection requests arrive over time in a random manner, the traffic is called dynamic. In the static traffic case, the lightpaths are permanent, and they can be configured in an arbitrary manner since all the requests are known in advance. In the dynamic traffic case, the lightpaths are established one-by-one after each request arrives.

The order of connection requests is not known a priori. Each arriving request has a holding time after which the network resources used by the lightpath are released.

The blockings resulting from the wavelength continuity constraint can be eliminated completely using wavelength converters, which are devices that can translate the incoming optical signal on one wavelength to another wavelength at the outgoing port. Today, wavelength conversion can be done by using opto-electronic technologies that convert the optical signal into electrical domain and then back to the optical domain at a different wavelength. Opto-electronic wavelength converters are generally bit-rate dependent that make them non-transparent. Use of optical wavelength converters that can achieve the wavelength translation completely in the optical domain is necessary for transparent or all-optical networks. However, these technologies are currently not mature enough in order to be deployed in real networks. Furthermore, the costs of optical wavelength converters are expected to remain considerably high for at least a few decades and it will not be possible to equip each node in the network with these devices. The solution to this problem is the equipment of only some of the nodes in the network with wavelength converters, which is called *sparse wavelength conversion*. Employing sparse wavelength conversion and suitable RWA algorithms, we study whether it is possible to increase the performance of the network to a large extent and even to obtain the same performance with *full wavelength conversion* where converters are deployed at all nodes.

The performance increase achieved by sparse wavelength conversion is analyzed in a number of researches studying the best placement of these wavelength converters in the network. The studies investigating the case of dynamic traffic aim to increase the blocking performance of the network with sparse conversion. For the static traffic case, the objective is to reduce the cost of network resources necessary to satisfy all the demand requests. Most of the studies assuming static traffic demands focuses on single fiber networks, and the network resource considered for minimization is the number of wavelengths on a fiber. However, in real life optical Wide Area Networks (WANs) are generally multi-fiber because of the technological limitations on the number of wavelengths that can be carried over a single fiber and the reduced cost of initially installing extra fibers compared to the cost of replacing the fibers in the network with new fibers supporting more wavelengths.

In this thesis, we consider multi-fiber networks with general topologies and static traffic demands. For the routing problem, the total cost of fibers is considered as the network resource to be minimized assuming full wavelength conversion. We use two different formulations for the routing part: a flow based Integer Linear Programming (ILP) formulation where all possible paths are considered as candidate paths and a path based ILP where only limited number of paths are considered. An iterative heuristic algorithm which gives priority to longer paths is presented for wavelength assignment problem. For wavelength converter placement problem, we propose a heuristic algorithm using Tabu Search (TS) method. Our objective is to find the locations of minimum number of wavelength converting nodes necessary to satisfy all the demand requests with the same total cost of fibers obtained in a network having full wavelength conversion capability. We also implement another heuristic using Greedy Search (GS) technique for performance comparison, and the solutions generated by the GS algorithm are also used as initial solutions for the TS algorithm. The performance of the TS algorithm is compared with the optimum converter placement solutions for a 32-node mesh network, and it is observed that the TS algorithm achieves the optimum solutions in 72% of the cases. The TS algorithm outperforms the GS algorithm in 40% of the cases. On the average, the TS algorithm places 9.3% more converters than the optimum solutions. The effect of the routing algorithm is also investigated, and the performances of the GS and TS algorithms are compared under different routing schemes: one calculated by solving the flow based ILP formulation, the others calculated by solving the path based ILP formulation with different number of considered paths. In order to investigate the influence of the network topology, we also run the TS and GS algorithms on the 19-node European Optical Network (EON) with different number of wavelengths and evaluate their performances. Because of the smaller size and densely connected topology of the EON, the routes used by the lightpaths are typically much shorter than the 32-node mesh network. This results in smaller number of wavelength converting nodes necessary to obtain the optimum performance, and consequently, the performances of the TS and GS algorithms are quite similar.

The rest of the thesis is organized as follows. In Chapter 2, we present an overview of the RWA and converter placement algorithms in the literature and our contribution. We describe our proposed solution for the RWA problem in Chapter 3. The Tabu Search based converter placement algorithm is described in Chapter 4. Numerical results and the comparison with optimum solutions for a sample network are presented in Chapter 5. The final chapter is devoted to the conclusions.

Chapter 2

Related Work

In this chapter we present a summary of the previous literature related to the problem of wavelength converter placement and then explain our contribution. Before discussing the solutions for the converter placement problem, we first present the related literature on the routing and wavelength assignment (RWA) problem since RWA and converter placement problems need to be solved in conjunction with each other.

2.1 Routing and Wavelength Assignment (RWA) in the Literature

The problem of establishing a lightpath for each connection request and assigning a wavelength to that lightpath is called the Routing and Wavelength Assignment (RWA) problem. The traffic can be static or dynamic depending on the nature of connection requests.

2.1.1 RWA under Static Traffic

In the RWA problem under static traffic, which is also known as the Static Lightpath Establishment (SLE) problem, either the set of connection requests are known beforehand or the available network resources are fixed. In the first case, the objective is to route all the demands and assign a wavelength to each of them minimizing some given network resources: the number of wavelengths as in [3, 4], the total cost of the fibers [5, 6, 7, 8] or a combined total cost of more than one type of resources [9]. In the second case, when the network resources are fixed, the objective is to maximize the number of demands that can be satisfied [10, 11].

The SLE problem can be formulated as an Integer Linear Programming (ILP) [6, 10, 11], and it is also shown to be NP-complete [12]. Because of this, different approaches are proposed instead of solving the ILP. In [7, 11], first LP relaxation of the ILP is solved, then rounding algorithms are applied in order to obtain an integer solution. In [3], routing problem is solved by ILP without considering the wavelength continuity constraint, and then the wavelength assignment problem is solved by graph coloring algorithms. Various heuristics are proposed in [5, 8, 9] solving the routing and wavelength assignment problems jointly for static traffic.

Another approach for managing static traffic is to use heuristics that are proposed for dynamic traffic. To accomplish this, the demands are sorted first and offered one by one to the network [6]. We also use a similar method for the wavelength assignment problem in our proposed solution.

2.1.2 RWA under Dynamic Traffic

In the dynamic traffic case, the problem is also referred to as the Dynamic Lightpath Establishment (DLE) problem. Each connection request comes over time and has a holding time. For each arriving request, a lightpath is established and it is released after the holding time of the request expires. The main objective in this problem is generally to minimize the blocking probability with a given set of resources or minimize the resources achieving a target blocking probability.

The DLE problem is more difficult than SLE since the connection requests arrive and depart in a random manner. Because of this, in most of the studies, the routing and wavelength assignment problems are solved separately using several heuristic methods. The basic approaches to the routing problem can be classified into three groups: fixed routing, fixed alternate routing and dynamic routing. In fixed routing, the routes for the demands between each node pair are calculated before the request arrives and the routes are fixed. A request is blocked if a free wavelength does not exist along its route. In fixed alternate routing, a number of routes are calculated for each node pair, and they are searched in a fixed order until a free wavelength is found along one of them [13, 14]. Both of these approaches do not consider the current state of the network. In dynamic routing, the routes are calculated dynamically when the request arrives according to the current status of the network [15, 16, 17]. Dynamic routing algorithms give the best performance among these three, but they have the highest computational complexity and need information about the current state of the network to be distributed to all nodes.

For the wavelength assignment (WA) problem, there are three most widely used heuristics: Random, First Fit (FF) and Most Used (MU). In the Random WA, for an incoming connection request, a wavelength is chosen randomly among the free wavelengths along the path. The aim is to distribute the traffic evenly among the wavelengths. In the FF algorithm, the wavelengths are ordered in a predetermined manner and when a connection request arrives, the wavelengths are searched for in that order until an available wavelength is found. The MU algorithm selects the wavelength which is most used in the network, among the available wavelengths. The idea is to route the demands using a much used wavelength if it is possible to reserve the less used free wavelengths for demands having longer paths. The MU algorithm is more complicated than Random and FF algorithms since it needs global network information about the free wavelengths. The MU and FF algorithms are shown to give a similar performance which is better than random wavelength assignment algorithm [14, 17, 18].

There are a large number of other proposed heuristics for wavelength assignment. Least Used (LU) algorithm is the opposite of MU, it chooses the least used wavelength among available wavelengths to balance the load on all wavelengths, however it has a performance worse than the random wavelength assignment. For multi-fiber networks, Min-Product [19], Least Loaded [20] and Relative Capacity Loss [21] algorithms are proposed. Wavelength assignment algorithms trying to minimize the usage of converters are also considered [13, 16, 22]. In [23], a genetic based algorithm is proposed for wavelength assignment.

2.2 Wavelength Converter Placement in the Literature

Wavelength converter placement is a problem that has been researched widely in recent years. A number of heuristic algorithms and ILP formulations are proposed.

Wavelength conversion can be classified into four different classes according to the proposed architecture: nodal converter, link converter, share-per-node converter and share-per-link converter. In the nodal converter architecture, the amount of wavelength conversion is unlimited at the node. This architecture gives the most flexibility but is also the most expensive. In the link converter case, the converters are dedicated to certain outgoing links of a node and unlimited conversion is provided for the lightpaths using these outgoing links. In the share-per-node architecture, wavelength conversion can be used by lightpaths passing through any of the outgoing links of the node like in the nodal converter, but the total amount of conversion allowed is limited. In the share-per-link architecture, limited amount of conversion is provided to a limited number of outgoing links of the node [22, 24]. In the rest of this thesis, the nodal converter architecture is considered unless it is stated otherwise. The terms "converter" and "converting node" are used interchangeably and the phrase "placing a converter at a node" is used in the sense that the node is provided with a number of wavelength converters equal to the total number of outports of the optical switch placed at that node.

The conversion type investigated can be full range or limited range: in full range conversion, an incoming wavelength can be converted to any other wavelength by the converter. In limited range conversion, each wavelength can be converted to a limited number of wavelengths within the neighborhood of the incoming wavelength. Full range or limited range nodal conversion is the type that is investigated most widely in the literature due to its simplicity. The works studying converter placement can be categorized in two main classes according to the traffic type they consider: static traffic and dynamic traffic. In the dynamic traffic case, the main criteria considered in locating the converters is the blocking probability. In the static case, the criteria is the network resources used to route all the demands, such as the number of wavelengths on each fiber or the number of fibers.

2.2.1 Wavelength Converter Placement Under Static Traffic

Most of the studies investigating wavelength converter placement under static traffic consider the number of wavelengths as the network resource considered for minimization. In these studies, the objective is either to reduce the number of wavelengths required to satisfy all the connection requests by placing a fixed number of converters or to satisfy all the requests using the same number of wavelengths required in the full conversion case, which is equal to the maximum link load (this is also called satisfying the L-assignability), by placing minimum number of converters.

The problem of satisfying any traffic demand matrix that can be routed under full wavelength conversion using the same number of wavelengths by employing sparse wavelength conversion is studied in [25, 26, 27]. This problem is called the minimum sufficient set problem and can be described as finding a set S of minimum number of nodes such that, by placing converters at the nodes in S, every set of paths can be routed with a number of wavelengths equal to its congestion bound [25]. This problem is proven to be NP-complete for general topologies [28]. However, it is shown that this problem can be solved in polynomial time for bi-directed networks with tree of rings topology [25]. This result is generalized also to directed networks of tree of rings [26]. [27] studies the same problem for networks with general topology and proves that for duplex communication channels, it can be solved in polynomial time and proposes a set of lemmas and an approximation algorithm for unidirectional channels, for which the problem is NP-complete. [29] investigates this problem from a different point of view, satisfying any traffic demand matrix using a constant, α, times the maximum link load. It is shown that, when α is chosen to be 3/2 for duplex channels and 5/3 for unidirectional channels, the converters required to guarantee to satisfy any traffic demands is reduced to nearly half of the converters required for α=1.

In these approaches, the demand patterns are not considered, and the aim is to guarantee to route any traffic demand matrix. For a known traffic demand matrix, it may be possible to satisfy the L-assignability by using a smaller number of converters.

[30] addresses the issue of optimal placement of converters under a known set of traffic demands. L-assignability is satisfied using limited range conversion. An ILP model including path protection is presented to minimize the number of converters. By examining possible scenarios with small scale networks, it is shown that placing only a single wavelength converting node is enough to prevent the blockings resulting from the wavelength continuity constraint. Solutions are presented for networks with a maximum number of 12 nodes and 4 wavelengths. It is stated that bigger instances closer to the real world metropolitan and wide area networks need a more efficient approach.

[31] and [32] propose heuristic algorithms to place the converters in a way to satisfy L-assignability. In [31], first the number of wavelengths required to route all the demands under full conversion is calculated. Then, the converters are placed one by one to the nodes with highest transit traffic until the target number of wavelengths is reached. [32] investigates the network design problem and divides it into two stages. The first stage is dimensioning and routing where the link capacities and the routes are calculated without considering the wavelength continuity constraint. The second stage is wavelength assignment and converter placement where each lightpath is tried to be assigned a wavelength one-by-one, i.e., in a greedy manner. If wavelength assignment cannot be done along a lightpath, one or more converters are placed along that lightpath to achieve wavelength assignment. A number of schemes are proposed for the processing order of the lightpaths. The drawback of these approaches is that, they propose to place the converters one by one. However, the optimum configuration may

not always be reached by placing the converters sequentially and these methods have a high likelihood of not achieving the optimum solution.

[33] investigates the problem of placing a given number of converters in ring networks under static traffic. The aim is to minimize the number of wavelengths required in order to route all the demands. Three different approaches using Genetic Algorithms (GA), Simulated Annealing (SA) and Tabu Search (TS) techniques are implemented for solving the RWA and converter placement problems in a combined manner, and their performances, based on the number of wavelengths used, are compared for different networks. A linear programming solution using Lagrangian heuristics is also used for comparison. It is stated that GA shows the best performance both in solution time and the quality of the generated solutions. These results are obtained only on the ring networks. An interesting observation which raises a question on the implementation quality of the SA and TS algorithms in this work is that, under full conversion, these algorithms' performances are worse than under no conversion case, for some demand patterns.

[34] studies a very similar problem to the one considered in this thesis: locating minimum number of converters minimizing the cost of fibers used to route all the demands. For the routing problem, a flow based ILP formulation minimizing the fiber cost is proposed. It is stated that, using this formulation it is not possible to obtain the optimum solution even for reasonably sized networks, the demand aggregation and a simple minimal cover formulation is applied to reduce the number of variables. Another ILP formulation is proposed for the wavelength assignment and placement of converters, and the optimal solution is generated by solving the ILP. However, as the network size, the number of wavelengths and the number of demands increase, the number of variables in the ILP formulation increase quickly and it may not be possible to obtain the optimum solution for

large networks. The largest problem solved in this work is a 32 node network with 16 wavelengths and contains a total of 150 lightpath requests.

[35] also considers the issue of minimizing the number of fibers with sparse wavelength conversion and proposes a heuristic approach. After the wavelength assignment is done, the links containing more fibers than required on that link in the full conversion case, in other words inefficient links, are detected. By the intersection of the paths with these links, subpaths are constructed. Converters are added to the two ends of these subpaths and wavelength assignment is redone for these subpaths. This procedure is repeated until the number of fibers required to satisfy the demands in the full conversion case is reached. Unlike our case, in this work, sparse link conversion is considered, and a wavelength converter can be used for only a single port of a node. It is stated that the number of converters is reduced to nearly 5% of the number required by the full conversion case by this method.

2.2.2 Wavelength Converter Placement Under Dynamic Traffic

Nearly all of the wavelength converter placement algorithms considering dynamic traffic focuses on reducing the blocking probability in the network. There are some optimal solutions for ring topologies under certain traffic assumptions and most of the studies investigating general topology networks propose solutions based on heuristic algorithms.

[36, 37] and [38] focuses on minimizing the end to end blocking probability on a path. [36] shows that for uniform link loads uniform placement of wavelength converters gives optimal results for the blocking probability of the path and proposes a dynamic programming solution for non-uniform link loads. This solution is then generalized to bus and ring networks, and its performance is compared

with random converter placement. [37] also proves that uniform placement gives the optimal results on ring topology for uniform link loads using limited range conversion. An analytical model is presented, and an expression for the degree of wavelength conversion is derived. In [38], the authors show that the end-to-end blocking probability on a path is minimized when the path is divided into segments with equal blocking probabilities under the assumption of independent link loads. They propose three different heuristic algorithms to divide the paths into segments with equal blocking probabilities. These approaches focusing on the blocking probability on a path can be applied to bus and ring networks.

In [39, 40] and [41], the relationship between RWA and converter placement algorithms is considered. The performance of different RWA algorithms under sparse wavelength conversion is investigated, and it is stated that conventional RWA algorithms do not work well under sparse conversion. A heuristic wavelength converter placement algorithm to be used in conjunction with dynamic least loaded routing and first fit wavelength assignment (LLR-FF) algorithm is proposed. [40] also proposes another heuristic converter placement algorithm to be used with fixed-alternate routing and first fit wavelength assignment (FAR-FF) algorithm.

There are a number of studies proposing heuristic algorithms placing the converters one by one for mesh topology networks. In most of them, the decision of choosing the nodes to place the converters is made considering the traffic patterns. In [42], 4 different such heuristics are presented using different traffic parameters of the nodes:incoming traffic, transit traffic, total outgoing traffic and weighted traffic. [37] proposes another heuristic which considers the transit traffic, adjacency to most congested links and the number of conversions made in the full conversion case at that node. A heuristic algorithm considering the interference lengths, path lengths and amount of traffic passing through the nodes for placement of wavelength converters is presented in [43]. In [44], the aim is to locate the converters to the nodes receiving higher traffic and adjacent to the nodes without wavelength converters, assuming uniform traffic. For this purpose, k-Minimum Dominating Set (k-MDS) is found in the network and the converters are placed at the nodes in that set.

Blocking probability is another parameter that is used widely in the converter placement algorithms. The blocking probabilities are either calculated using analytical models [22, 42, 45, 46] or obtained by simulations [47]. In [42], two different heuristics placing the converters one by one in a way to minimize the average blocking probability and maximum blocking probability respectively are suggested. [45] presents an exhaustive search algorithm for the optimal solution calculating the blocking probabilities of different combinations of the converters. The search space is reduced by using an auxiliary graph for each node. In [22], the converters are initially placed uniformly. Then, the configuration of the converters is changed one node at a time according to the blocking probabilities calculated for the new configuration.

Genetic based algorithms are also employed in solving the converter location problem [46, 47]. In [47], uniform placement of the converters is used as the starting point and the objective function is the overall blocking probability of the network. The blocking probabilities are calculated by using a simulator for each configuration of the converters. A similar approach which uses an approximate analytical model to calculate the blocking probabilities instead of simulations is proposed in [46].

An optimization model for solving the problem of converter placement to minimize the overall blocking probability is proposed in [48] . The success probability is formulated as a polynomial function of the location of the converters. Using this formulation, the problem is modelled as minimization of a polynomial function of 0-1 variables under a linear constraint, and a search algorithm is presented to find the optimum location of the converters.

2.3 Our Contribution

There are a number of studies investigating the RWA problem for the multi-fiber networks in the literature, however most of the works studying the converter placement problem consider single fiber links and ignore the benefits of using multiple fibers. The objective in these studies is generally to reduce the maximum number of wavelengths on the fibers. As stated in [11, 19] and [49], using multiple fibers has a dramatic effect on the network performance by reducing the blockings resulting from the wavelength continuity constraint. Also, there is the fact that the telecommunication operators rather install multi-fiber networks, because the cost of trench-digging to bury the optical fibers is much more higher than the material cost of a fiber [7]. Because of these reasons, we focus on multi-fiber networks in this thesis, and our main objective is to place the minimum number of converters necessary for achieving the minimum fiber cost which is obtained in a network having full wavelength conversion capability.

We assume static traffic demands and a general network topology. Some optimal solutions are proposed for the converter placement problem on general topology networks under static traffic demands [30, 34]. However, because of the limitations of ILP, these approaches are not suitable for very large problems. As the number of nodes in the network, the number of lightpath requests and the number of wavelengths on the fibers increase, the number of variables of the ILP increases quickly. For larger problems, efficient heuristics are needed, but most of the existing converter placement heuristics place the converters one by one and tend to miss the optimal solution.

For placing wavelength converting nodes, we implement a heuristic algorithm that uses tabu search, which is a technique that is highly efficient for large optimization problems. This algorithm can find solutions in a reasonable amount of time even for large networks with a large number of wavelengths and lightpath requests. We use an ILP formulation to solve the routing problem and a heuristic algorithm for wavelength assignment. The details of our proposed solutions to the routing and wavelength assignment problems are explained in the next chapter. A nice feature of our converter placement algorithm is that it can be used in conjunction with different routing and wavelength assignment algorithms. We also implement a greedy search algorithm for converter placement and use its performance as a basis for comparison with the tabu search algorithm. The performance of our tabu search algorithm is also compared with the optimal solutions presented in [34], and it is shown that in most of the cases, the Tabu Search algorithm achieves the optimal solution.

Chapter 3

Routing and Wavelength Assignment (RWA)

In this thesis, our main objective is to propose a new algorithm, which is scalable to large networks with a satisfactory performance, for sparse wavelength converter placement under static traffic. The tabu search converter placement algorithm proposed in this thesis runs for a large number iterations, and at each iteration the RWA problem is solved several times. Considering this fact, in order to generate a solution in a reasonable amount of time with our converter placement algorithm, the used RWA algorithm should be efficient and fast. Because of speed and complexity considerations, the routing and wavelength assignment problems are considered separately in our proposed solution for the RWA problem. The routing problem is solved first without considering the wavelength continuity constraint and it is solved just for once. The wavelength assignment algorithm is solved several times at every iteration of the converter placement algorithm using different possible configurations of the wavelength converting nodes.

3.1 Routing Problem

Our criteria in placing the converters is to use the same amount of fibers obtained with the full wavelength conversion while converters are placed only at selected nodes. Concluding from this point of view, the routes to be used in conjunction with the sparse conversion network are obtained considering full wavelength conversion. We present a path based ILP formulation minimizing the cost of total fibers, to solve the routing problem. The k shortest paths are calculated using a depth-first search algorithm presented in [2]. The link costs are used as lengths, so the shortest path means the path with the lowest cost.

The network is represented by an undirected graph where the links and the connections are bidirectional. The set of k shortest paths between all node pairs is given by P. Let Z denote the set of all node pairs and L represent the set of links. The element C_l of the cost vector C stands for the cost of installing a fiber on the link l. For a node pair $z = (m, n) \in$ Z, d_z denotes the number of lightpath requests between nodes m and n. The decision variable f_l denotes the number of fibers on link l and the routing variable X_{pz} represents the number of lightpaths for node pair z that are assigned to path p. The number of wavelengths on each fiber is denoted by W. The link-path incidence matrix is given by $J = [j_{lp}]$, where

$$j_{lp} = \begin{cases} 1 & if\ link\ l\ is\ on\ path\ p \\ 0 & otherwise \end{cases}$$

The ILP formulation for the routing problem is given by

$$\text{Minimize} \sum_{l \in L} f_l \times C_l$$

Subject to

$$\sum_{p \in P} X_{pz} = d_z \ \ \forall z \in Z, d_z \in D \quad \text{(demand constraints)}$$

$$\sum_{z \in Z} \sum_{p \in P} X_{pz} j_{lp} \leq W \times f_l \ \ \forall l \in L \quad \text{(capacity constraints)}$$

$$f_l \in Z^+ \ \ \forall l \in L$$

$$X_{pz} \in Z^+ \ \ \forall z \in Z, \forall p \in P$$

The set of routing variables $\{X_{pz}\}$ in the optimum solution indicates paths used by the lightpaths. The objective function that is minimized represents the total fiber cost. The demand constraints express that the total number of lightpaths assigned to a node pair is equal to the number of lightpath requests between this node pair. The capacity constraints ensure that the total number of lightpaths passing through a link cannot exceed the capacity of that link.

For the optimum solution of the routing problem, a flow based ILP formulation is presented in [34]. In this formulation, the network is represented by the graph $G = (N, L)$, where N is the set of nodes and L is the set of edges. The set of lightpath requests is represented by R, s_r denotes the source and d_r denotes the destination node of the request r. W represents the number of wavelengths on a fiber. The decision variable X_{ijr} represents the flow of lightpath requests r from node i to node j:

$$X_{ijr} = \begin{cases} 1 & if\ demand\ r\ flows\ from\ node\ i\ to\ node\ j \\ 0 & otherwise \end{cases}$$

The decision variable f_{ij} denotes the number of fibers between the nodes i and j and c_{ij} stands for the cost of installing a fiber between nodes i and j. The indicator function y_{ir} is defined as

$$y_{ir} = \begin{cases} 1 & if\ i = s_r \\ -1 & if\ i = d_r \\ 0 & otherwise \end{cases}$$

The ILP formulation is given by

$$\text{Minimize} \sum_{(i,j)\in L} f_{ij} \times C_{ij}$$

Subject to

$$\sum_{j\in N} X_{ijr} - \sum_{j\in N} X_{jir} = y_{ir} \quad \forall\, i \,\in\, N,\, r \,\in\, R \quad \text{(flow constraints)}$$

$$\sum_{r\in R} (X_{ijr} + X_{jir}) \leq W \times f_{ij} \quad \forall\, (i,j) \,\in\, L \quad \text{(capacity constraints)}$$

$$f_{ij} \in Z^{+} \quad \forall\, (i,j) \,\in\, L$$

$$X_{ijr} \in [0,1] \quad \forall\, (i,j) \,\in\, L, \forall\, r \,\in\, R$$

In the above equations, the flow constraints state that if the number of flows of a certain demand coming into a node and going out from that node are different, that node is the source or destination of that demand. The capacity constraints state that the number of lightpaths passing through a link is less than or equal to the capacity of that link. It is stated in [34] that, with this formulation, it is not possible to obtain the optimum solution even for reasonably sized networks, i.e., topologies with less than 15 nodes and aggregation is suggested to find the optimum solutions for larger networks. We run the converter placement algorithms both using the routes calculated by solving this formulation and using the routes calculated by the path based formulation and investigate the effects of the routing algorithm used.

3.2 Wavelength Assignment Problem

Since the wavelength assignment algorithm runs at each iteration of the converter placement algorithm, we propose a heuristic algorithm for the wavelength assignment problem. Our iterative heuristic algorithm is based on the longest path first approach. First, the number of fibers on each link are initialized to the number of fibers in the full conversion case, which is obtained from the solution of the routing algorithm. Then, all the lightpaths, which are obtained from the solution of the routing algorithm, are divided into segments according to the placement of the converters if wavelength converters exist in the current network configuration. For a given lightpath, each segment corresponds to the portion of the lightpath lying between two subsequent WIXCs along that lightpath. Figure 3.1 illustrates how a sample lightpath is divided into segments. For the full wavelength conversion case, segments correspond to individual links and for the no wavelength conversion case, each segment corresponds to a lightpath.

These segments are sorted according to their lengths in a descending order. Starting from top of the list, the first available wavelength is assigned to each segment. When no available wavelength is found along a segment, that segment

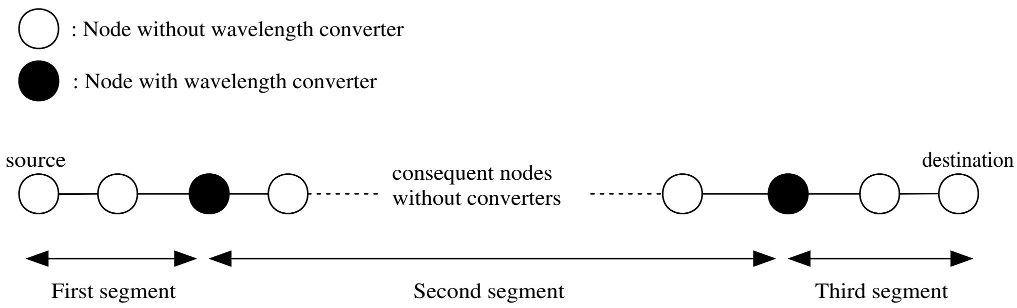

Figure 3.1: Division of a lightpath into segments

is placed at the top of the list, in other words the list is reordered, and all wavelength assignments are done from the beginning. This procedure is repeated for a maximum number of iterations *reorder_number*. When the maximum number of iterations is reached and there is no available wavelength along a segment, the wavelength which is unavailable on links with minimum total fiber cost along that segment is determined, the number of fibers on these links are incremented and that wavelength is assigned to the segment. The pseudo-code for this algorithm is given below.

```
1. set n=1,i=1
2. divide the lightpaths assigned to each node pair
into segments
3. order the segments according to their lengths
4.while (i<number of segments)
  determine the first available wavelength for the segment in the
    i-th place in the list
  if (no available wavelength is found)
    if (n<reorder_number)
      set n=n+1
      place this segment to the first place in the list
      undo all the wavelength assignments made so far
      set i=1
    else
```

```
      find the wavelength w which is unavailable on links with
        minimum total fiber cost along the segment
      increase the number of fibers on the links for which
        wavelength w is not available along segment i
      set i=i+1
  else
    assign this wavelength on all links along the segment
    set i=i+1
5. stop
```

In this algorithm, the value of the *reorder_number* has an important effect on the total cost of fibers in the solution. However, we observed that there is no straight relationship between *reorder_number* and the cost of fibers. Increasing *reorder_number* may also result in a worse solution (cost of fibers may increase) as it may result in a better solution (with a lower cost of fibers). To produce the best result, in our proposed solution for the wavelength assignment problem, this algorithm is run with different values of *reorder_number* from 0 to a specified number *reorder_limit*. By running the algorithm with different demands and wavelength converter schemes, we observed that setting the value of *reorder_number* to 1/4 of the number of created segments guarantees to obtain the best solution. After this limit, any further reordering does not give a better solution than the best solution found so far.

In the next chapter, we study the problem of placing minimum number of wavelength converting nodes such that the total fiber cost is the same as the full conversion case.

Chapter 4

Converter Placement

In this thesis, our main objective is to minimize the number of converting nodes to satisfy a given set of lightpath requests with the same total cost of fibers as required in the case of full conversion and to find the optimal locations for these converters. The routes to be used by the lightpaths and the number of fibers required on each link in the full conversion case are obtained from the outputs of the routing algorithms described in the Chapter 3. For the converter placement problem, we propose a tabu search algorithm and also implement a simpler greedy search algorithm for comparison purposes and in order to generate initial solutions for the tabu search algorithm. These algorithms use the wavelength assignment algorithm described in Chapter 3.

4.1 Greedy Search (GS) Algorithm

The GS algorithm aims to place the converters one by one at each iteration. The flowchart of the algorithm is shown in Figure 4.1. The algorithm starts with no converting nodes in the network. Each move in the algorithm consists of adding a converter to one of the nodes with no converters. For each of the nodes with

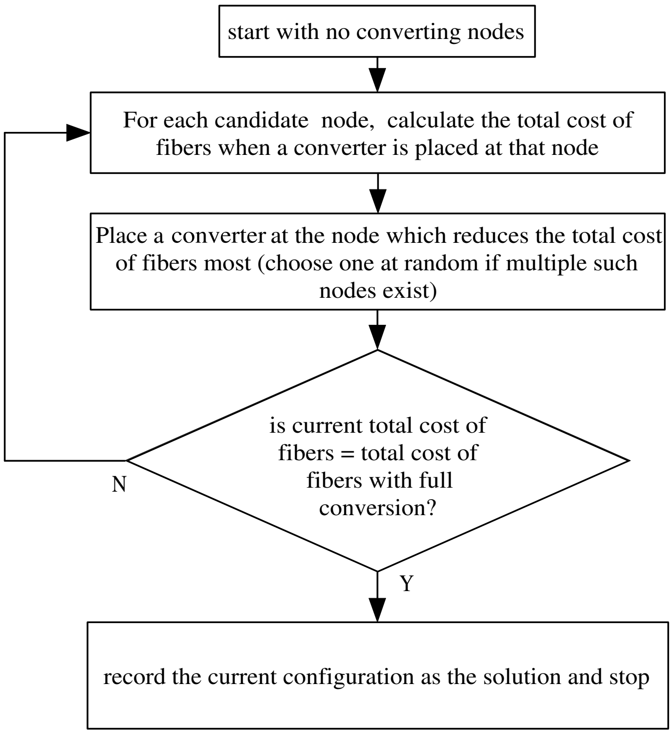

Figure 4.1: Flowchart of the GS algorithm

no converters, the total cost of fibers required to satisfy the lightpath requests if a converter is placed at that node along with the other converting nodes in the network, is calculated. Among the non-converting nodes, the one for which the calculated total cost of fibers is the lowest is chosen to place the next converter. When there are multiple such nodes, one of them is chosen randomly. When the target minimum cost of fibers calculated by the routing algorithm is attained, the algorithm stops. The routes used by the lightpaths are calculated by the routing algorithm described in Chapter 3, and in order to determine the number of fibers on each link for each converter placement configuration, the wavelength assignment algorithm described Chapter 3 is used. The GS algorithm is executed a number of times in order to generate multiple solutions.

4.2 Tabu Search (TS) Algorithm

Tabu Search is an iterative improvement procedure employing adaptive memory and was proposed by Glover [50]. It has been used for a wide range of hard optimization problems from resource planning to telecommunications. It starts from an initial solution and gradually improves the objective function by a series of moves. Its main difference from other iterative search techniques is that it allows non-improving moves to escape from local optima. To avoid entrainment in cycles, previously visited solutions are declared tabu for a number of iterations and the moves leading to tabu solutions are forbidden.

In our TS based converter placement algorithm, the search space consists of all possible converter placement configurations achieving the target minimum cost of fibers. The objective function is the number of converting nodes in the network. There are three types of possible moves: add move, drop move and exchange move. In an add move, a converter is placed to one of the nodes that do not contain a wavelength converter. A drop move consists of removing the converter from one of the nodes with a converter. An exchange move is a combination of these two moves: a converter is removed from a converter containing node and is placed at another node that do not contain one.

There are three types of tabu lists, one for each type of move: drop tabu list, add tabu list and exchange tabu list. Each entry in these lists contain three types of information area: the converters to be changed, the current converter placement configuration and a tenure variable which indicates the number of iterations that entry will remain in the list. The first type of information area contains the node to deploy a converter for an add tabu list, the node to remove the converter from for a drop tabu list. For an exchange tabu list, this information area consists of two nodes, to deploy a converter to the first and remove the converter from the other. The second area contains the information of the wavelength converting nodes just before the move in the first area is made. If the converters that will be changed with a move and the converter placement configuration before the move is made exist in one of the entries of the tabu lists, that move is considered tabu and is not carried out.

The initial solution of the TS algorithm can be any converter placement configuration giving the target minimum cost of fibers. The full conversion configuration or the solutions generated by the GS algorithm can be used as an initial solutions.

At each step of the algorithm, the list of all feasible moves is calculated. A feasible move is a move that results in a converter placement configuration giving the minimum cost of fibers calculated in the routing part and which is not in one of the tabu lists. If there exist feasible drop moves, next move is chosen randomly among them. Otherwise, if feasible, the next move is chosen among the exchange moves. If neither a drop nor an exchange move is feasible, the next move is chosen among the feasible add moves. Improvement of the objective function is achieved by giving the first priority to the drop moves and then to the exchange moves. Whenever a move is made, the move together with the existing configuration of converting nodes and a tenure value, is added to the tabu list. The tenure value is chosen randomly. At each step, after the move is made, the tenure values of the entries in the tabu lists are decreased by one and the entries with 0 tenure value are removed from the lists. The best solution, which is the configuration with the minimum number of converting nodes found so far, is stored in the memory and updated if a better solution is found. There are two stopping criteria for the algorithm: the conditions of no feasible moves and no improvement in the objective function for a maximum number of iterations.

With this state of the TS algorithm described so far, when a solution is found the algorithm has a tendency to return to that solution after a number of iterations since drop moves always have a higher priority than others. In order to overcome this problem and find other solutions that are not in the close neighborhood of the previously visited solutions, a diversification step is introduced so that unvisited regions of the solution space are also visited. This diversification step is executed when no improvement is achieved in the objective function for a certain number of iterations. In the diversification step, the drop and exchange moves are not considered for a number of iterations, only add moves are made and a solution with a larger number of converting nodes is attained. After the diversification step ends, other local optima can be achieved by a series of moves also including drop and exchange moves.

The flowchart of the TS converter placement algorithm is presented in Figure 4.2. There are three important parameters and two variables mentioned in the flowchart: no_imp_limit, $diverse\_start$ and $diversification\_limit$ parameters and no_imp and $diversification$ variables. The algorithm stops if no improvement is obtained in the objective function for no_imp_limit iterations. $diverse\_start$ represents the number of non improving iterations before the diversification step starts, and $diversification\_limit$ is the number of iterations that the diversification step lasts. no_imp variable stores the number of non improving moves after the minimum value of the objective function is attained and $diversification$ stores the number of iterations executed after the algorithm last entered the diversification step.

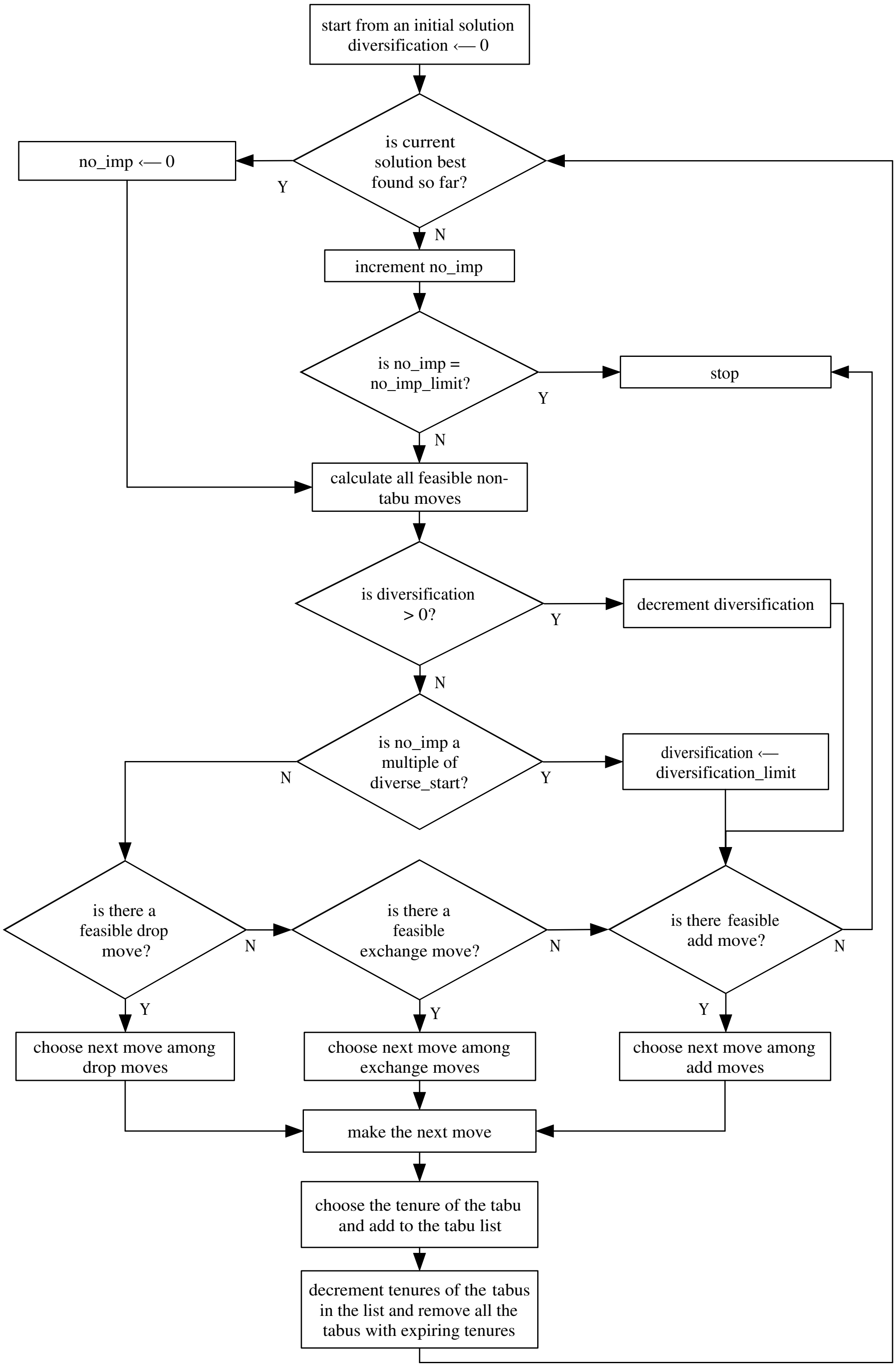

Figure 4.2: Flowchart of the TS algorithm

Chapter 5

Numerical Results and Discussions

In the first part, we investigate the performance of the TS algorithm on a sample network with 32 nodes and 50 links, for which the optimum solutions were obtained in [34]. We compare the performances of GS and TS converter placement algorithms with the optimum solutions, using the same routes obtained by using the flow formulation in [34].

Then, with the same network and demand patterns, we use the path based ILP formulation proposed in Chapter 3 for routing, for three different values of number of considered shortest paths: k=3, 5 and 8. For each of these sets of routes, we employe the GS and TS algorithms and compare their performances. We also show the effect of the routing algorithm on the generated solutions.

In order to observe the effect of the network topology, we run the TS and GS algorithms also on the 19-node EON topology proposed in [37] with randomly generated traffic patterns and different values of number of wavelengths. For both topologies, the average of the total traffic passing through each node and the distribution of the converter placements generated by the TS algorithm are calculated and their relation is investigated.

5.1 TS Algorithm Parameters

The parameter *no_imp_limit* is set to 100, so the TS algorithm stops if no improvement is obtained in the minimum number of converting nodes for 100 moves. The values of *diverse_start* and *diversification_limit* are chosen as 25 and 16, respectively: if the best solution is not improved for 25 moves, the diversification step is applied, and only add moves are considered for 16 moves. With these values, it is guaranteed that the diversification step is executed at least three times before the algorithm stops and nearly half of the nodes are deployed converters in these steps, to allow the algorithm visit different regions of the search space. The tabu tenures are assigned randomly between certain values. In order to analyze the effect of tabu tenures on the best solutions, we tested the TS algorithm for three different ranges of tabu tenures: [5-10], [10-20] and [20-40] for W=8, i.e., there are 8 wavelengths on each fiber. All of these ranges produce the best solutions with the same number of wavelength converting nodes with all connection request sets. However, the number of different solutions achieving the minimum number of converting nodes are slightly different: with nine different demand patterns the total numbers of best solutions produced are 23, 26 and 25 for tabu tenure ranges of [5-10], [10-20] and [20-40], respectively. In all the results presented in the rest of this chapter, the tabu tenure range of [10-20] is used.

5.2 Performance on the 32-Node Mesh Network

5.2.1 Comparison with Optimum Solutions

In [34], an optimum solution for our wavelength assignment and converter placement problems is presented. First the routing problem is solved by a flow based ILP formulation with the objective of minimizing the total cost of fibers assuming full conversion. Then, the wavelength assignment and converter placement problems are solved by employing an ILP formulation. This is not a completely optimum solution of the whole problem since the paths used are fixed and calculated assuming full conversion. However, it is the optimum solution for the wavelength assignment and converter placement problems with the calculated routes. When comparing the converter placement solutions generated by our TS algorithm with the optimum solutions, we use the routes calculated in that work in order to obtain the same target minimum fiber cost.

We make the comparisons on the network which was proposed in [34] and is shown in Figure 5.1. The algorithms are compared for two different numbers of wavelengths, W=8 and W=16. Nine different demand sets which are taken from [34] are used for each value of W. The average number of connection request demands in a demand set is 96 for W=8 and 80 for W=16.

The converters placed by the TS and GS algorithms and the optimal placements are presented for W=8 and W=16 and nine demand sets for each value of W are shown in Tables 5.1 and 5.2. For each demand set, the GS algorithm is run 10 times and the best solution among all runs is reported. As it is observed from the results, the TS algorithm produces the optimum solutions in 5 of 9 demand patterns for W=8 and 8 of 9 demand patterns for W=16, i.e., in 72% of all runs. The total number of converting nodes placed with each algorithm is

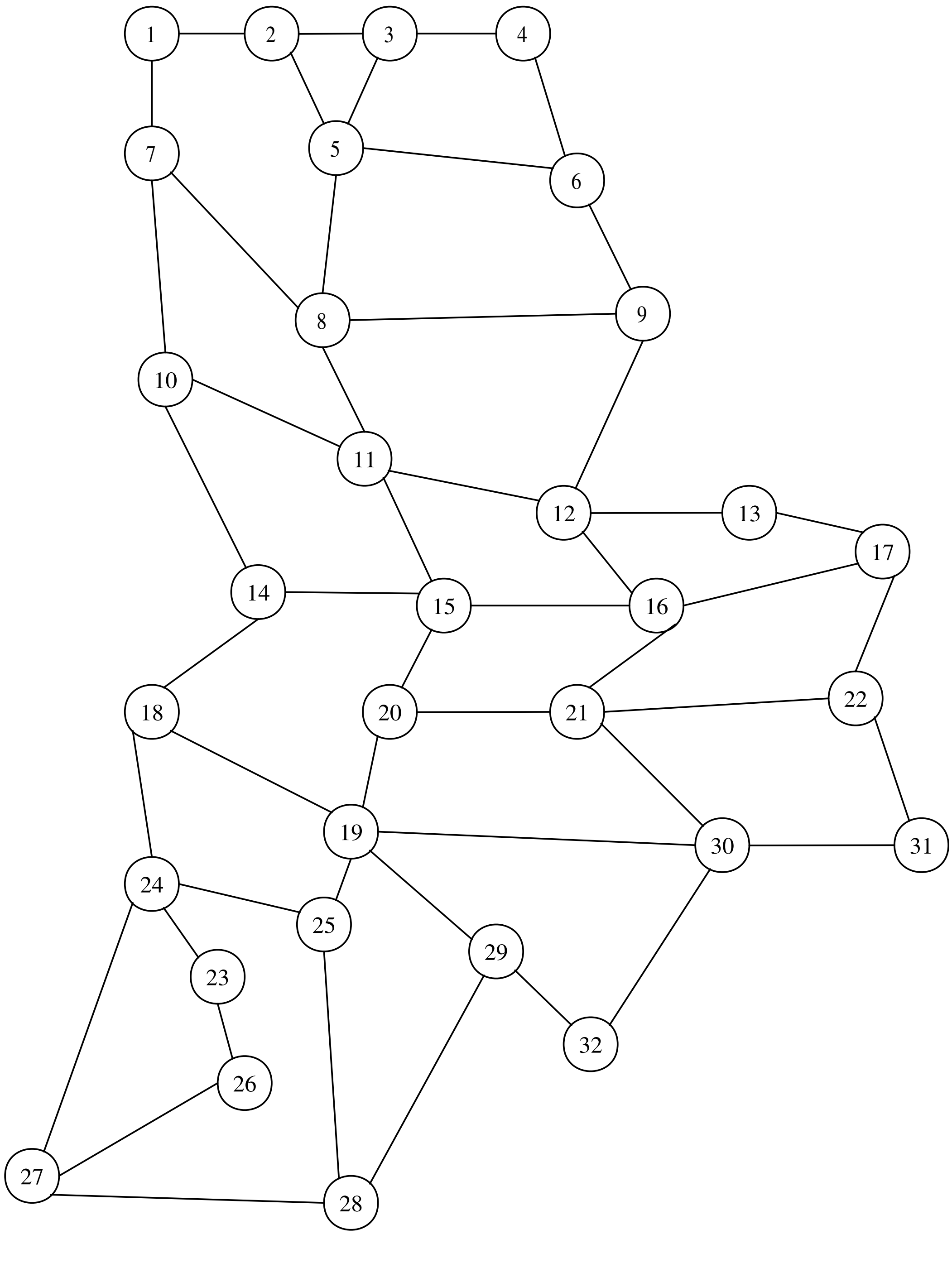

Figure 5.1: The 32 node mesh network

W=8	GS Solutions		TS Solutions		Optimum Solutions	
Demand Set	Number of conv.	Converting Nodes	Number of conv.	Converting Nodes	Number of conv.	Converting Nodes
1	6	2, 9, 12, 14, 16, 20	6	2, 9, 12, 14, 16, 19	6	2, 9, 12, 14, 16, 19
2	10	6, 8, 9, 14, 15, 16, 18, 20, 29, 30	9	6, 8, 9, 14, 15, 18, 19, 29, 30	7	6, 8, 14, 18, 19, 29, 30
3	5	12, 13, 15, 16, 18	4	12, 15, 16, 18	4	12, 15, 16, 18
4	4	5, 6, 15, 16	4	5, 6, 15, 16	4	5, 6, 15, 16
5	10	2, 3, 4, 12, 15, 22, 23, 26, 29, 31	4	8, 12, 22, 29	4	12, 17, 22, 29
6	12	2, 9, 13, 16, 19, 20, 22, 23, 26, 27, 28, 31	3	9, 11, 16	2	9, 16
7	6	7, 11, 14, 19, 28, 29	4	7, 14, 28, 29	3	7, 11, 14
8	9	2, 4, 7, 11, 16, 18, 26, 27, 31	2	2, 11	2	2, 11
9	1	15	1	15	0	

Table 5.1: *The number of converting nodes and their locations in the solutions generated by the GS and TS algorithms using optimum routing, and the optimum solutions for W=8*

shown in Table 5.3. The number of converting nodes in the optimum solutions corresponds to 8.6% less than the total number of converting nodes placed by the TS algorithm. For the demand patterns for which the TS algorithm fails to find the optimum solution, we ran the wavelength assignment algorithm with the optimum converter placement and we found out that the target number of fibers cannot be reached in any of them. This fact shows that, the failure of the TS algorithm to find the optimum solution is not due to the inefficiency of the converter placement algorithm, but it is a consequence of the wavelength assignment algorithm which is not optimal.

We observe that in 39% of the solutions, the TS algorithm improves the solution provided by the GS algorithm. The GS algorithm achieves the optimum solution in 56% of the cases, however the main drawback of the algorithm is that, in some cases it generates extremely inefficient solutions containing much more converting nodes than the optimum solution. The reason of this inefficiency is

W=16	GS Solutions		TS Solutions		Optimum Solutions	
Demand Set	Number of conv.	Converting Nodes	Number of conv.	Converting Nodes	Number of conv.	Converting Nodes
1	2	15, 16	2	15, 16	2	15, 16
2	2	11, 12	2	11, 12	2	11, 12
3	1	6	1	6	1	6
4	5	11, 14, 15, 16, 25	5	11, 14, 15, 16, 25	5	11, 14, 15, 16, 25
5	4	6, 12, 14, 29	4	6, 12, 14, 29	4	6, 12, 14, 29
6	4	15, 21, 25, 28	4	15, 21, 25, 28	4	15, 21, 25, 28
7	6	7, 8, 12, 14, 16, 17	6	7, 8, 12, 14, 16, 17	6	7, 8, 12, 14, 16, 17
8	11	2, 6, 7, 8, 14, 15, 16, 20, 22, 25, 28	6	7, 8, 14, 16, 25, 28	5	7, 8, 14, 25, 28
9	3	14, 25, 28	3	14, 25, 28	3	14, 25, 28

Table 5.2: *The number of converting nodes and their locations in the solutions generated by the GS and TS algorithms using optimum routing, and the optimum solutions for W=16*

W	GS	TS	OPTIMUM
8	63	37	32
16	65	33	32
Total	128	70	64

Table 5.3: *The total number of converting nodes placed by the TS and GS algorithms and the optimum solution*

that, placing a converter at a node alone may not decrease the number of fibers much, but when two or more such nodes are occupied with converters together, their combination may give a much better result and the greedy approach fails to reach that combination since it places the converters one-by-one.

The average of total run times of the TS and GS algorithms and the time to reach the best solution are presented in Table 5.4. The TS algorithm is run starting from two different initial solutions, one of these is the full conversion configuration and the other is the solution generated by the GS algorithm. The cases in which the TS algorithm does not improve the solution of the GS algorithm are not considered when calculating the average. According to the results, starting from the solution produced by the GS algorithm, the TS algorithm reaches the best solution in less time, because starting from the full conversion case, some amount of time is spent dropping most of the converters in the full conversion case. However, the runtime of the GS algorithm should also be considered when the TS algorithm uses the solutions provided by the GS algorithm as initial converter configuration and this eliminates the time advantage of using the solutions generated by the GS algorithm. The GS algorithm achieves the best solution in a very small amount of time when the number of converting nodes in the solution is small, but when this number increases, the time to reach the best solution and the total runtime of the GS algorithm increases significantly.

5.2.2 Performance Comparison under Different Routing Schemes

To observe the effect of the routing algorithm used, we executed the TS and GS algorithms for the same demand patterns under different routing schemes. We calculated the routes by the path based ILP formulation presented in Chapter 3, with k=3, 5 and 8 shortest paths. The number of converting nodes in the

	W=8		W=16	
	Best solution time	Total runtime	Best solution time	Total runtime
GS	44.22 sec.	350.67 sec.	465.56 sec.	734.78
TS starting from full conversion	63.11 sec.	1156.33 sec.	48.11 sec.	970.67 sec.
TS using the solution of GS	9.17 sec.	1068.17 sec.	7.00 sec.	1795.00 sec.

Table 5.4: *The average of times to reach the best solution and total run times of GS algorithm, TS algorithm starting from full conversion and TS algorithm starting from the solution of GS*

W=8	K=3		K=5		K=8		Optimum Routing	
Demand Set	TS	GS	TS	GS	TS	GS	TS	GS
1	3	4	5	5	6	7	6	6
2	6	7	3	4	4	5	9	10
3	5	6	5	5	8	8	4	5
4	4	5	5	7	1	1	4	4
5	3	4	3	5	2	6	4	10
6	1	1	2	2	3	4	3	12
7	2	3	3	4	3	4	4	6
8	1	1	1	1	2	2	2	9
9	1	1	1	1	2	2	1	1
Total	26	32	28	34	31	39	37	63
Average	2.89	3.56	3.11	3.78	3.44	4.33	4.11	7.00

Table 5.5: *The average number of converting nodes placed by the TS and GS algorithms for different routing schemes for W=8*

solutions produced by the two algorithms for each demand, and the averages are given in Tables 5.5 and 5.6.

When the average of all four routing schemes is taken, the TS algorithm outperforms the GS algorithm in 58% of the solutions for W=8 and in 22% for W=16. The GS algorithm performs well in the cases when there are smaller number of converting nodes in the solution, but when a large number of converting nodes are needed, it tends to diverge from the optimum solution significantly.

W=16	K=3		K=5		K=8		Optimum Routing	
Demand Set	TS	GS	TS	GS	TS	GS	TS	GS
1	0	0	1	1	0	0	2	2
2	2	2	4	4	3	3	2	2
3	0	0	1	1	1	1	1	1
4	1	1	6	6	6	6	5	5
5	1	1	1	1	2	2	4	4
6	1	1	3	3	4	4	4	4
7	2	3	5	5	6	7	6	6
8	4	5	4	4	7	8	6	11
9	4	5	6	18	4	6	3	3
Total	15	18	31	43	33	37	33	38
Average	1.67	2.00	3.44	4.78	3.67	4.11	3.67	4.22

Table 5.6: *The average number of converting nodes placed by the TS and GS algorithms for different routing schemes for W=16*

W	TS	GS
8	3.39	4.67
16	3.11	3.78
Overall	3.25	4.24

Table 5.7: *The average number of converting nodes placed by the TS algorithm over all routing schemes*

As shown in Table 5.7, the average number of converting nodes in the solutions generated by the TS and GS algorithms is lower for W=16 than for W=8. When the converter placement solutions for W=16 are examined, it can be seen that most of the solutions contain one or two converting nodes. This is because, when there are more number of wavelengths per fiber, the number of wavelength mismatch blockings decreases and a smaller number of wavelength converting nodes are needed. This explains why the performance difference between the two algorithms is higher for W=8. An important fact to take into consideration is that, in these simulations the number of demands is approximately the same for the two different wavelengths, for the cases where the number of demands is increased with the number of wavelengths per fiber, these conclusions will not be valid.

W=8	K=3	K=5	K=8	Optimum routes
Ave. fiber cost	23109.89	22721.56	22453.67	22222.78
Ave. number of fibers	59.78	59.78	58.67	58.22
Ave. path length	4.31	4.38	4.41	4.44

Table 5.8: *Average fiber cost, number of fibers and path lengths with all the routing schemes for W=8*

W=16	K=3	K=5	K=8	Optimum routes
Ave. fiber cost	15348.11	14107.11	13386.22	12708.89
Ave. number of fibers	39.22	36.89	36.11	34.78
Ave. path length	4.52	4.78	4.85	5.09

Table 5.9: *Average fiber cost, number of fibers and path lengths with all the routing schemes for W=16*

It can be observed from Tables 5.5 and 5.6 that, as the number of shortest paths considered while solving the routing problem increases, the total number of converting nodes placed by the TS algorithm also increases. The increase in the average number of converting nodes continues when optimum routes are considered for W=8. There are two main reasons for the increase in the number of placed converters. First, as more paths are considered in the routing, our objective function, which is the total fiber cost decreases and the number of fibers, also decreases with the total cost. Second, when a larger number of shortest paths are considered, longer paths can be utilized and the average number of hops of the lightpaths generally tends to increase (this is not always true as it will be discussed later). These results can be seen from Tables 5.8 and 5.9. With less fibers (i.e., less space switching) and longer paths (i.e., more opportunities for conflict), the number of wavelength mismatch blockings increase, and larger number of converting nodes are needed.

W=8	Fiber Cost				Number of Fibers			
Demand set	K=3	K=5	K=8	Opt. Rout.	K=3	K=5	K=8	Opt. Rout.
1	17724	17304	16936	16662	45	46	46	43
2	16545	16003	15612	15441	42	42	40	39
3	17347	16747	15716	15516	42	44	41	41
4	20451	20221	20170	19725	54	53	53	52
5	24321	23997	23699	23419	61	61	60	59
6	24724	24362	24137	23467	67	68	65	65
7	22978	22341	22332	22312	61	58	59	58
8	31779	31531	31502	31495	82	82	80	83
9	32120	31988	31979	31968	84	84	84	84

Table 5.10: *Total fiber cost and total number of fibers for each demand set with all the routing schemes for W=8*

The total fiber cost and the total number of fibers for each individual demand are shown in Table 5.10 for W=8 and in Table 5.11 for W=16. Table 5.12 and Table 5.13 present the average path lengths for each individual demand. When Tables 5.12 and 5.13 are examined, it can be observed that increasing the number of paths considered in the routing algorithm may sometimes decrease the average path length. This result may seem in contradiction with our statement above, but this is not true, because the shortest paths are calculated using the costs of the links as lengths. Therefore, the $(k+1)-th$ shortest path may have a smaller number of hops than the $k-th$ shortest path. Furthermore, using a longer path for one node pair may result in shorter paths for multiple node pairs which may decrease the average path length. However, in most of the cases, the opposite of this situation is valid, and increasing the number of considered paths results in an increase in the average path length.

5.2.3 Traffic Statistics and Converting Node Placement Distribution

In this part, we present the percentage of the cases that a converter is placed at each node in the solutions generated by the TS algorithm. We consider all the

W=16	Fiber Cost				Number of Fibers			
Demand set	K=3	K=5	K=8	Opt. Rout.	K=3	K=5	K=8	Opt. Rout.
1	15363	13335	13046	11300	39	34	35	32
2	14657	13485	12245	11956	36	35	33	33
3	13785	13211	11920	11330	36	34	34	31
4	15027	13939	13846	12804	39	37	36	34
5	15373	14440	13514	12495	39	38	36	34
6	14600	13212	12462	12105	37	35	35	34
7	16743	14991	14504	14187	43	40	39	38
8	16782	15607	14673	14332	44	41	39	39
9	15803	14744	14266	13871	40	38	38	38

Table 5.11: *Total fiber cost and total number of fibers for each demand set with all the routing schemes for W=16*

W=8	Av. Path Length			
Demand set	K=3	K=5	K=8	Opt. Rout.
1	4.32	4.40	4.43	4.47
2	4.57	4.48	4.85	4.88
3	4.10	4.33	4.33	4.43
4	4.49	4.63	4.61	4.66
5	4.37	4.45	4.35	4.35
6	4.61	4.70	4.47	4.66
7	4.15	4.23	4.21	4.29
8	3.99	4.03	4.09	4.06
9	4.23	4.16	4.30	4.17

Table 5.12: *The average pathlength for each demand set with all the routing schemes for W=8*

W=16	Av. Path Length			
Demand set	K=3	K=5	K=8	Opt. Rout.
1	4.40	4.55	4.78	5.02
2	4.73	5.08	5.43	5.35
3	4.28	4.57	4.57	5.47
4	4.73	5.20	5.03	5.08
5	4.49	4.70	4.68	5.30
6	4.06	4.51	4.60	4.86
7	4.60	4.91	4.86	4.96
8	4.82	4.83	4.89	4.95
9	4.57	4.71	4.81	4.79

Table 5.13: *The average pathlength for each demand set with all the routing schemes for W=16*

solutions generated using all four different routing schemes and take the average. The traffic passing through the nodes is also analyzed and three quantities corresponding to the amount of traffic passing through the node are calculated for each node: the amount of transit traffic, which is the number of demands passing through the node, the amount of transit traffic times the average length of the paths passing through the node and the amount of transit traffic times the degree of the node.

Figure 5.2 presents the distribution of the percentage of the cases the nodes are placed converters; Figures 5.3, 5.4 and 5.5 show the distribution of the parameters explained above for W=8. Figures 5.6, 5.7, 5.8 and 5.9 exhibit the same distributions for W=16. As seen from the graphics, all the three parameters have a similar distribution which shows a correlation with the converting node placement distribution. The first five nodes with the highest percentage of placing a converter are nodes 15, 14, 16, 12 and 25 for W=8 and nodes 14, 25, 16, 15 and 28 for W=16. For both values of W, these five nodes are among the first twelve nodes with the highest amount of transit traffic. However, this correlation is not enough for making the converter placements according to these traffic parameters and for some nodes the distributions diverge greatly. For example, there is a large amount of traffic passing through node 19 for both values of W but that node does not have a high percentage of converter placement (below 15% for W=8 and 10% for W=16).

5.3 Performance on 19-Node European Optical Network (EON)

In this part, we investigate the performance of the TS and GS algorithms on the 19-node EON as shown in Figure 5.10. For the routing part, we only use the paths generated by the path based ILP formulation presented in Chapter 3. The

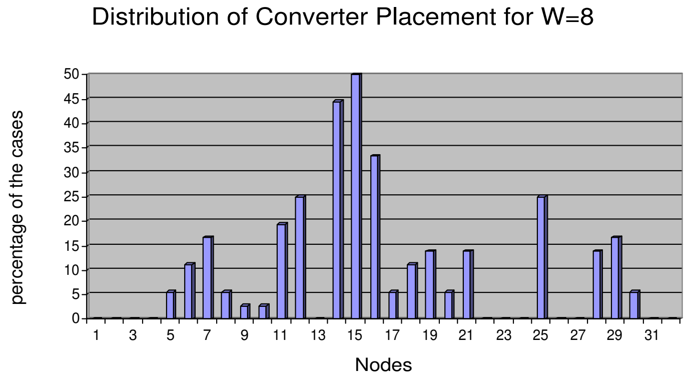

Figure 5.2: The percentage of the cases that a converter is placed at the node for each node for W=8

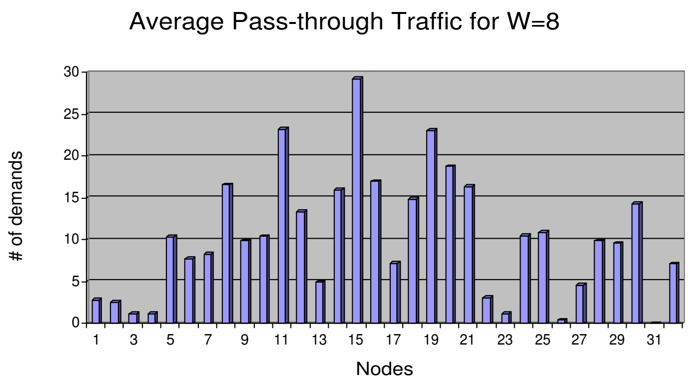

Figure 5.3: The average transit traffic for each node for W=8

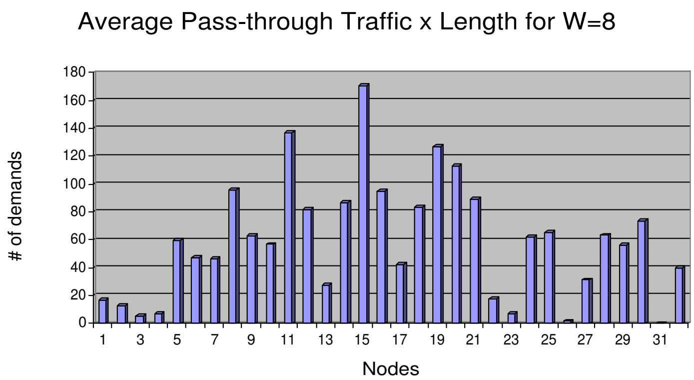

Figure 5.4: The average transit traffic times average path length for each node for W=8

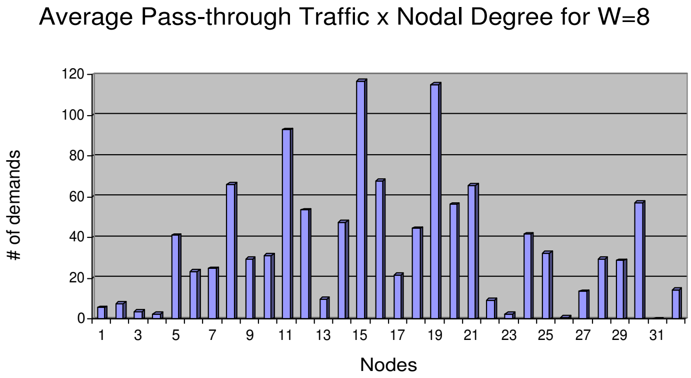

Figure 5.5: The average transit traffic times the degree of the node for each node for W=8

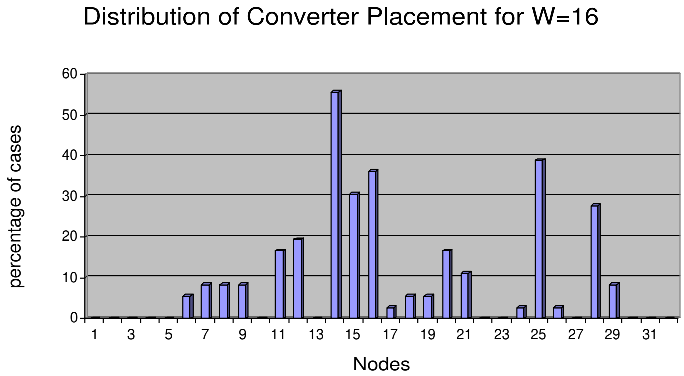

Figure 5.6: The percentage of the cases that a converter is placed at the node for each node for W=16

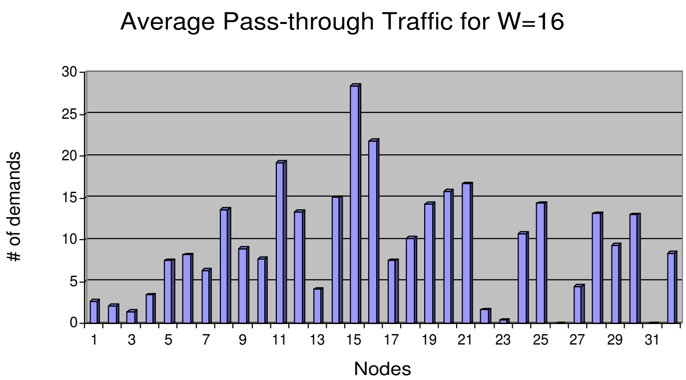

Figure 5.7: The average transit traffic for each node for W=16

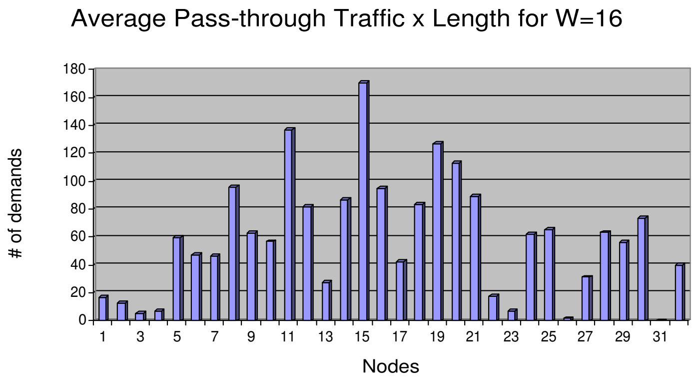

Figure 5.8: The average transit traffic times average path length for each node for W=16

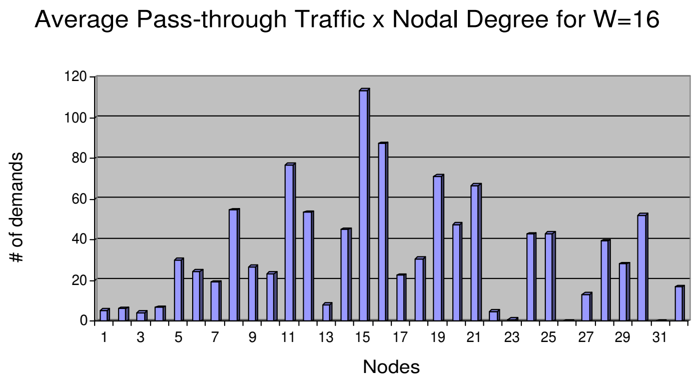

Figure 5.9: The average transit traffic times the degree of the node for each node for W=16

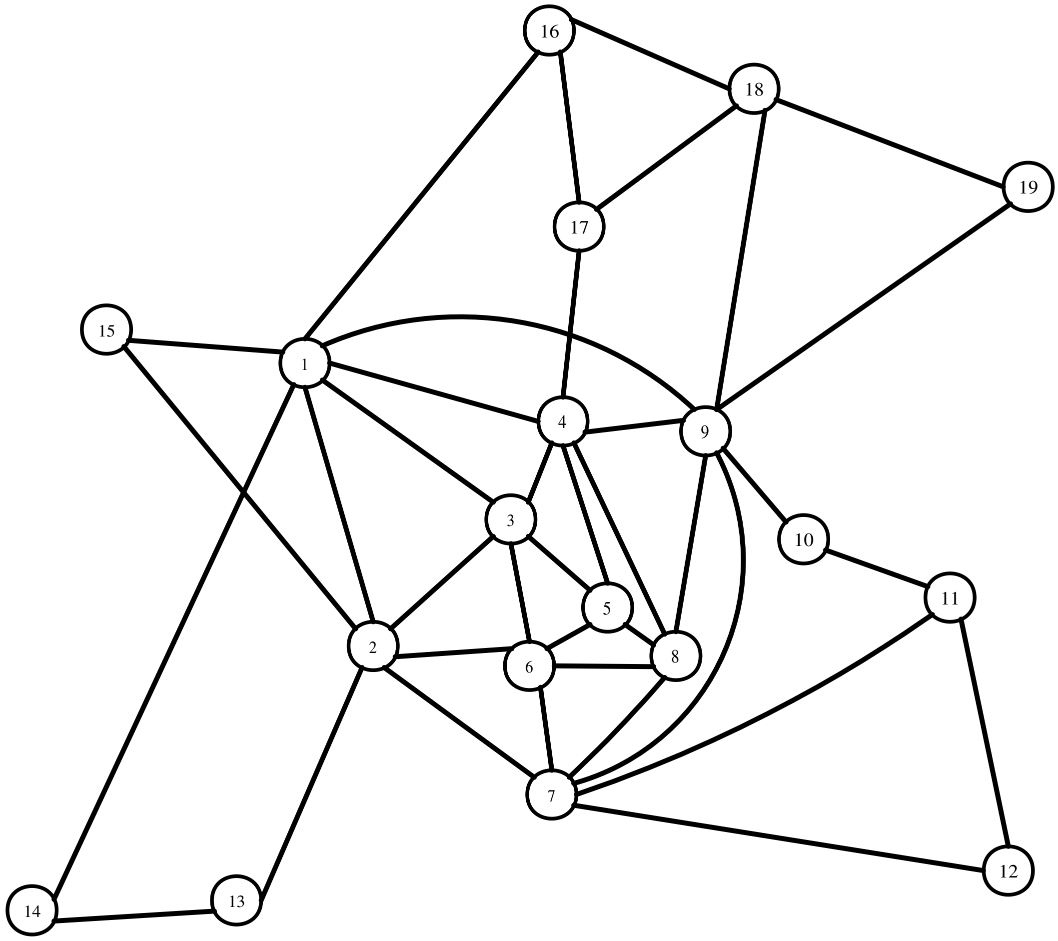

Figure 5.10: 19-node EON

costs of the links are taken as unity, so the objective function is to minimize the total number of fibers.

The first eight shortest paths are considered while solving the routing problem, i.e., k=8. The algorithms are tested for three different number of wavelengths: W=16, 32 and 64. 50 demands sets are created for each wavelength number. For W=16, a traffic demand between [0-2] is created randomly for each node pair, this range is between [0-4] for W=32 and [0-8] for W=64.

The average number of converting nodes in the solutions obtained by using the TS algorithm are shown in Table 5.14, and the distribution of the solutions according to the number of converting nodes is given in Table 5.15. The GS algorithm produced the same solutions with the TS algorithm in all of the trials

	W=16	W=32	W=64
Average path length	2.60	2.61	2.63
Average number of converting nodes	0.8	0.96	1.04

Table 5.14: *The average path length and number of converting nodes for the experiments conducted using EON*

	Percentage of the solutions (%)		
W	0 conv.	1 conv.	2 conv.
16	26	68	6
32	10	84	6
64	12	72	16

Table 5.15: *The percentage of the 0-converter, 1-converter and 2-converter solutions for the experiments conducted using EON for different wavelengths*

for W=16 and W=32 and in 96% of the trials for W=64. The proximity of the performances of the algorithms can be explained by the small number of converting nodes in the solutions. The maximum number of wavelength converting nodes in the generated solutions is 2 for all wavelengths. The average number of converting nodes is smaller than 1 for W=16 and 32 and slightly larger than 1 for W=64. The GS algorithm is guaranteed to find any 1-converter solution which can be obtained with our wavelength assignment algorithm, because in a 1-converter solution, placing the converter to that node in the solution results in the target minimum number of fibers. The main reason for the small number of converting nodes in the solutions is the smaller path lengths. The EON has a smaller number of nodes compared to the 32-node mesh network, and it also has a larger average nodal degree compared with the 32-node network (average nodal degree is 3.79 for EON and 3.12 for the 32-node network). Because of these two effects, path lengths are much shorter for EON.

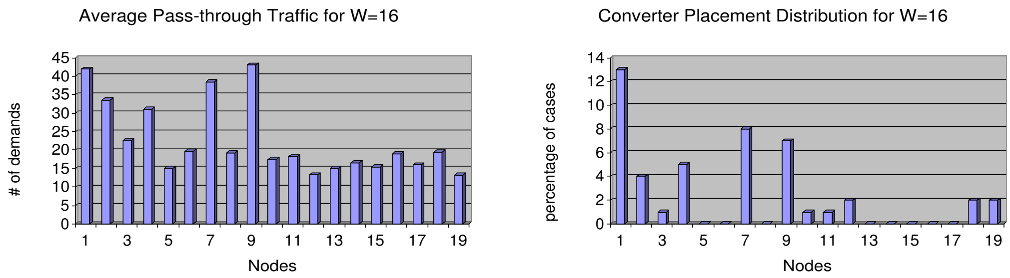

Figure 5.11: The average pass-through demands and converting node placement distribution for W=16

5.3.1 Traffic Statistics and Converting Node Placement Distribution

The relation between the traffic statistics and the distribution of the converting node placements on the EON network are in accordance with our conclusions for the trials with the 32-node mesh network.

The distribution of the converting node placements and the pass through demands for W=16, 32 and 64 are presented in Figures 5.11, 5.12 and 5.13, respectively. As it is seen from the graphs, the nodes 1, 2, 4, 7 and 9 are the nodes with the highest amount of transit traffic for all wavelength numbers. When the converter placement distributions are examined, the same nodes are also the nodes with the highest percentage of being placed a converter. However, there are cases where a node is receiving a higher amount of transit traffic than another node, but it has a smaller percentage of being placed a converter. So, a node with high amount of transit traffic may have a large likelihood of being placed a converter, but we cannot state that there is a one-to-one correspondence.

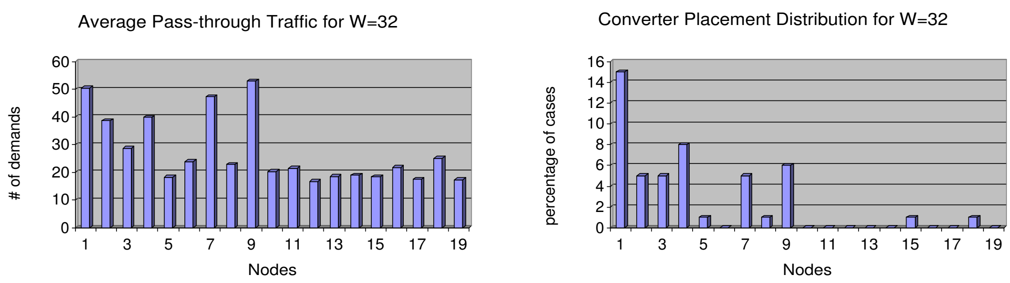

Figure 5.12: The average pass-through demands and converting node placement distribution for W=32

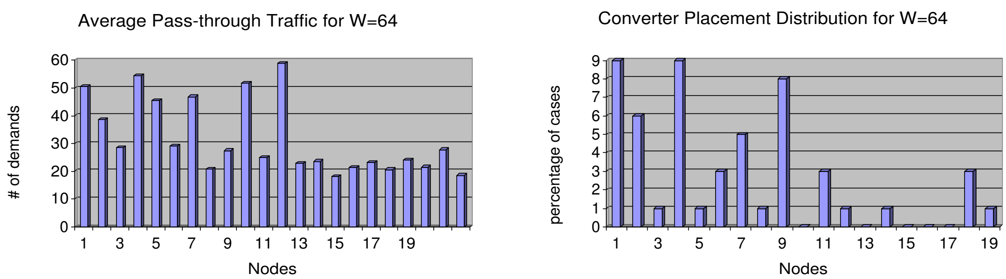

Figure 5.13: The average pass-through demands and converting node placement distribution for W=64

Chapter 6

Conclusions

In this thesis, we proposed a tabu search based heuristic algorithm for the sparse placement of wavelength converting nodes. The main objective is to place the minimum number of wavelength converting nodes necessary for achieving the minimum total fiber cost which is obtained in a network having full wavelength conversion capability. We use flow and path based ILP formulations for the routing problem. We propose a heuristic wavelength assignment algorithm to be used in the converter placement algorithm. A heuristic converter placement algorithm using greedy search method is also implemented for comparison purposes and for generating initial solutions for the TS algorithm. Both the GS and the TS algorithms can be run with different routing schemes and different wavelength assignment algorithms.

The solutions generated by both algorithms are compared with the optimum solutions for a 32-node mesh network. The TS algorithm achieves the optimum solutions in 72% of the cases and it places 9.3% more converting nodes than the optimum solutions on the average. The performances of the GS and TS algorithms are investigated for a flow based routing solution and path based routing solutions with different number of considered shortest paths. The TS algorithm improves the solutions generated by the GS algorithm in 40% of the results. We also observe that as the number of considered paths for routing increases, the target minimum cost of fibers decreases and the number of converting nodes in the generated solutions increases.

We also examined the performances of GS and TS algorithms using another network with 19-nodes. The GS algorithm generates the same results with the TS algorithm nearly in all the cases. The reason for this is that, the average lengths of the paths were much smaller compared to the 32-node network, resulting from the small size of this network and its densely connected topology. With shorter paths used, less wavelength mismatch blockings occur and a smaller number of wavelength converting nodes is needed. The GS algorithm performs considerably well for small number of converting nodes, in fact it guarantees to find the optimum solution in the cases where only one converting node is enough.

We also investigated the relationship between the number of demands passing through a node and the likelihood that a converter is placed at that node. The nodes with higher amount of passing demands has a larger percentage of being placed a converter. This information can be used to modify the TS algorithm. In the cases where the TS algorithm misses the optimum solution, we ran our wavelength assignment algorithm with the optimum converter placement configurations and observed that the target cost of fibers could not be reached. For future work, for networks where the TS algorithm tends to miss the best solution, it can be used in conjunction with another wavelength assignment algorithm and it can be modified to use the traffic information, giving more weight to the the moves placing a converter at the nodes with more transit traffic.

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