Routing and Wavelength Assignment Schemes in Scalable Wavelength-Routed Optical Networks

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Routing and Wavelength Assignment Schemes in Scalable Wavelength-Routed Optical Networks

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概要

データ転送における帯域の急速な需要増加に応えるために、光ネットワークは、将来を担う根幹なネットワークアーキテクチャと位置付けられている。波長ルーティング光ネットワークは、高帯域かつ低遅延を要求する通信の需要の増加に応えることができる。

光ネットワークへの将来的な需要に対応するために、メトロまたは地域ネットワーク用の光キャリア管理とドメインレベルの分割に関する研究が行われてきた。その結果、MCLS(multi-carrier light source) ノードのマルチキャリア光源を、各光パスの発ノード光源装置に置き換えることにより、光キャリアの再利用を可能とするマルチキャリア分散ネットワーク（WRMD: wavelength-reusable multi-carrier-distributed）は光キャリアの管理を簡略化することを可能にした。一方で、大規模なネットワークの管理を拡張化するために、ネットワークを複数のドメインに分割し、ドメイン内およびドメイン間での管理をするマルチドメインネットワークと呼ばれる大規模ネットワークがある。本論文では、WRMD ネットワークおよびマルチドメインネットワークにおける RWA 方式について述べる。

WRMD ネットワークにおいては、経路および波長割当方式（RWA: routing and wavelength assignment）を提案する。RWA 方式は、WRMD ネットワークにおいて光キャリアの接続性および光経路に対する要求を考慮しながら、波長資源の再利用し、必要な波長数を最小化する。単一または複数というそれぞれの MCLS ノード数に対応する 2 つの研究成果を示す。RWA 問題とは，光パスの経路の設定に必要な最小波長数を求めるための整数線形計画問題（ILP: integer linear programming）である。大規模ネットワークにおいては、ILP によるアプローチでは、RWA 問題を実用的な計算時間で解くことが困難である。そこで、RWA 問題を実用的な時間で解くために、発見的な RWA 方式を導入する。

マルチドメイン光ネットワークにおいては、高信頼な RWA 方式、すなわち完全なるエンドツーエンド間でのプライマリおよびバックアップ経路を提供する方式を提案する。提案方式では、経路に対するトータルコストを発着ノード間のトラフィックを分割することで最小化する。この方式は、フルメッシュトポロジー結合における階層的な経路計算を基にした ILP を用いている。この方式には、2 つの段階があり、1 段階目では、ドメイン間のトポロジについて ILP 問題を解き、その解をドメイン内の ILP 問題に与える。2 段階目で、その ILP 問題を各ドメイン内で解く。最終的に、各ドメイン内での

計算結果を一連のルーティングに関連付ける。さらに、3 つのプロテクション手法、すなわち、同一ドメイン順序手法、独立リンク手法、および、独立ドメイン手法が、プライマリまたはバックアップ経路の分割のために用いられる。

ネットワークにおけるリソース割当方式の性能について、様々な観点で評価した。この方式は既存の分配型ヒューリスティック方式の計測およびさらなる解析のための基準値を与えることが可能である。

Abstract

The exponential growth of the bandwidth demand for data transmission capacity has made an optical network a promising candidate for the future core network architecture. A wavelength-routed optical network (WRON) has the potential to meet rising demands for high bandwidth and low latency communication.

In conventional WRON, it is more difficult to manage optical carriers as the number of wavelengths increases. In addition, it is difficult to manage the entire network with full knowledge of network resources on single-domain scenarios. In order to make the conventional WRON more scalable and manageable, researches on optical carrier management for metro/regional networks and domain-level partitioning for large-scale optical networks are conducted. Accordingly, wavelength-reusable multi-carrier-distributed (WRMD) network is able to simplify the optical carrier management by placing a multi-carrier light source (MCLS) in an MCLS node, as the communication light source device. In order to utilize network resources efficiently, a large network that is partitioned into several domains, called multi-domain network, can take place. In this thesis, RWA schemes in WRMD network and multi-domain network are introduced.

In the WRMD network, a routing and wavelength assignment (RWA) scheme is considered. The RWA scheme in the WRMD network must take into account both optical carrier connections and requested lightpaths using the reuse of the optical carrier connections while minimizing the number of required wavelengths. There are two investigated cases, depending on the number of MCLS nodes: either one or multiple. First, the RWA problem is formulated as the integer

linear programming (ILP) problem of obtaining the minimum number of required wavelengths to satisfy the given lightpath setup requests. For large-scale networks, the ILP approach is not practical solution times. A heuristic RWA scheme is then introduced to solve the RWA problem in practical times.

In the multi-domain optical network, a survivable RWA scheme, which provides complete end-to-end primary and backup path pairs, is considered. In this thesis, the survivable lightpath provisioning scheme that allows traffic splitting to minimize the cumulative cost of a set of paths is introduced. This scheme employs an ILP formulation based on hierarchical path computation with full-mesh topology abstraction. There are two phases in the scheme. The first phase solves the ILP problem on an inter-domain topology and then feeds the results as intra-domain requests. The second phase solves the ILP problem in each related domain. Finally, all the intra-domain solutions are concatenated along routing sequences. Moreover, three different protection strategies, namely same domain sequence, link disjoint, and domain disjoint, are considered with varying degrees of primary and backup route separation.

The performance of the RWA schemes in each network is evaluated in many points as well as many different network topologies. Therefore, the schemes can provide reference values to gauge the existing distributed heuristics and to further analysis.

To my parents

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Acronyms

DD Domain disjoint

DMUX Demultiplexer

EON Elastic optical network

ER Explicit route

FR Fixed route

IETF Internet engineering task force

ILP Integer linear programming

IP/MPLS Internet protocol/multi-protocol label switching

KSP k-shortest path

k-SP k-shortest paths

LD Laser diode

LD Link disjoint

LR Loose route

LWF Less number of required wavelengths first

MCLS Multi-carrier light source

MN MCLS node

MOD Modulator

MTL Maximum transmission length

ACRONYMS

MUX Multiplexer

NCF Nearest optical carrier first

NE Near ending node

NGN Next generation network

NM Near MCLS node

NRZ Non-return-to-zero

OADM Optical add-drop multiplexer

OCR Optical carrier regenerator

OOK On-off keying

OXC Optical cross-connect

PCE Path computation element

RSVP-TE Resource reservation protocol-traffic engineering

RWA Routing and wavelength assignment

RX Receiver

RZ Return-to-zero

SDN Software defined networking

SDS Same domain sequence

SLE Static lightpath establishment

WAN Wide area network

WC Wavelength converter

WDM Wavelength division multiplexing

WRMD Wavelength-reusable multi-carrier-distributed

WSS Wavelength selective switch

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Chapter 1

Introduction

With the exponential growth of the Internet data traffic and the ever-increasing demands for higher throughput, an optical network is the candidate to provide the required capacity and flexibility for high-speed networks [1]. In optical networks based on wavelength-division multiplexing (WDM), different users share the network capacity on the principle of simultaneous allocation of distinct wavelengths on fiber links, which then build the optical paths [2]. In these networks, the term user refers to any application requesting the allocation of an optical channel (wavelength). With growing demand for high-bandwidth optical connections, the variety and the number of users increase, and so does the complexity of their handling. Therefore, the appropriate allocation of network resources is essential for the accommodation of particular user connections [3].

For optical networks employing WDM technology, a lightpath is established between a pair of source and destination nodes to transmit information [4]. A lightpath consists of an optical channel, or wavelength, between two network nodes that is routed through multiple intermediate nodes, as shown in Fig. 1.1. In routing and wavelength assignment (RWA) problem, a prime task is how to determine both a route and wavelengths for a connection request [5]. Moreover, while WDM may provide larger bandwidth to users and more revenue to service providers, it also has some potential problems. The most serious is the survivability of WDM systems. Because of the large amount of traffic a fiber carries, a single failure in a WDM system would cause severe service loss. Therefore,

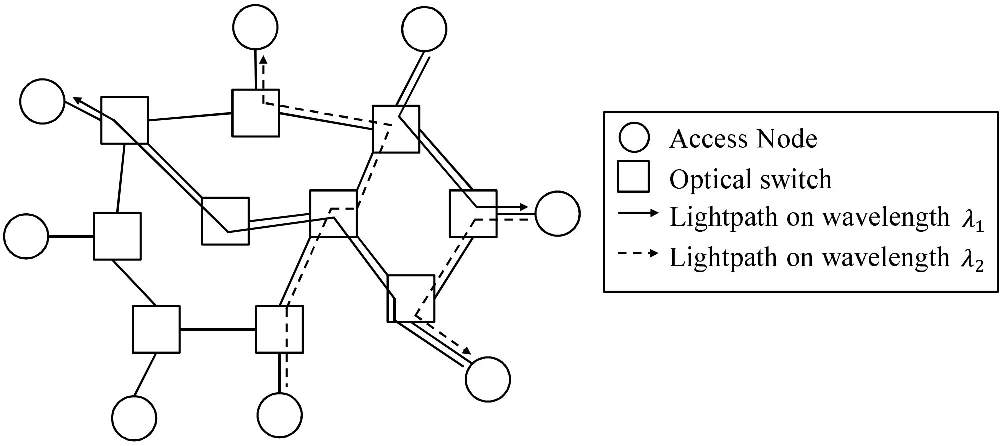


Figure 1.1: Optical networks employing WDM technology.

in order to design a survivable optical network, one must lay out the possible failures under which the network must be survivable [6].

With the development of optical networks, low network cost and network scalability are becoming important requirements for future optical networks besides high-capacity transmission. Cost has always been one of the most important criteria for optical network design. To deal with the traffic explosion, we have to increase the number of WDM channels (wavelengths) and the speed of each channel in optical networks. Therefore, the implementation cost, power consumption, and complexity of network management increase as adding more light sources in each network node [7, 8]. Upwards scalability is achieved by increasing the number of nodes in the network. The single-domain topology approaches pose many restrictions such as high storage cost, slow convergence time, and low scalability [9, 10]. In this thesis, two kinds of optical networks, which are wavelength reusable multi-carrier-distributed (WRMD) network and multi-domain optical network, are presented.

1.1 Wavelength-reusable multi-carrier-distributed network

A multi-carrier-distributed optical network with wavelength reuse capability [7, 11, 12, 13] is an attractive solution. This network is called the wavelength-reusable multi-carrier-distributed (WRMD) network. The WRMD network places a multi-carrier light source (MCLS) in an MCLS node, as the communication light source device. The MCLS generates stable and multiple optical carriers at the same time over long periods [14] - [19]. The individual wavelengths are used as optical carriers. MCLS generates the optical carriers and passes them to all requesting source nodes for lightpath establishment. By replacing many widely dispersed laser diodes (LDs) with the single MCLS, the difficulties posed by monitoring and controlling a large number of LDs are eliminated. The single MCLS is easier to control. Therefore, the network management of the WRMD network is easier than that of the conventional optical add-drop multiplexer (OADM) networks. Furthermore, each node in the WRMD network is equipped with an optical carrier regenerator (OCR) [11] - [13]. The OCR allows the nodes to reuse a wavelength to satisfy multiple disjoint lightpath requests.

Wavelength management in the WRMD network is more complex than that in the conventional OADM network. Generally, the routing and wavelength assignment (RWA) problem in the conventional OADM network is to provide routes to the requested lightpaths and to assign wavelengths on each of the links along this route among the possible choices so as to optimize a certain performance metric. Meanwhile, the RWA problem in the WRMD network must take into account both optical carrier connections and requested lightpaths while maximizing the reuse of the optical carrier connections. In this thesis, I address the static RWA problem, also known as the static lightpath establishment (SLE) problem. In SLE problem, the requests of lightpaths are known in advance and the routing and wavelength assignment are performed off-line. The general objective of the RWA problem is to minimize the number of wavelengths needed to set a certain set of lightpaths for a given physical topology [5, 20].

Wavelength assignment for the WRMD ring network was presented in [7]. None of the source nodes includes an LD. Each requested lightpath directly receives a generated optical carrier from the MCLS node or a reused optical carrier from the destination node of other requested lightpath. Therefore, the source node has several light sources from which it can receive an optical carrier. Carrier distribution has to be managed so as to minimize the number of wavelengths.

In the ring topology, an optical carrier connection, which connects the MCLS node and a requested lightpath, or between two requested lightpaths, is uniquely determined because the connecting direction is limited [21]. It is very simple to select the optical carrier connection since there are only two possible paths, which are the clockwise and anticlockwise directions.

On the other hand, in the mesh topology, there are several paths, called carrier lightpaths, for one optical carrier connection. One of the carrier lightpaths is used for the optical carrier connection. Therefore, the mesh topology makes distributing optical carriers and assigning wavelengths much more complex than the ring topology [22]. A mathematical model for wavelength assignment to minimize the number of required wavelengths for the WRMD mesh network was introduced in [23]. This model provides reference values, including upper and lower bounds, which are useful for benchmarking purposes.

However, the scheme of both [7] and [23] are unable to change the routes of optical carrier connections and requested lightpaths since they are fixed. In practical cases, all routes of optical carrier connections and requested lightpaths are required to be designed to minimize the number of wavelengths. The work in [7] - [23] provided only a wavelength assignment scheme. The routing of optical carrier connections and requested lightpaths was not considered. As a result, the number of wavelengths required for lightpath establishment was large. In order to minimize the number of wavelengths, the RWA scheme that decides both the routes and the wavelengths of lightpaths while minimizing the number of wavelengths is still an open question and should be addressed.

Recently, an RWA scheme for the WRMD ring network was presented in [24]. A heuristic RWA scheme is introduced to solve the RWA problem and minimize the number of wavelengths required for lightpath establishment. However, only a ring topology was considered in the original paper.

1.2 Multi-domain optical network

Optical networks are expected to operate as multiple routing domains due to technological constraints, administrative functions, trust relationship, and other considerations. In multi-domain optical networks, there are many more complexities than single-domain ones, since the detailed domain-internal topology and resource information are not propagated across domain boundaries due to scalability and privacy concerns [25] - [31]. This makes it difficult to design protection schemes for multi-domain optical networks. More recently, researchers have started to implement a range of multi-domain protection schemes based on partial global state information [32] - [34]. These strategies rely on distributed path computation and signaling to resolve complete end-to-end primary and backup path pairs [35] - [38]. However, within the multi-domain context, protection schemes can be further delineated as per the availability of global diversity state, i.e., per-domain protection or end-to-end path protection. I focus on end-to-end path protection schemes, which have been designed to achieve better domain diversity between primary and backup routes than the per-domain protection schemes. These schemes assume some type of global skeleton view of the network, typically via hierarchical inter-domain routing protocols [39] - [42]. The topology abstraction approach, which is adopted to hide internal domain states so as to resolve routing scalability and security issues, can affect the accuracy of the routing state information [43, 44]. Note that the full-mesh topology abstraction approach provides more accurate intra-domain usage state than the simple node approach [40].

Several works have recently focused on this line of work [32] - [34]. The work in [32] presented an enhanced abstraction of the network domain topologies to compute link-disjoint primary and backup routes. However, this enhanced abstraction introduces significant routing overhead which implies significant scalability issues. The work in [33] presented a path protection scheme and showed that the utilization of partially overlapped domain sequences guarantees the most effective utilization of network resources. The work in [34] presented a mechanism for computing a pair of link-disjoint paths considering the wavelength continuity constraint. The primary and backup routes are allowed to traverse the same

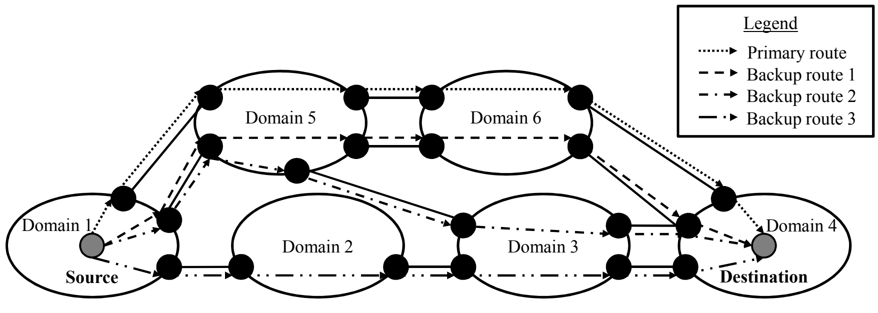


Figure 1.2: Primary and backup skeleton routes with different domain-diversity requirements.

domain sequence or partially overlapped domain sequences. The work in [45] presented several approaches based on an enhanced abstraction with intra-domain disjointness information to find a pair of disjoint end-to-end routes. The primary and backup routes may traverse multiple domains from source to destination and result in minimum total cost.

A pair of paths are domain-diverse if they do not transit any of the same domains [42]. Therefore, multi-domain protection schemes can be delineated as per the level of domain diversity between primary and backup routes, as shown in Fig. 1.2.

1.3 Problem statements

As mentioned before, the wavelength management in the WRMD network is more complex than that in the conventional OADM network, since the RWA schemes in the WRMD network must take into consideration both optical carrier connections and requested lightpaths while maximizing the reuse of the optical carrier connections. Furthermore, for large-scale networks that must support increasing numbers of lightpaths, there may be a need to have more than one MCLS node to use wavelength resources efficiently. To the best of my knowledge, however, no studies have addressed the use of multiple MCLS nodes in the WRMD mesh networks.

In multi-domain optical networks, I observe that these existing multi-domain protection solutions are heuristic algorithms, and use graph-theoretic approaches to compute intra-domain and inter-domain route sequences with dated or inaccurate routing information. Therefore, it is desirable to derive more formal analyses to establish improved bounds on achievable performance. Recently, the work in [46] presented an optimization design for multi-domain protection considering only link disjointness. Furthermore, to handle various types of traffic demands, which may occur in the case of very high demand or insufficient capacity, a survivable lightpath provisioning scheme should effectively accommodate the incoming traffic by splitting them into multiple paths at the same time. To the best of my knowledge, however, no studies have addressed the support of various types of traffic demands.

1.4 Contributions

In this thesis, I propose an RWA scheme for WRMD mesh networks to minimize the number of required wavelengths for lightpath establishment. The RWA problem is first formulated into an integer linear programming (ILP) problem that provides the optimum route and wavelength pairs for lightpaths. However, the ILP approach does not offer practical computation times for large-scale networks. A heuristic RWA scheme is then introduced to solve the RWA problem. The scheme consists of a routing algorithm and a wavelength assignment algorithm, which are performed separately. I introduce requested lightpath selection policies for the wavelength assignment algorithm. There are three policies: random, near ending node (NE), and near MCLS node (NM). The contribution lies in how to decide both routes and wavelengths of lightpaths so as to minimize the number of required wavelengths in the WRMD network. In addition, I also investigate the location of the MCLS node to reduce the number of required wavelengths in the WRMD mesh network.

For large-scale networks that need to have more than one MCLS node, I propose an RWA scheme that supports multiple MCLS nodes for WRMD mesh networks to minimize the number of required wavelengths for lightpath establishment. Similar to WRMD mesh network with one MCLS node, I introduce lightpath selection policies for the wavelength assignment algorithm. There are two policies: nearest optical carrier first (NCF), and less number of required wavelengths first (LWF). Furthermore, I also investigate the number of MCLS nodes as well as the locations of the MCLS nodes to reduce the number of required wavelengths in the WRMD mesh network.

Moreover, I present an optimization approach for survivable lightpath provisioning that allows traffic splitting in multi-domain optical networks to minimize the cumulative cost of a set of paths. To handle dated or inaccurate routing information, I focus on the full-mesh topology abstraction approach, since it provides better performance than the alternatives. I formulate an ILP model based on hierarchical path computation. There are two phases in the proposed approach. The first phase solves the ILP problem on the inter-domain topology and then feeds the results as intra-domain requests. The second phase solves the ILP problem in each related domain. Finally, I concatenate all the intra-domain solutions along routing sequences. Three different protection strategies, namely same domain sequence (SDS), link disjoint (LD), and domain disjoint (DD), are considered with varying degrees of primary and backup route separation. Furthermore, to support various types of traffic demands, I evaluate my scheme for two different numbers of requested wavelengths. In the first case, the number of requested wavelengths is less than link capacity. The link capacity is defined as the number of wavelengths on each link. In the second case, the number of requested wavelengths is greater than link capacity. For the latter case, the proposed scheme allows traffic splitting among feasible primary and backup routes.

1.5 Organization of the thesis

Figure 1.3 shows the organization of this thesis. The thesis consists of seven chapters. Two kinds of resource allocations and solutions are described from chapter 2 to 6. Routing and wavelength assignment schemes and their solutions are described in chapter 2 to 5. Survivable lightpath provisioning scheme and its solution are described in chapter 6. Chapter 7 concludes the details of the thesis.

Chapter 2 presents a mathematical model in order to minimize the number of required wavelengths for WRMD mesh networks with one MCLS node. The

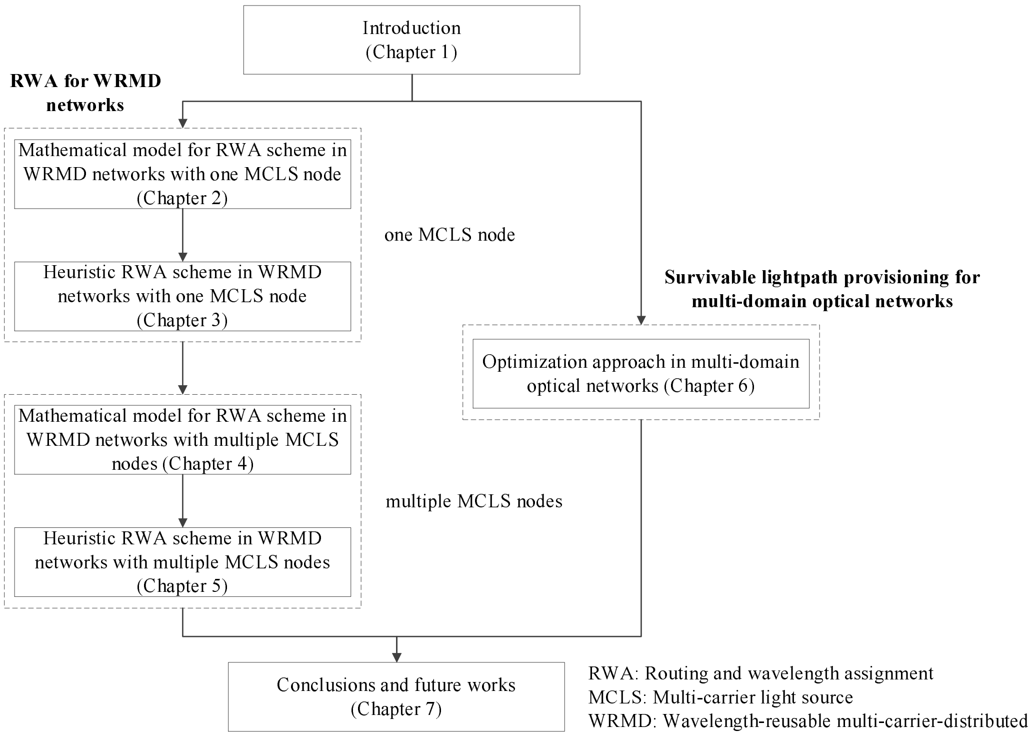


Figure 1.3: Organization of the thesis.

RWA problem is formulated into an integer linear programming (ILP) problem that provides the optimum route and wavelength pairs for lightpaths.

Chapter 3 presents a heuristic RWA scheme to solve the RWA problem for large-scale networks with one MCLS node. I introduce requested lightpath selection policies for the wavelength assignment algorithm. There are three policies: random, near ending node (NE), and near MCLS node (NM). Performance of the scheme is evaluated in different networks.

Chapter 4 presents a mathematical model in order to minimize the number of required wavelengths for WRMD mesh networks with multiple MCLS nodes. Performance of the model is evaluated as the number of MCLS nodes.

Chapter 5 presents a heuristic RWA scheme to solve the RWA problem for large-scale networks with multiple MCLS nodes. I introduce lightpath selection policies for the wavelength assignment algorithm. There are two policies: nearest optical carrier first (NCF), and less number of required wavelengths first (LWF).

Moreover, the number of MCLS nodes and the locations of the MCLS nodes are also investigated to reduce the number of required wavelengths in the WRMD mesh network.

Chapter 6 presents an optimization approach for survivable lightpath provisioning that allows traffic splitting in multi-domain optical networks to minimize the cumulative cost of a set of paths. Three different protection strategies, namely same domain sequence (SDS), link disjoint (LD), and domain disjoint (DD) are considered with varying degrees of primary and backup route separation. Furthermore, performance of the approach is evaluated from two points: the effect of traffic demands and the effect of link capacity.

Chapter 7 concludes this thesis. Appendix is described after chapter 7. Calculation of cost-effectiveness analysis in chapter 2 is described in appendix A.

Chapter 2

Mathematical model for RWA scheme in WRMD networks with one MCLS node

This chapter presents an integer linear programming (ILP) model to determine an optimum route and wavelength pairs for lightpaths that minimizes the number of required wavelengths in wavelength-reusable multi-carrier-distributed (WRMD) mesh networks. The purpose of the ILP optimization is to determine how to distribute constrained resources in order to optimize a single objective, e.g., described herein, to minimize the number of required wavelengths. First of all, an overview of WRMD network is presented, including the architecture of WRMD network, carrier regeneration, and rules of wavelength assignment. Then, the mathematical model is presented. The performance of the ILP model is evaluated in terms of the number of required wavelengths, compared to the fixed route (FR) scheme and the conventional optical add-drop multiplexer (OADM) network. Simulations show that the ILP model reduces the number of required wavelengths, compared to the FR scheme. Moreover, the number of required wavelengths in the WRMD network approaches that in the conventional OADM network if the allowable number of carrier regenerations is increased.

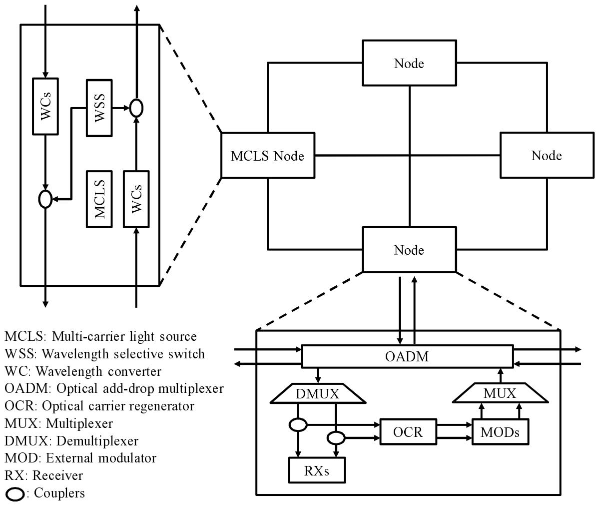


Figure 2.1: WRMD network architecture.

2.1 Introduction

The WRMD network was introduced to simplify optical carrier management, since the MCLS easily allows control of optical carriers with high wavelength grid accuracy [12]. Furthermore, it was reported that the WRMD network is superior to the conventional OADM network in terms of network cost and power consumption on ring topologies in [47]. An example of the WRMD network with mesh topology, as shown in Fig. 2.1, consists of three nodes and an MCLS node, where the MCLS node also works as a regular node. Each node consists of an optical add-drop multiplexer (OADM), OCR, multiplexers (MUXs)/demultiplexers (DMUXs), external modulators (MODs), and receivers (RXs). The MCLS node consists of an MCLS, a wavelength selective switch (WSS) and wavelength converters (WCs). The MCLS node is used to generate and provide optical carriers to all requested lightpaths. Each link consists of two optical fibers carrying information in opposite directions.

At each node in the WRMD network, specific optical carriers are dropped by the OADM of the source nodes and used for uplink transmission. A data stream is added to the network, and is modulated with the optical carrier, while the data is dropped at the destination nodes. Thus, the OADM for multi-carrier distribution is not only responsible for adding and dropping data, but also for dropping optical carriers. The dropped data stream and optical carrier are separated and regenerated by the OCR. The regenerated optical carrier is re-injected into the network, and is used to establish another requested lightpath. Similar to the property of optical carrier duplication, the optical carrier can be split into several copies and each copy is used to establish another requested lightpath.

2.1.1 Carrier regeneration

In the WRMD mesh network, the optical carrier regeneration means that an optical return-to-zero (RZ) clock signal synchronized and wavelength-matched with an injected RZ data signal is generated from the data signal. An optical carrier for wavelength reuse is able to be easily regenerated from a reused RZ data signal in the network [12]. Therefore, in this thesis, I focus on on-off keying (OOK) modulation, which is the most commonly used modulation scheme in optical communication and can use either non-return-to-zero (NRZ) or RZ signal formats. The regenerated optical carriers are used to establish other requested lightpaths. The number of wavelengths needed for lightpath establishment is reduced. In fact, however, carrier quality is drastically degraded after several regenerations. In other words, the optical carrier reuse number must be limited to prevent excessive degradation in optical signal quality.

Figure 2.2 shows how OCR reduces the number of wavelengths needed for lightpath establishment. In Fig. 2.2, the WRMD mesh network consists of four nodes. One of them works as the MCLS node. There are two requested lightpaths, which are from node 2 to node 3 and node 4 to the MCLS node. Node 2 receives a wavelength from the MCLS node as an optical carrier. The requested data stream from node 2 modulates the optical carrier. The modulated optical signal is transmitted to node 3. At node 3, the data stream is demodulated from the received optical signal, and is dropped. The optical carrier is regenerated by the OCR, and is transmitted to node 4. At node 4, the requested data stream modulates the regenerated optical carrier. The modulated optical signal is transmitted to the MCLS node. At the MCLS node, the data stream

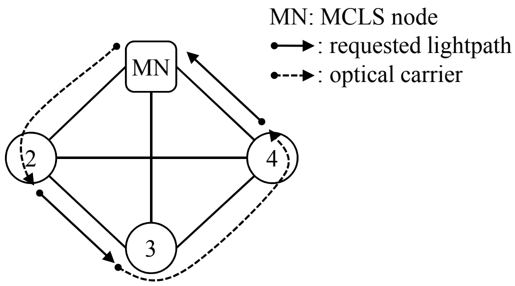


Figure 2.2: Lightpath establishment with optical carrier regeneration.

is demodulated from the received optical signal, and is dropped. In this example, only one wavelength is used to establish two requested lightpaths. In other words, the network with OCR can reduce the number of wavelengths needed to establish all requested lightpaths using the routing and wavelength assignment (RWA) scheme, compared to that without OCR.

2.1.2 Rules of wavelength assignment

Wavelength assignment in the WRMD mesh network must obey the following three rules:

1. Each wavelength can be used to establish several requested lightpaths, as shown in Fig. 2.3(a).
2. Each requested lightpath is satisfied by using an optical carrier generated by the MCLS node or a reused optical carrier from another established lightpath, as shown in Fig. 2.3(b).
3. To avoid collision, optical carriers and requested lightpaths on the same link must be assigned different wavelengths, as shown in Fig. 2.3(c).

2.2 Mathematical model

The following notations are introduced to describe the RWA problem mathematically. A network is represented as undirected graph $G = (V, E)$, where V is the

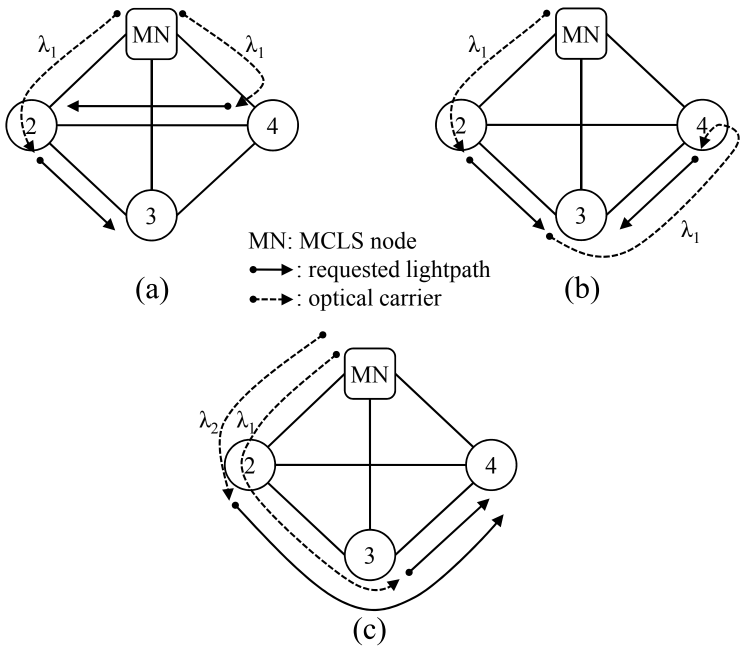


Figure 2.3: WRMD mesh network rules and conditions.

set of network nodes and E is the set of bidirectional links. Let W be the set of wavelengths generated by the MCLS. Let w be wavelength index, where $w \in W$ ($w = 1, 2, \cdots, w_{max}$). $r \in R$ indicates the number of times an optical carrier is reused, where $R = \{0, 1, \cdots, R_{max}\}$. R_{max} is the maximum number of times an optical carrier can be reused. $r = 0$ means that the optical carrier is directly generated from the MCLS node. Let P be a set of lightpath requests, and C be a set of optical carrier connections. Let s_p and d_p be the source and destination nodes of lightpath $p \in P$, where $s_p, d_p \in V$. Let s_c and d_c be the source and destination nodes of optical carrier $c \in C$, where $s_c, d_c \in V$. Let (i, j) be a link between two network nodes, where $(i, j) \in E$.

Assumptions made for addressing the RWA problem are as follows.

- The number of nodes is given.
- Bi-directional connection is realized by two connections having opposite directions.
- The lightpath request matrix P is given.

- The maximum number of times an optical carrier can be reused, R_{max}, is given for each wavelength.

2.2.1 Terminologies

The RWA problem is formulated below as an ILP problem [48]. The following notations are used in describing the network and lightpaths. Let N be the number of nodes, and M be the MCLS node (MN). Let $q_p(p, w, r)$ be a binary decision variable that is set to one if lightpath request $p \in P$ uses wavelength $w \in W$ with $r \in R$, otherwise zero. Let $q_c(c, w, r)$ be a binary decision variable that is set to one if optical carrier $c \in C$ uses wavelength $w \in W$ with $r \in R$, otherwise zero. Let $x(p, i, j)$ be a binary decision variable that is set to one if lightpath request $p \in P$ is routed on $(i, j) \in E$, otherwise zero. Let $z(c, i, j)$ be a binary decision variable that is set to one if optical carrier $c \in C$ is routed on $(i, j) \in E$, otherwise zero. Let $y(w)$ be a binary decision variable that describes the usage of wavelength w, where $w \in W$. This variable is 1 if wavelength w is used at least once. Let $m(p, i, j, w, r)$ be a binary decision variable that is set to one if lightpath request $p \in P$ is routed on $(i, j) \in E$ using wavelength $w \in W$ with $r \in R$, otherwise zero. Let $n(c, i, j, w, r)$ be a binary decision variable that is set to one if optical carrier $c \in C$ is routed on $(i, j) \in E$ using wavelength $w \in W$ with $r \in R$, otherwise zero.

2.2.2 Integer linear programming (ILP) model formulation

The objective function is represented as

$$\min \sum_{w \in W} y(w) \tag{2.1}$$

so that this ILP minimizes the number of required wavelengths when creating connections for all lightpaths.

The constraints are as follows.

$$\sum_{r \in R} \sum_{w \in W} q_p(p, w, r) = 1, \forall p \in P \tag{2.2a}$$

$$\sum_{r\in R}\sum_{w\in W} q_c\left(c,w,r\right) \leq 1, \forall c \in C \tag{2.2b}$$

$$\sum_{j:(i,j)\in E} x\left(p,i,j\right) - \sum_{j:(i,j)\in E} x\left(p,j,i\right) = 1, \forall p \in P, i = s_p \tag{2.2c}$$

$$\sum_{j:(i,j)\in E} x\left(p,i,j\right) - \sum_{j:(i,j)\in E} x\left(p,j,i\right) = 0, \forall p \in P, i \neq s_p, d_p \tag{2.2d}$$

$$\sum_{j:(i,j)\in E} z\left(c,i,j\right) - \sum_{j:(i,j)\in E} z\left(c,j,i\right) = 1, \forall c \in C, i = s_c \tag{2.2e}$$

$$\sum_{j:(i,j)\in E} z\left(c,i,j\right) - \sum_{j:(i,j)\in E} z\left(c,j,i\right) = 0, \forall c \in C, i \neq s_c, d_c \tag{2.2f}$$

$$\begin{gathered}\sum_{r\in R}\left\{m\left(p,i,j,w,r\right) + m\left(p',i,j,w,r\right) + \right.\\ \left. n\left(c,i,j,w,r\right) + n\left(c',i,j,w,r\right)\right\} \leq y\left(w\right),\\ \forall p,p'\left(p\neq p'\right) \in P, \forall c,c'\left(c\neq c'\right)\in C, (i,j)\in E, w\in W\end{gathered} \tag{2.2g}$$

$$\begin{gathered}q_p\left(p,w,r\right) \leq \sum_{c\in C:d_c=s_p} q_c\left(c,w,r\right),\\ \forall p\in P, w\in W, r\in R\end{gathered} \tag{2.2h}$$

$$\begin{gathered}q_c\left(c,w,r\right) \leq \sum_{p\in P:d_p=s_c} q_p\left(p,w,r-1\right),\\ \forall c\in C, w\in W, r\in R\setminus\{0\}\end{gathered} \tag{2.2i}$$

$$q_c\left(c,w,0\right) = 0, \forall w\in W, c\in C : s_c \neq M \tag{2.2j}$$

$$y\left(w\right) \geq y\left(w+1\right), \forall w \in W\setminus\{w_{max}\} \tag{2.2k}$$

$$m\left(p,i,j,w,r\right) \leq x\left(p,i,j\right), \forall p\in P, (i,j)\in E, w\in W, r\in R \tag{2.2l}$$

$$m\left(p,i,j,w,r\right) \leq q_p\left(p,w,r\right), \forall p\in P, (i,j)\in E, w\in W, r\in R \tag{2.2m}$$

$$\begin{gathered}m\left(p,i,j,w,r\right) \geq x\left(p,i,j\right) + q_p\left(p,w,r\right) - 1,\\ \forall p\in P, (i,j)\in E, w\in W, r\in R\end{gathered} \tag{2.2n}$$

$$n\left(c,i,j,w,r\right) \leq z\left(c,i,j\right), \forall c \in C, (i,j) \in E, w \in W, r \in R \tag{2.2o}$$

$$n\left(c,i,j,w,r\right) \leq q_c\left(c,w,r\right), \forall c \in C, (i,j) \in E, w \in W, r \in R \tag{2.2p}$$

$$\begin{aligned} n\left(c,i,j,w,r\right) \geq z\left(c,i,j\right) + q_c\left(c,w,r\right) - 1, \\ \forall c \in C, (i,j) \in E, w \in W, r \in R \end{aligned} \tag{2.2q}$$

Eq. (2.2a) ensures the assignment of lightpaths to all connection requests. Eq. (2.2b) ensures that each optical carrier connection is established at most once with at most one wavelength. Eqs. (2.2c) and (2.2d) are the flow conservation constraints between the incoming and outgoing flows at each node for lightpaths. Eqs. (2.2e) and (2.2f) are the flow conservation constraints between the incoming and outgoing flows at each node for optical carrier connections. Eq. (2.2g) ensures that different lightpaths and optical carrier connections must use different wavelengths for each link. Eq. (2.2h) ensures that a lightpath is established if a source node receives an optical carrier. Eq. (2.2i) ensures that an optical carrier is reused if a lightpath is established. On the other hand, an optical carrier with r should be replaced by another optical carrier with $r-1$. Eq. (2.2j) ensures that optical carrier connection $c \in C$ that is not generated from the MCLS node must not produce any optical carrier with $r=0$. Note that Eqs. (2.2h) to (2.2j) guarantee the prevention of loop generation. Eq. (2.2k) states that wavelengths are used in ascending order of wavelength index w. Eqs. (2.2l) to (2.2n) indicate a Boolean expression of $m(p,i,j,w,r) = x(p,i,j) * q_p(p,w,r)$ with linear forms with binary variables, where $m(p,i,j,w,r)$ is set to one only when both $x(p,i,j)=1$ and $q_p(p,w,r)=1$. Eqs. (2.2o) to (2.2q) indicate a Boolean expression of $n(c,i,j,w,r) = z(c,i,j) * q_c(c,w,r)$ with linear forms with binary variables, where $n(c,i,j,w,r)$ is set to one only when both $z(c,i,j)=1$ and $q_c(c,w,r)=1$.

2.3 Results and discussions

I evaluate the performance of the RWA scheme in terms of the number of required wavelengths, compared with that of the fixed route (FR) scheme [23]. The RWA scheme determines both route and wavelength for each lightpath request. Therefore, all routes of optical carrier connections and requested lightpaths are required to be designed to minimize the number of wavelengths. On the other hand, the FR scheme considers the fixed (pre-defined) routes of optical carrier connections and requested lightpaths. Therefore, the effect of all routes of optical carrier connections and requested lightpaths is investigated. Moreover, the RWA scheme in the WRMD mesh network is compared with that of the conventional OADM network, which has its own multiple LDs at each node. In the conventional OADM network, the shortest path algorithm is used as the routing decision and the largest degree first is used as the wavelength assignment algorithm to calculate the number of required wavelengths. In addition, the effect of optical carrier reuse is evaluated. In the evaluation, I assume that each link contains 8 wavelengths, the bandwidth of each request is one wavelength channel, and the duration of the request is infinite. I use a Linux-based computer with Intel®Core™i7-3770 CPU @ 3.40GHz and 32GB of memory.

In order to evaluate the effectiveness of the RWA scheme, the number of required wavelengths is investigated. The number of required wavelengths in the ILP approach is compared with that of the FR scheme [23], which does not take into account the routing of optical carrier connections and requested lightpaths in the WRMD mesh network. The FR scheme is used as a reference scheme as it is only an existing scheme for the WRMD mesh network. I consider the three network topologies presented in [23], as shown in Fig. 2.4.

Figure 2.5 shows the numbers of required wavelengths obtained by the FR scheme and ILP approach for five requested lightpaths in the three different network topologies. The ILP approach outperforms the FR scheme and gives the minimum number of required wavelengths. For this reason, the pre-defined routes of optical carrier connections and requested lightpaths may be not suitable for the RWA scheme. Therefore, the ILP approach is able to provide reference values for further analysis. Note that the number of required wavelengths in the WRMD network approaches that in the conventional OADM network if the allowable number of carrier regenerations is increased.

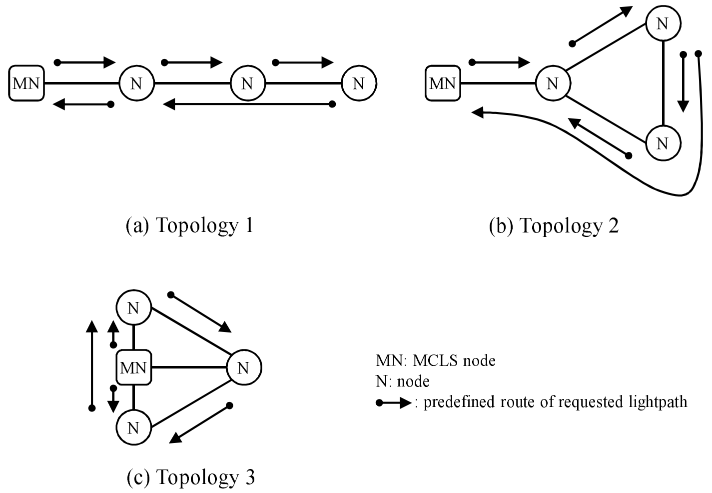


Figure 2.4: Network topologies for comparison with fixed routes.

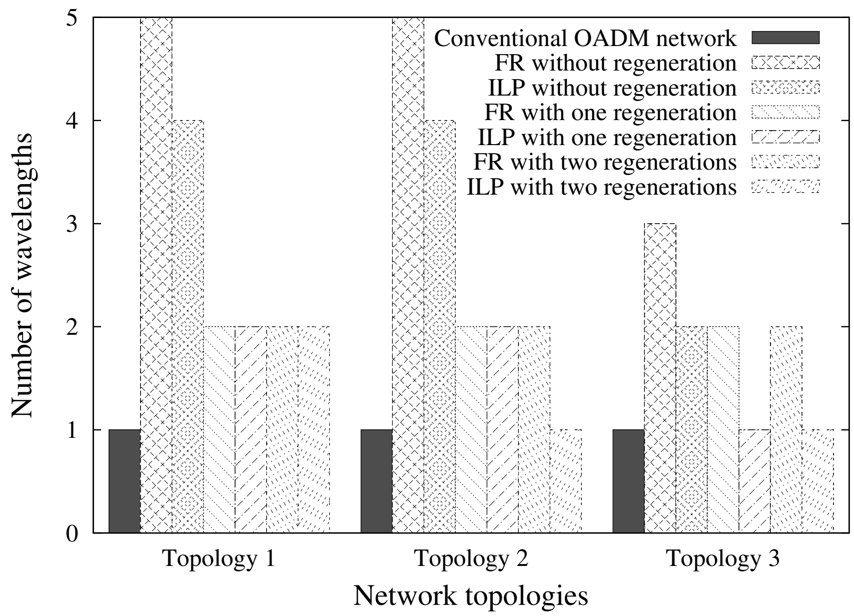


Figure 2.5: Comparison of the number of required wavelengths of FR scheme and ILP approach.

2.4 Summary

A mathematical model for the WRMD mesh network that minimizes the number of required wavelengths for lightpath establishment was proposed. It determines an optimum route and wavelength pairs for lightpaths. I focused on the static scenario, which assumes that lightpath setup requests are statically given in advance. Simulations showed that the mathematical model reduces the number of required wavelengths, compared to the FR scheme. The number of required wavelengths reduces as the allowable number of carrier regenerations increases. Furthermore, I noted that the number of required wavelengths in the WRMD network approaches that in the conventional OADM network if the allowable number of carrier regenerations is increased.

Chapter 3

Heuristic RWA scheme in WRMD networks with one MCLS node

It is known that when the size of the integer linear programming (ILP) problem becomes large, the ILP problem cannot be performed within practical time. In order to overcome this difficulty, a heuristic RWA approach is needed. This chapter proposes an heuristic routing and wavelength assignment (RWA) scheme for wavelength-reusable multi-carrier-distributed (WRMD) mesh networks to minimize the number of required wavelengths for lightpath establishment. Moreover, three requested lightpath selection policies, namely random, near ending node (NE), and near MCLS node (NM), are introduced to create the lightpath chains. Since a longer transmission length has larger transmission loss and results in more strict limitation of optical carrier regeneration [49], each requested lightpath selection policy also takes into account the transmission length. Simulation results show that the heuristic RWA scheme with the NM policy achieves better performance than that with the other policies.

3.1 Presented heuristic algorithm

The heuristic RWA scheme consists of a routing algorithm and a wavelength assignment algorithm, which are performed separately. The routing algorithm decides the routes of lightpaths. I use the shortest path routing algorithm to find the minimum cost from source to destination. The wavelength assignment algorithm requires the routes before it can be run. There are two steps in the wavelength assignment algorithm. In the first step, chains of lightpaths are created. In this step, a requested lightpath is selected to establish connection, based on a requested lightpath selection policy. An optical carrier is generated from the MCLS node, and travels along a carrier lightpath to the selected requested lightpath. The optical carrier is regenerated at the end node of the selected requested lightpath. Other requested lightpath is selected. The optical carrier travels along the other carrier lightpath to the requested lightpath. A path from the MCLS node to the end node of the last requested lightpath, including carrier lightpaths and requested lightpaths, is called a chain of lightpaths. Moreover, due to the property of optical carrier duplication, I also consider the common source node of requested lightpaths and the regeneration point. The optical carrier can be separated and regenerated to establish another requested lightpath. In the second step, each lightpath chain is assigned a wavelength. Wavelength assignment is then solved as a graph coloring problem [48]. As shown in Fig. 3.1, the heuristic RWA scheme first decides the routes by the routing algorithm. Wavelengths are then assigned by the wavelength assignment algorithm.

3.1.1 Terminologies

To describe the RWA scheme, the additional terminologies are defined. l denotes the transmission length, L_{max} is the maximum transmission length (MTL) that a lightpath chain is allowed to use. SP denotes a current starting pointer. The shortest distance is defined as the length of connection that may span more than one fiber link between two nodes in the network. A carrier lightpath is set according to the shortest distance between SP and s_p.

3.1.2 Algorithm description

The wavelength assignment algorithm is described in the following. At the beginning, each requested lightpath is indexed. SP is set at the MCLS node and

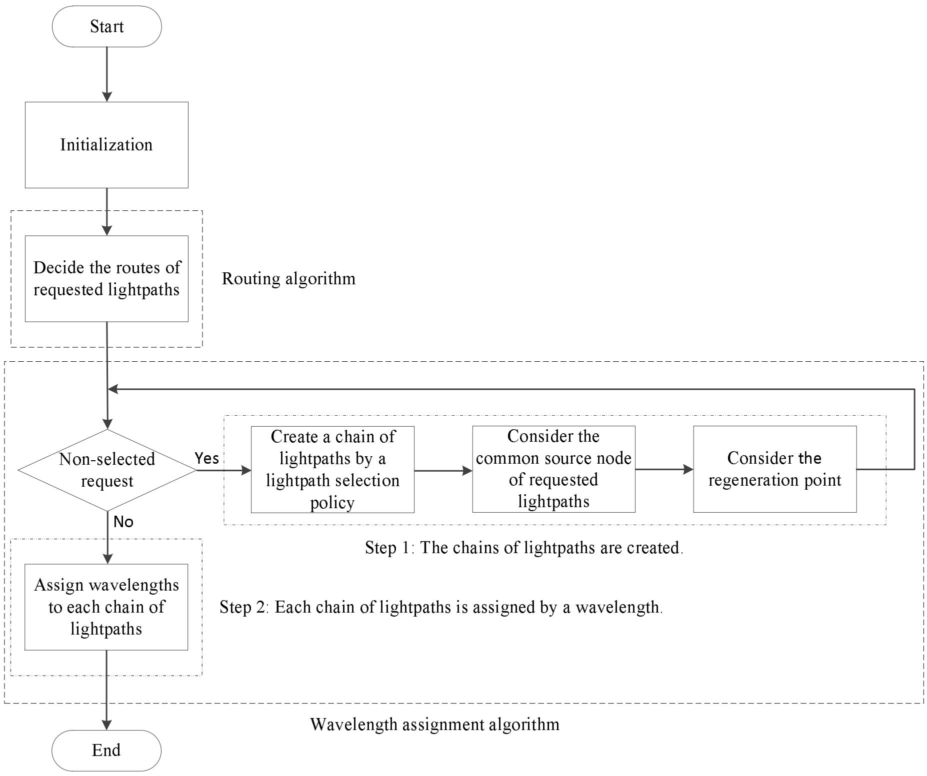


Figure 3.1: Flowchart of heuristic RWA scheme.

w is set to 1 as the initial value. There are three requested lightpath selection policies as follows.

3.1.2.1 Random policy

A non-selected requested lightpath is a requested lightpath that is not included in any chain of lightpaths. One of the non-selected requested lightpaths is randomly selected. This policy is simple since only the shortest distance either between the MCLS node and the selected requested lightpath, or between the destination node of requested lightpath and the selected requested lightpath needs to be calculated for each requested lightpath. The requested lightpath selection process is as follows.

- Step 1: Set r to 0 and set l to 0.

- Step 2: Randomly select non-selected p. If there is no p to select, then a chain of lightpaths is created, set SP at the MCLS node, increase w by one, and repeat from step 1.

- Step 3: Set up a connection between SP and d_p.

- Step 4: Increase r by one and increase l by distance of p.

- Step 5: If $r \leq R_{max}$ and $l \leq L_{max}$, then set SP at d_p and repeat from step 2.

- Step 6: Consider the common selected source s_p of other non-selected p. If there is any non-selected p to select, then repeat from step 3.

- Step 7: Consider the regeneration point. If there is any non-selected p to select, then repeat from step 3.

- Step 8: If there is any non-selected p left, then set SP at the MCLS node and repeat from step 1. Otherwise, requested lightpath selection is finished.

3.1.2.2 Near ending node (NE) policy

The NE policy considers the requested lightpath with the shortest distance from SP to s_p. SP is moved to d_p every time the requested lightpath is selected. This policy easily manages the requested lightpaths since it uses only one pattern to select each requested lightpath. However, there are some disadvantages of this policy since it has to calculate the shortest distance between the destination node of requested lightpath and the non-selected requested lightpath every time. The requested lightpath selection process is as follows.

- Step 1: Set r to 0 and set l to 0.

- Step 2: Select non-selected p with the shortest distance between SP node and s_p. In case there are more than one non-selected p, randomly select one non-selected p. If there is no p to select, then a chain of lightpaths is created, set SP at the MCLS node, increase w by one, and repeat from step 1.

- Step 3: Set up a connection between SP and d_p.
- Step 4: Set SP at the d_p.
- Step 5: Increase r by one and increase l by distance of p.
- Step 6: If $r \leq R_{max}$ and $l \leq L_{max}$, then repeat from step 2.
- Step 7: Consider the common selected source s_p of other non-selected p. If there is any non-selected p to select, then repeat from step 3.
- Step 8: Consider the regeneration point. If there is any non-selected p to select, then repeat from step 3.
- Step 9: If there is any non-selected p left, then go to step 1. Otherwise, requested lightpath selection is finished.

3.1.2.3 Near MCLS node (NM) policy

This policy takes account of the requested lightpath with the shortest distance from SP to s_p, and after that, SP is set to d_p. In addition, after a chain of lightpaths is created, SP is set at the MCLS node. The NM policy decreases the calculation time of the NE policy. Moreover, it has a better chance of realizing the chain of lightpaths successfully since the length of carrier lightpath is relatively lower than that of other policies. The requested lightpath selection process is as follows.

- Step 1: Set r to 0 and set l to 0.
- Step 2: Select non-selected p with the shortest distance between SP node and s_p. In case there are more than one non-selected p, randomly select one non-selected p. If there is no p to select, then a chain of lightpaths is created, set SP at the MCLS node, increase w by one, and repeat from step 1.
- Step 3: Set up a connection between SP and d_p.
- Step 4: Increase r by one and increase l by distance of p.

- Step 5: If $r \leq R_{max}$ and $l \leq L_{max}$, then set SP at d_p and repeat from step 2.
- Step 6: Consider the common selected source s_p of other non-selected p. If there is any non-selected p to select, then repeat from step 3.
- Step 7: Consider the regeneration point. If there is any non-selected p to select, then repeat from step 3.
- Step 8: If there is any non-selected p left, then set SP at the MCLS node and repeat from step 1. Otherwise, requested lightpath selection is finished.

After the chains of lightpaths are created by one of the requested lightpath selection policies, a wavelength is assigned to each chain by solving a graph coloring problem. I use a heuristic algorithm, called the largest degree first [48], to solve a graph coloring problem, since it has been widely used in graph coloring researches and the effectiveness has been confirmed.

3.1.3 Example

Figure 3.2 shows an example of the three requested lightpath selection policies. There are six requested lightpaths: first, requested lightpath $i = 1$ travels along route 1 $\rightarrow$ 2; second, requested lightpath $i = 2$ travels along route 2 $\rightarrow$ 3; third, requested lightpath $i = 3$ travels along route 3 $\rightarrow$ 6; fourth, requested lightpath $i = 4$ travels along route 2 $\rightarrow$ 5; fifth, requested lightpath $i = 5$ travels along route 4 $\rightarrow$ 5; and finally, requested lightpath $i = 6$ travels along route 5 $\rightarrow$ 6. I assume that node 1 is the MCLS node (MN), the allowable number of carrier regenerations is one, and the MTL of a lightpath chain is infinite. In the random policy, as in Fig. 3.2(a), the algorithm randomly selects non-selected requested lightpath $i = 3$, and then randomly selects another non-selected requested lightpath, $i = 4$. Next, with regard to the common selected sources among other non-selected requested lightpaths, there is no common source. Then, with regard to the regeneration point, it selects another non-selected requested lightpath $i = 5$. The first chain of lightpaths is then created along route 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 6 $\rightarrow$ 5 $\rightarrow$ 2 $\rightarrow$ 5 and 6 $\rightarrow$ 3 $\rightarrow$ 4 $\rightarrow$ 5. After that, it randomly selects a non-selected requested lightpath, which is requested lightpath $i = 6$, and then randomly selects another non-selected requested lightpath $i = 2$. Although the non-selected requested lightpath $i = 1$ still remains, it cannot be selected given the consideration of the common selected sources among other non-selected requested lightpaths and the regeneration point, because it conflicts with wavelength assignment rule 3. The second chain of lightpaths is created along route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 5 \rightarrow 2 \rightarrow 3$. Next, a non-selected requested lightpath $i = 1$ is randomly selected. There is no non-selected requested lightpath left. The third chain of lightpaths is created along route $1 \rightarrow 2$. After the chains of lightpaths are created, a wavelength is assigned to each chain. λ_1 is assigned to the first lightpath chain. λ_2 is assigned to the second lightpath chain. λ_3 is assigned to the third lightpath chain.

In the NE policy, as in Fig. 3.2(b), SP is set at the MCLS as the initial value. The algorithm selects the non-selected requested lightpath that has the shortest distance from SP to its source node. Then, this policy selects non-selected requested lightpath $i = 1$. SP is then moved to the destination node of requested lightpath $i = 1$, which is node 2. Another requested lightpath is selected as the shortest distance from SP, non-selected requested lightpath $i = 2$ is selected. Next, with regard to the common selected sources among other non-selected requested lightpaths, it selects non-selected requested lightpath $i = 4$. Then, with regard to the regeneration point, it selects another non-selected requested lightpath $i = 5$. The first chain of lightpaths is created along route $1 \rightarrow 2 \rightarrow 3$, $2 \rightarrow 5$, and $2 \rightarrow 4 \rightarrow 5$. SP is moved to node 5. The requested lightpath $i = 6$ is selected because it has the shortest distance. SP is the moved to node 6. The requested lightpath $i = 3$ is selected at last. The second chain of lightpaths is created along route $1 \rightarrow 2 \rightarrow 5 \rightarrow 6 \rightarrow 3 \rightarrow 6$. After the chains of lightpaths are created, λ_1 is assigned to the first lightpath chain, and λ_2 is assigned to the second lightpath chain.

In the NM policy, as in Fig. 3.2(c), SP is set at the MCLS as the initial value. The first chain of lightpaths is created in the same way as in the NE policy which is along route $1 \rightarrow 2 \rightarrow 3$, $2 \rightarrow 5$, and $2 \rightarrow 4 \rightarrow 5$. SP is then reset to the MCLS node. Requested lightpath $i = 3$ is selected because it has the shortest distance from SP. Requested lightpath $i = 6$ is then selected. The second chain of lightpaths is created along route $1 \rightarrow 2 \rightarrow 3 \rightarrow 6 \rightarrow 5 \rightarrow 6$. After the chains

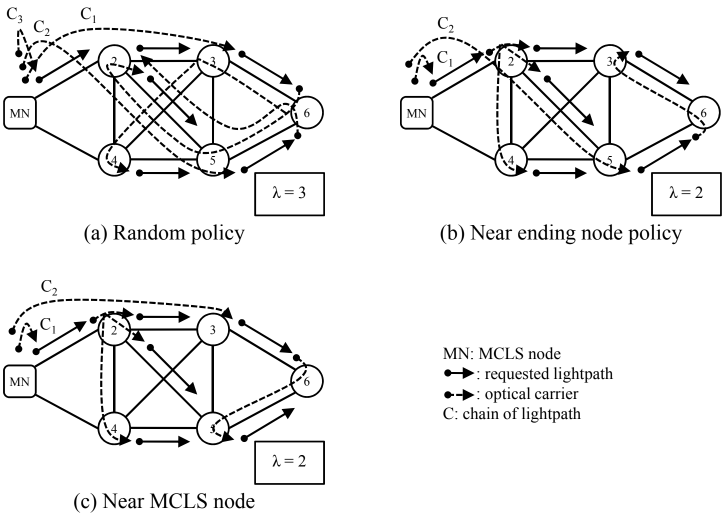


Figure 3.2: Example of three requested lightpath selection policies.

of lightpaths are created, λ_1 is assigned to the first lightpath chain, and λ_2 is assigned to the second lightpath chain.

3.2 Results and discussions

3.2.1 Effectiveness of RWA scheme

I evaluate the effectiveness of the heuristic RWA scheme by comparing it to the ILP approach. However, since the ILP approach is hard to solve in any practical time, I first investigate the number of required wavelengths for the three different network topologies, as shown in Fig. 4.1. The number of requested lightpaths is set to five. I average the values over the numbers of required wavelengths for 100 randomly generated, different sets of requested lightpaths. Then, I investigate the heuristic RWA scheme using the three requested lightpath selection policies for large-scale networks, namely Synthetic network, European COST 239 network, and U.S. long distance network as shown in Fig. 3.4. I assume that node 1 of each network topology is the MCLS node. The number of requested lightpaths is set to 200 and 300. I average the values over the numbers of required wavelengths for 100 randomly generated, different sets of requested lightpaths. In addition, I investigate the impact of the MTL of a lightpath chain on the number of required

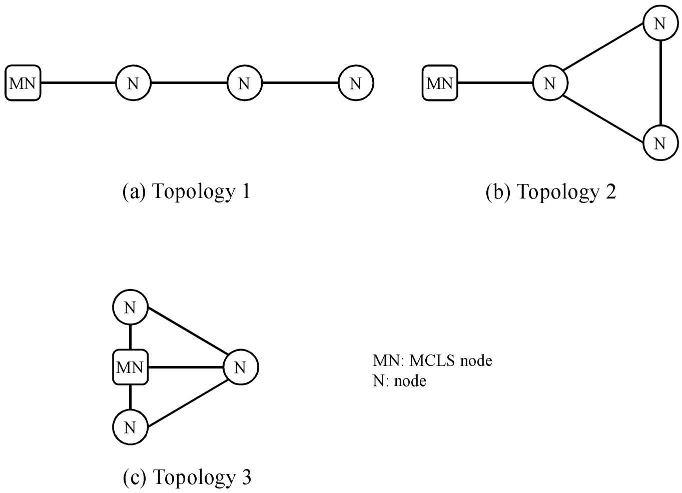
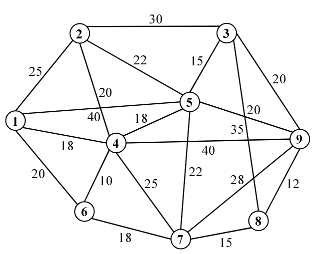


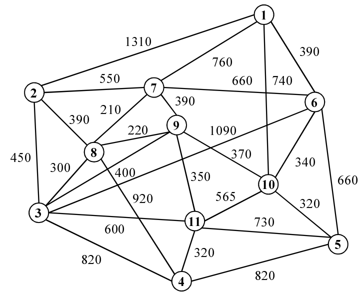
Figure 3.3: Network topologies for comparison of ILP approach and heuristic RWA scheme.

wavelengths. I consider two scenarios. In the first scenario, the MTL of a lightpath chain is set to infinite for all networks, In the second scenario, the MTL of a lightpath chain is set to 100 miles, 1000 km, and 1000 miles for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. In the evaluation, I assume that each link contains 8 wavelengths for small networks and 256 wavelengths for large-scale networks, the bandwidth of each request is one wavelength channel, and the duration of the request is infinite. I use a Linux-based computer with Intel®Core$^{\text{TM}}$i7-3770 CPU @ 3.40GHz and 32GB of memory.

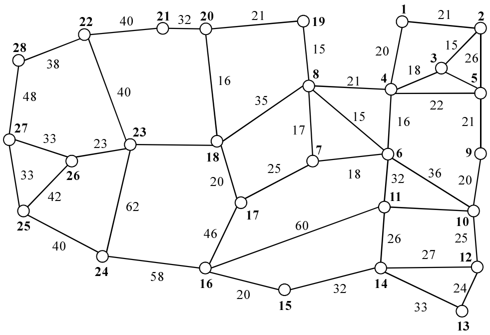
Figure 3.5 shows the numbers of required wavelengths by the ILP approach and heuristic RWA scheme without regeneration in the three different network topologies. For Topology 1, the heuristic RWA scheme achieves the optimal number of required wavelengths, which is same as that obtained by the ILP approach. For Topology 2 and Topology 3, the heuristic RWA scheme approaches the optimal number of required wavelengths. Figures 3.6 and 3.7 show the number of required wavelengths of the ILP approach and the heuristic RWA scheme with one and two regenerations, respectively. It observes that the heuristic RWA scheme with NE and NM policies approaches the optimal number of required



(a) Synthetic network. Distances are in miles.



(b) European COST 239 network. Distances are in km.



(c) U.S. long distance network. Distances are in tens of miles.

Figure 3.4: Network topologies examined.

wavelengths, while with the random policy it is not able to approach the optimal solution. Note that in case of two regenerations, the heuristic RWA scheme with NE and NM policies achieves the optimum number of wavelengths, compared to the conventional optical add-drop multiplexer (OADM) network. Moreover, for Topology 2 and Topology 3, the ILP approach with two regenerations achieves better performance than the conventional OADM network.

The standard deviation of the number of required wavelengths is investigated to measure the spread of a distribution. For Topology 1 without regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.52, 0.52, 0.52, and 0.52, respectively. For Topology 1 with one regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.53, 0.79, 0.48, and 0.52, respectively. For Topology 1 with two regenerations, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.48, 0.99, 0.53, and 0.48, respectively. For Topology 2 without regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.57, 0.57, 0.57, and 0.57, respectively. For Topology 2 with one regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0, 0.63, 0.48, and 0.42, respectively. For Topology 2 with two regenerations, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.52, 0.53, 0.63, and 0.63, respectively. For Topology 3 without regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.32, 0.82, 0.82, and 0.82, respectively. For Topology 2 with one regeneration, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.52, 0.84, 0.67, and 0.63, respectively. For Topology 3 with two regenerations, the standard deviations of the numbers of required wavelengths of the ILP approach, random policy, NE policy, and NM policy are 0.52, 0.53, 0.63, and 0.57, respectively. The standard deviations of the numbers of required wavelengths of the conventional OADM network for Topology 1, Topology 2, and Topology 3 are 0.63, 0.67, and 0.57, respectively. It observes that the standard deviations of the numbers of required wavelengths are relatively small. To easily show the difference in the number of required wavelengths, the average number of required wavelengths is further rounded up or down to a whole number.

Figures 3.8 and 3.9 show the number of required wavelengths of the heuristic RWA scheme in the three different policies for the Synthetic network with 200 and 300 requested lightpaths, respectively. I observe similar behavior with regard to the number of required wavelengths. Since the conventional OADM network does not consider any carrier regeneration, its number of required wavelengths

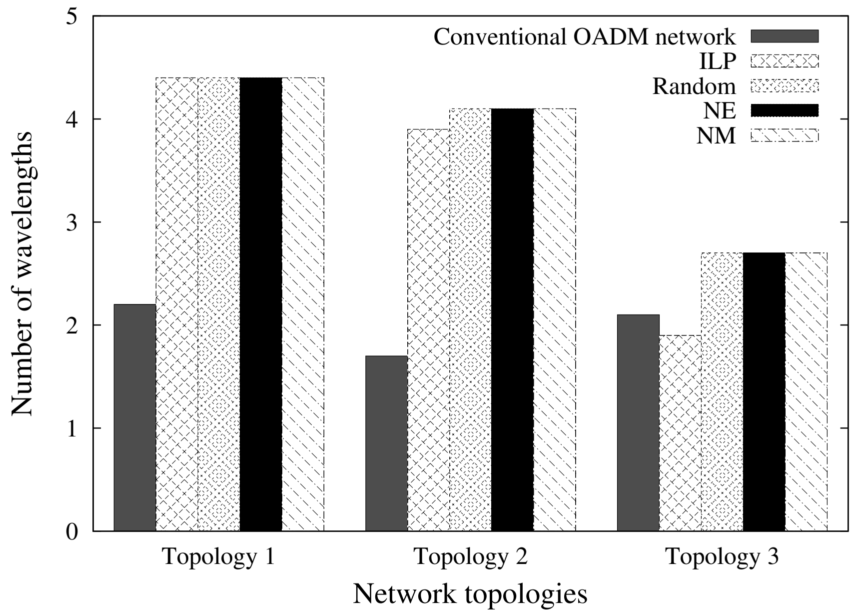


Figure 3.5: Comparison of the number of required wavelengths of ILP approach and heuristic RWA scheme without regeneration.

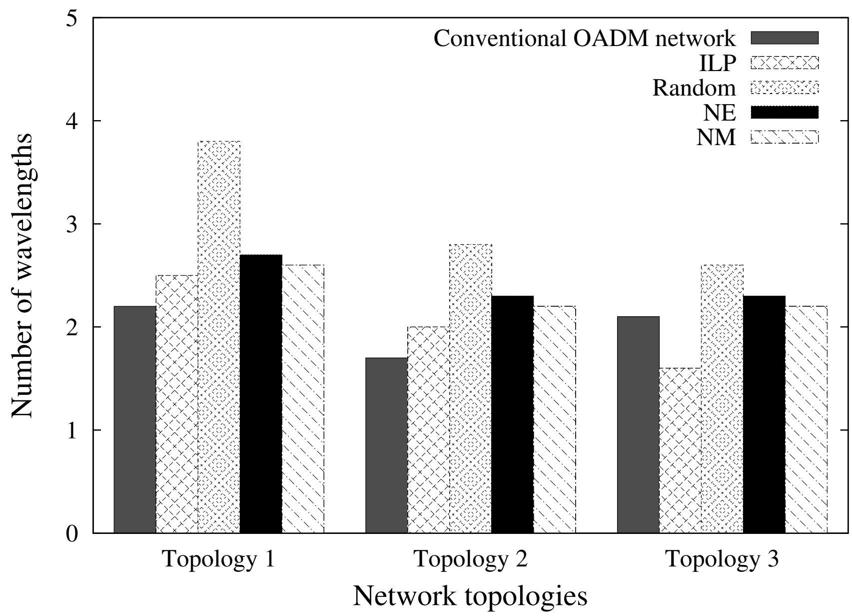


Figure 3.6: Comparison of the number of required wavelengths of ILP approach and heuristic RWA scheme with one regeneration.

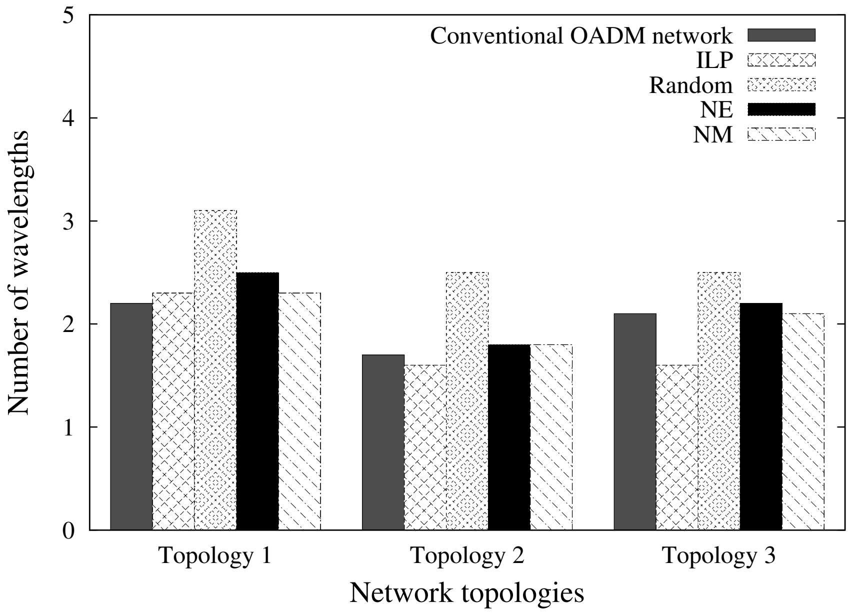


Figure 3.7: Comparison of the number of required wavelengths of ILP approach and heuristic RWA scheme with two regenerations.

does not depend on the allowable number of carrier regeneration varies. The heuristic RWA scheme without regeneration demands a large number of required wavelengths; the number decreases as the allowable number of carrier regenerations increases. Furthermore, the heuristic RWA scheme with one regeneration reduces the number of required wavelengths by more than 35% from that without regeneration. However, the heuristic RWA scheme with two regenerations and the NM policy reduces the number of required wavelengths by 50% from that without regeneration. This is because the NM policy takes into account a requested lightpath that has the shortest distance from the MCLS node to its source node, so it offers a better chance of completing the chain of lightpaths successfully more than other policies. On the other hand, the random policy proceeds in a distributed manner. In the NE policy, the algorithm considers the requested lightpath that has the shortest distance from SP to its source node. After that, SP is set to the destination node of the selected requested lightpath. For this reason, the average length of carrier lightpaths is long. As a result, both random and NE policies have less chance of completing the creation of lightpath chains than the NM policy.

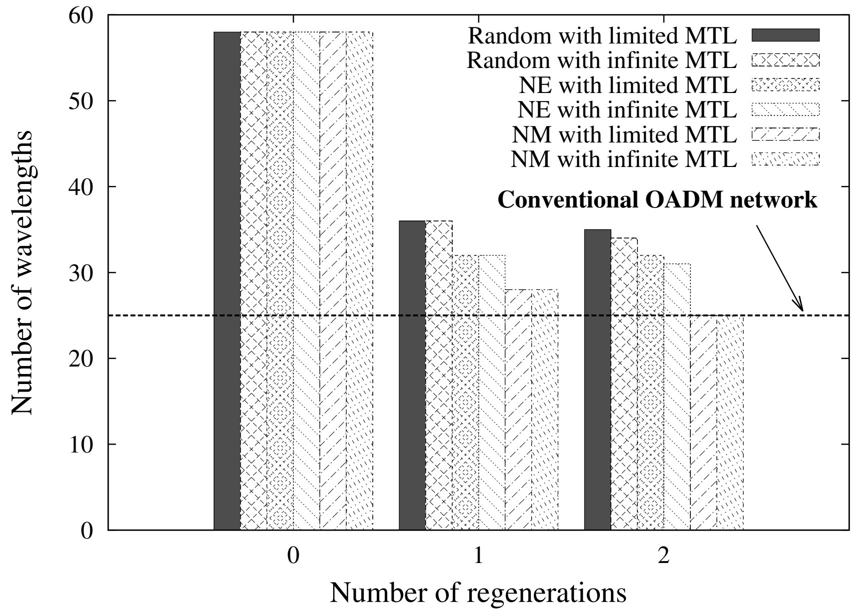


Figure 3.8: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for Synthetic network with 200 requested lightpaths.

Since the average length of carrier lightpaths is short, there is less chance of their overlapping. Therefore, the NM policy has lower wavelength requirements than the other policies. Note that the heuristic RWA scheme with the NM policy and two regenerations approaches the optimum number of wavelengths, compared to the conventional OADM network. In addition, I also note that the number of required wavelengths for limited MTL is only slightly larger than that for infinite MTL. For all the requested lightpath selection policies, the heuristic RWA scheme with limited MTL restricts the available number of carrier regenerations, so there is less chance of completing the creation of lightpath chains than that with infinite MTL.

Figures 3.10 and 3.11 show the number of required wavelengths of the heuristic RWA scheme in the three different policies for the European COST 239 network with 200 and 300 requested lightpaths, respectively. I observe that the NE and NM policies reduce the number of required wavelengths by 50% with one regeneration and 57% with two regenerations, compared to that without regeneration.

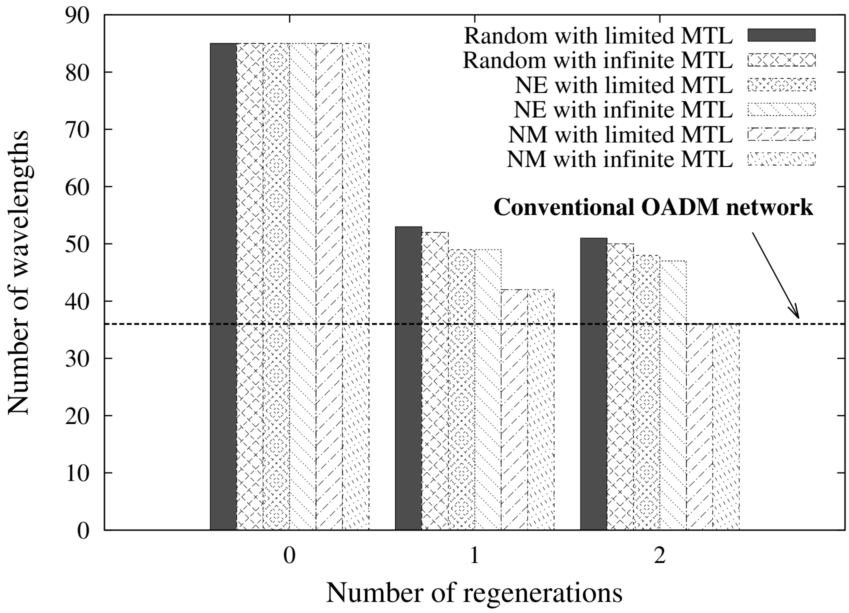


Figure 3.9: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for Synthetic network with 300 requested lightpaths.

Similar to the Synthetic network, the number of required wavelengths for limited MTL is only slightly larger than that for infinite MTL.

Figures 3.12 and 3.13 show the number of required wavelengths of the heuristic RWA scheme in the three different policies for the U.S. long distance network with 200 and 300 requested lightpaths, respectively. I observe that, for all the requested lightpath selection policies, the heuristic RWA scheme with one regeneration reduces the number of required wavelengths by more than 57%, compared to that without regeneration. Furthermore, for the NM policy, the heuristic RWA scheme with two regenerations reduces the number of required wavelengths by more than 70% from that without regeneration. Note that the number of required wavelengths for the heuristic RWA scheme with one regeneration and limited MTL is only slightly larger than that with one regeneration and infinite MTL, while the number of required wavelengths for the heuristic RWA scheme with two regenerations and limited MTL is relatively larger than that with two regenerations and infinite MTL.

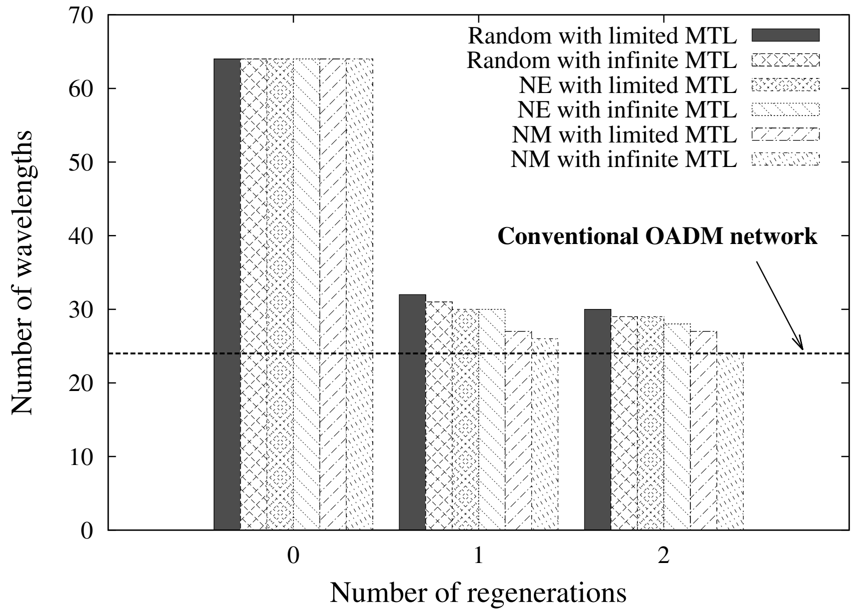


Figure 3.10: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for European COST 239 network with 200 requested lightpaths.

3.2.2 Dependency of location of MCLS node

I compare the number of required wavelengths in the WRMD mesh network to that in the conventional OADM network. In addition, the MCLS node location is also investigated, since its placement in the WRMD mesh network affects the number of required wavelengths. I use the heuristic RWA scheme with the NM policy and two regenerations for the WRMD mesh network, since it achieves the best performance among the policies.

Figures 3.14, 3.15, and 3.16 show the ratio of the number of wavelengths required by the WRMD network in each MCLS node to that of the conventional OADM network for the Synthetic, European COST 239 and U.S. long distance networks with 300 requested lightpaths, respectively. I investigate the impact of the MCLS node location on the number of required wavelengths. As shown in Fig. 3.14, the optimum MCLS node location in the Synthetic network is nodes 1, 2, and 3. Figure 3.15 shows that the optimum MCLS node location in the

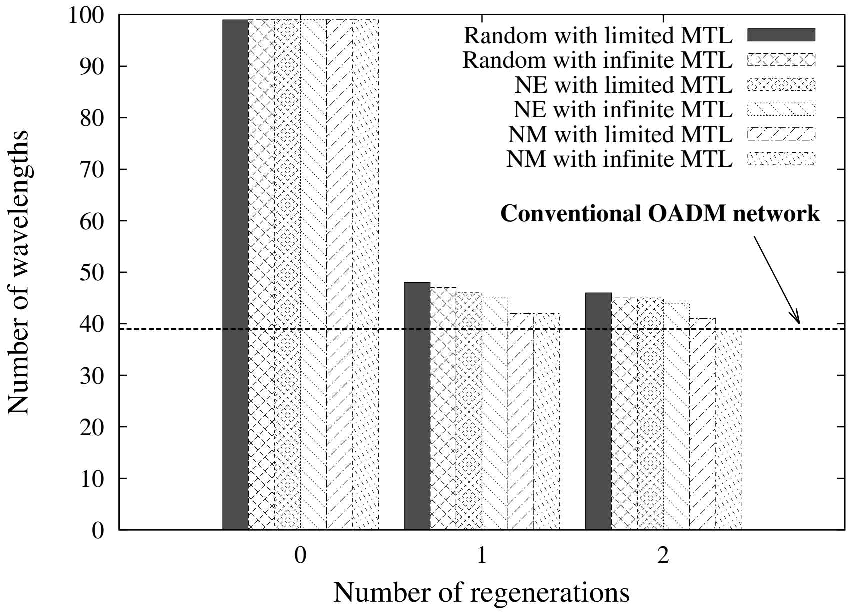


Figure 3.11: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for European COST 239 network with 300 requested lightpaths.

European COST 239 network is nodes 1, 2, 3, 5, 7, and 8. Finally, in the U.S. long distance network, the optimum MCLS node location is nodes 1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 13, 14, 16, 17, and 20, as depicted in Fig. 3.16. This means that the WRMD network with the optimum MCLS node location requires the same number of wavelengths as the conventional OADM network.

3.3 Summary

The heuristic RWA scheme for the WRMD mesh network that minimizes the number of required wavelengths for lightpath establishment was proposed. It consists of a routing algorithm and a wavelength assignment algorithm, which are performed separately to solve the RWA problem. The shortest path routing policy is adopted in the routing decision. The wavelength assignment algorithm has two steps. The first step is to create chains of lightpaths and the second step is to assign a wavelength to each lightpath chain. In addition, three requested

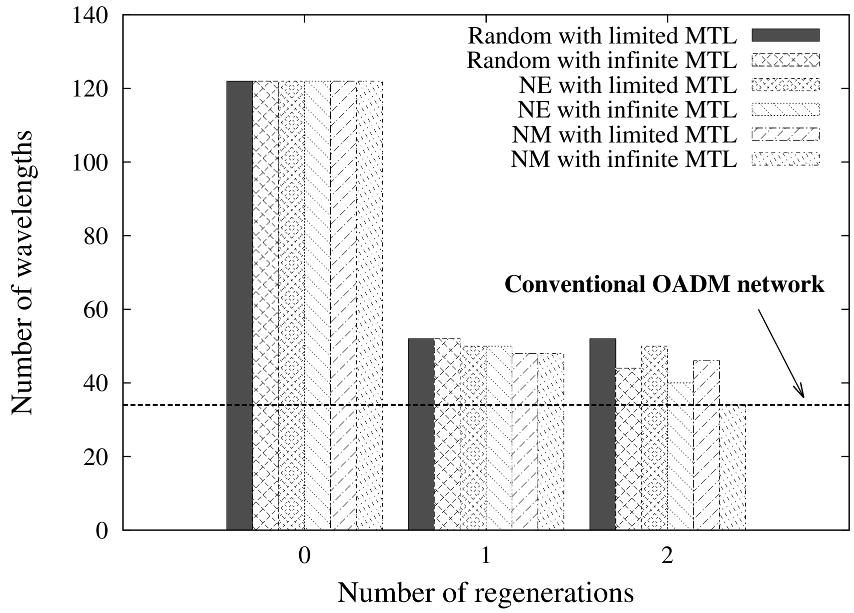


Figure 3.12: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for U.S. long distance network with 200 requested lightpaths.

lightpath selection policies, random, NE, and NM policies, are introduced in this chapter to create the lightpath chains. The results showed that the heuristic RWA scheme with one regeneration and the three requested lightpath selection policies reduces the number of required wavelengths by more than 30%. Moreover, the scheme with the NM policy and two regenerations reduces the number of required wavelengths by at least 50%, compared to that without carrier regeneration. In addition, I noted that suitable selection of the MCLS node location also reduces the number of required wavelengths. The number of required wavelengths in the WRMD network approaches that in the conventional OADM network if the allowable number of carrier regenerations is increased and the MCLS node location is optimum.

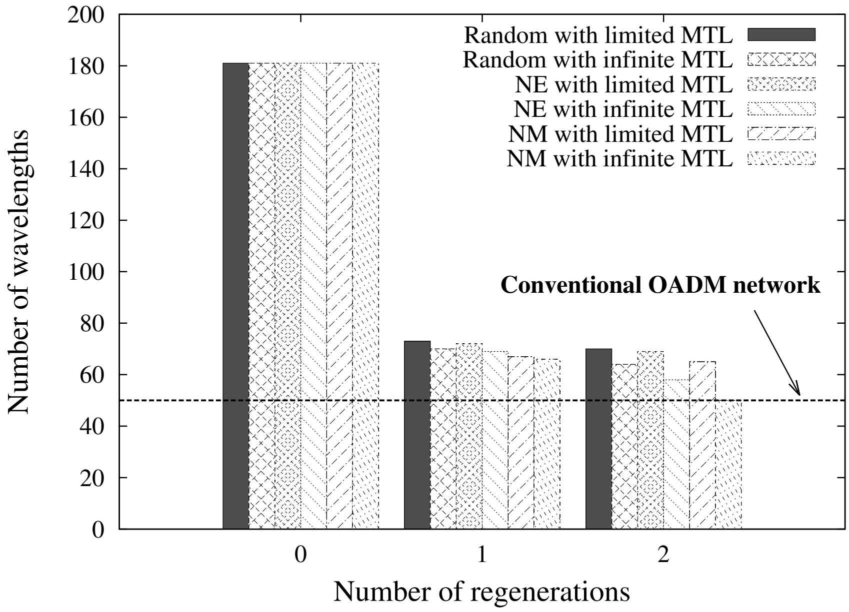


Figure 3.13: Number of required wavelengths with the heuristic RWA scheme (different requested lightpath selection policies) for U.S. long distance network with 300 requested lightpaths.

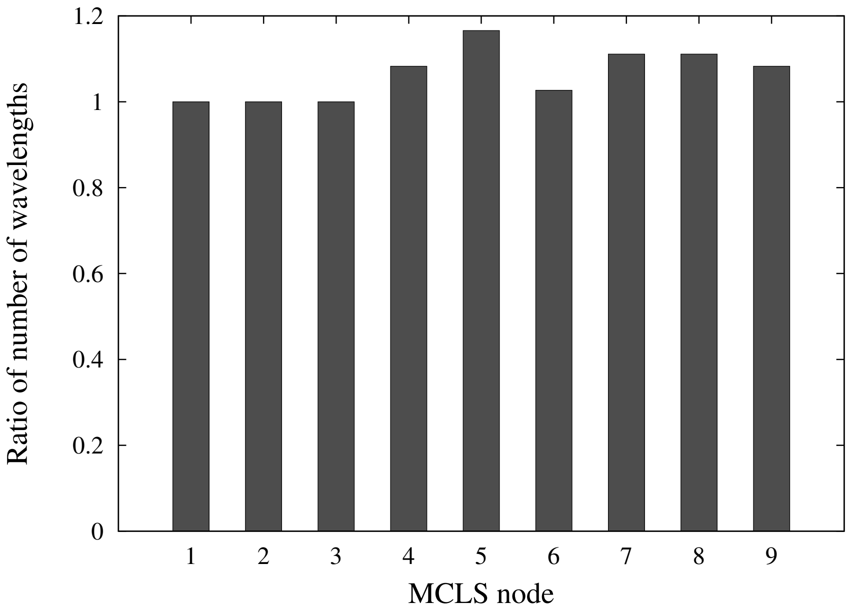


Figure 3.14: Comparison of number of wavelengths in each MCLS node for Synthetic network with 300 requested lightpaths.

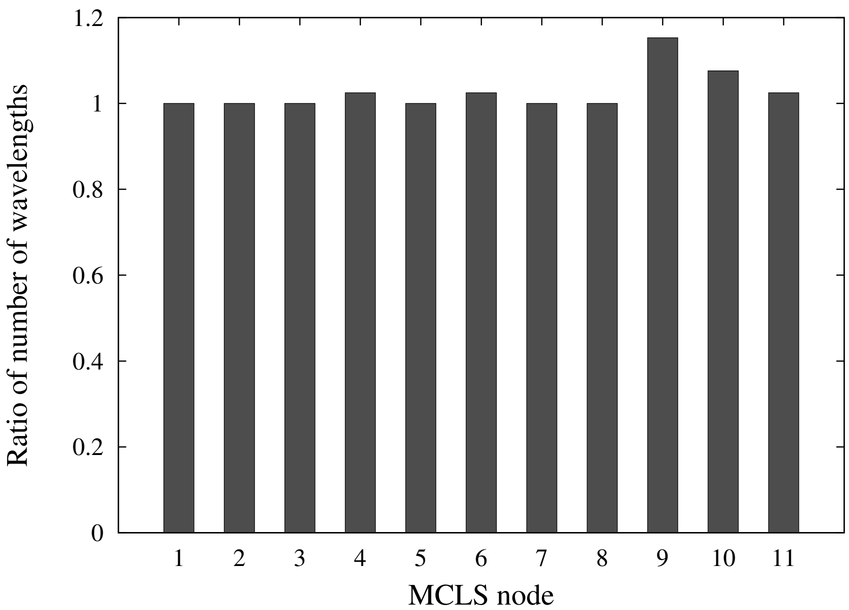


Figure 3.15: Comparison of number of wavelengths in each MCLS node for European COST 239 network with 300 requested lightpaths.

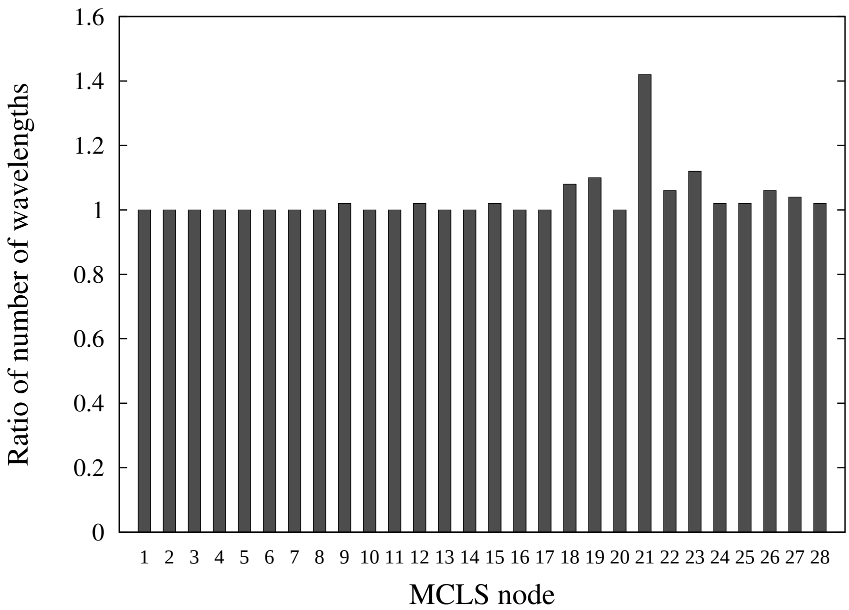


Figure 3.16: Comparison of number of wavelengths in each MCLS node for U.S. long distance network with 300 requested lightpaths.

Chapter 4

Mathematical model for RWA scheme in WRMD networks with multiple MCLS nodes

This chapter presents an integer linear programming (ILP) model that supports multiple light-source nodes to minimize the number of required wavelengths for wavelength-reusable multi-carrier-distributed (WRMD) mesh networks. The routing and wavelength assignment (RWA) problem is formulated as the ILP problem of obtaining the minimum number of required wavelengths to satisfy the given lightpath setup requests. The purpose of the ILP optimization is to determine how to distribute constrained resources in order to minimize the number of required wavelengths. Simulation results show that the number of required wavelengths reduces as the allowable number of carrier regenerations increases. Furthermore, the number of required wavelengths decreases as the number of MCLS nodes increases.

4.1 Mathematical model

For large-scale networks that must support increasing numbers of lightpaths, there may be a need to have more than one MCLS node to use wavelength resources efficiently. To the best of my knowledge, however, no study has addressed the use of multiple MCLS nodes in the WRMD mesh networks. Therefore, the mathematical model for WRMD networks with multiple MCLS nodes is given in this section.

4.1.1 Terminologies

The objective of the RWA problem is to minimize the number of wavelengths required for establishing the requested lightpaths. Solving the RWA problem means determining all routes and wavelengths of requested lightpaths with the minimal number of wavelengths.

The following notations are introduced to describe the RWA problem mathematically. A network is represented as undirected graph $G = (V, E)$, where V is the set of network nodes and E is the set of bidirectional links. Let W be the set of wavelengths generated by the MCLS. Let w be wavelength index, where $w \in W$ ($w = 1, 2, \cdots, w_{max}$). $r \in R$ indicates the number of times an optical carrier is reused, where $R = \{0, 1, \cdots, R_{max}\}$. R_{max} is the maximum number of times an optical carrier can be reused. $r = 0$ means that the optical carrier is directly generated from the MCLS node. $p \in P$ indicates a lightpath request, where P is the set of lightpath requests. $c \in C$ indicates an optical carrier connection, where C is the set of optical carrier connections. Let $s_p \in V$ and $d_p \in V$ be the source and destination nodes of lightpath $p \in P$, respectively. Let $s_c \in V$ and $d_c \in V$ be the source and destination nodes of optical carrier connection $c \in C$, respectively. Let $(i, j) \in E$ be a link between two network nodes.

Assumptions made for addressing the RWA problem are as follows.

- The number of nodes is given.
- Bi-directional connection is realized by two connections having opposite directions.
- The lightpath request matrix P is given.
- The maximum number of times an optical carrier can be reused, R_{max}, is given for each wavelength.

I formulate the RWA problem for the WRMD network with multiple MCLS nodes as an ILP problem. The following notations are used to describe the ILP problem. Let N be the number of nodes, and M be the set of MCLS nodes (MNs). Let $q_p(p, w, r)$ be a binary decision variable that is set to one if lightpath request $p \in P$ uses wavelength $w \in W$ with $r \in R$, otherwise zero. Let $q_c(c, w, r)$ be a binary decision variable that is set to one if optical carrier $c \in C$ uses wavelength $w \in W$ with $r \in R$, otherwise zero. Let $x(p, i, j)$ be a binary decision variable that is set to one if lightpath request $p \in P$ is routed on $(i, j) \in E$, otherwise zero. Let $z(c, i, j)$ be a binary decision variable that is set to one if optical carrier $c \in C$ is routed on $(i, j) \in E$, otherwise zero. Let $y(w)$ be a binary decision variable that indicates the usage of wavelength w, where $w \in W$. This variable is 1 if wavelength w is used at least once. Let $a(p, i, j, w, r)$ be a binary decision variable that is set to one if lightpath request $p \in P$ is routed on $(i, j) \in E$ using wavelength $w \in W$ with $r \in R$, otherwise zero. Let $b(c, i, j, w, r)$ be a binary decision variable that is set to one if optical carrier $c \in C$ is routed on $(i, j) \in E$ using wavelength $w \in W$ with $r \in R$, otherwise zero.

4.1.2 Integer linear programming (ILP) model formulation

The objective function is represented as

$$\min \sum_{w \in W} y\,(w) \tag{4.1}$$

this ILP minimizes the number of required wavelengths while creating connections for all lightpaths.

The constraints are as follows.

$$\sum_{r \in R} \sum_{w \in W} q_p\,(p, w, r) = 1, \forall p \in P \tag{4.2a}$$

$$\sum_{r \in R} \sum_{w \in W} q_c\,(c, w, r) \leq 1, \forall c \in C \tag{4.2b}$$

$$\begin{aligned} \sum_{j:(i,j) \in E} x\,(p, i, j) - \sum_{j:(i,j) \in E} x\,(p, j, i) = \sum_{r \in R} \sum_{w \in W} q_p\,(p, w, r), \\ \forall p \in P, i = s_p \end{aligned} \tag{4.2c}$$

$$\sum_{j:(i,j)\in E} x(p,i,j) - \sum_{j:(i,j)\in E} x(p,j,i) = 0, \forall p \in P, i \neq s_p, d_p \tag{4.2d}$$

$$\begin{aligned}\sum_{j:(i,j)\in E} z(c,i,j) - \sum_{j:(i,j)\in E} z(c,j,i) = \sum_{r\in R}\sum_{w\in W} q_c(c,w,r),\\ \forall c \in C, i = s_c\end{aligned} \tag{4.2e}$$

$$\sum_{j:(i,j)\in E} z(c,i,j) - \sum_{j:(i,j)\in E} z(c,j,i) = 0, \forall c \in C, i \neq s_c, d_c \tag{4.2f}$$

$$\begin{aligned}\sum_{r\in R}\{a(p,i,j,w,r) + a(p',i,j,w,r) +\\ b(c,i,j,w,r) + b(c',i,j,w,r)\} \leq y(w),\\ \forall p,p'(p\neq p') \in P, \forall c,c'(c\neq c') \in C, (i,j)\in E, w\in W\end{aligned} \tag{4.2g}$$

$$\begin{aligned}q_p(p,w,r) \leq \sum_{c\in C:d_c=s_p} q_c(c,w,r),\\ \forall p\in P, w\in W, r\in R\end{aligned} \tag{4.2h}$$

$$\begin{aligned}q_c(c,w,r) \leq \sum_{p\in P:d_p=s_c} q_p(p,w,r-1),\\ \forall c\in C, w\in W, r\in R\setminus\{0\}\end{aligned} \tag{4.2i}$$

$$q_c(c,w,0) = 0, \forall w\in W, c\in C : s_c \notin M \tag{4.2j}$$

$$y(w) \geq y(w+1), \forall w \in W\setminus\{w_{max}\} \tag{4.2k}$$

$$a(p,i,j,w,r) \leq x(p,i,j), \forall p\in P, (i,j)\in E, w\in W, r\in R \tag{4.2l}$$

$$a(p,i,j,w,r) \leq q_p(p,w,r), \forall p\in P, (i,j)\in E, w\in W, r\in R \tag{4.2m}$$

$$\begin{aligned}a(p,i,j,w,r) \geq x(p,i,j) + q_p(p,w,r) - 1,\\ \forall p\in P, (i,j)\in E, w\in W, r\in R\end{aligned} \tag{4.2n}$$

$$b(c,i,j,w,r) \leq z(c,i,j), \forall c\in C, (i,j)\in E, w\in W, r\in R \tag{4.2o}$$

$$b(c,i,j,w,r) \leq q_c(c,w,r), \forall c\in C, (i,j)\in E, w\in W, r\in R \tag{4.2p}$$

$$b\left(c,i,j,w,r\right) \geq z\left(c,i,j\right) + q_c\left(c,w,r\right) - 1, \quad \forall c \in C, (i,j) \in E, w \in W, r \in R \tag{4.2q}$$

Eq. (4.2a) ensures the assignment of lightpaths to all connection requests. Eq. (4.2b) ensures that each optical carrier connection is established at most once with at most one wavelength. Eqs. (4.2c) and (4.2d) are the flow conservation constraints on the incoming and outgoing flows at each node for lightpaths. Eqs. (4.2e) and (4.2f) are the flow conservation constraints on the incoming and outgoing flows at each node for optical carrier connections. Eq. (4.2g) ensures that different lightpaths and optical carrier connections must use different wavelengths for each link. Eq. (4.2h) ensures that a lightpath is established if a source node receives an optical carrier. Eq. (4.2i) ensures that an optical carrier is reused if a lightpath is established. On the other hand, an optical carrier with r should be replaced by another optical carrier with $r-1$. Eq. (4.2j) ensures that optical carrier connection $c \in C$ that is not generated from any MCLS nodes must not produce any optical carrier with $r = 0$. Eqs. (4.2h) to (4.2j) guarantee the prevention of loop generation. Eq. (4.2k) states that wavelengths are used in ascending order of wavelength index w. Eqs. (4.2l) to (4.2n) indicate a Boolean expression of $a(p,i,j,w,r) = x(p,i,j) * q_p(p,w,r)$ with linear forms with binary variables, where $a(p,i,j,w,r)$ is set to one only when both $x(p,i,j) = 1$ and $q_p(p,w,r) = 1$. Eqs. (4.2o) to (4.2q) indicate a Boolean expression of $b(c,i,j,w,r) = z(c,i,j)*q_c(c,w,r)$ with linear forms with binary variables, where $b(c,i,j,w,r)$ is set to one only when both $z(c,i,j) = 1$ and $q_c(c,w,r) = 1$.

4.2 Results and discussions

I evaluate the performance of the heuristic RWA scheme from three points. First, the number of required wavelengths in the mathematical model is compared with that demanded by the heuristic RWA scheme. Second, the number of required wavelengths by the heuristic RWA scheme is determined under different parameters. Finally, the impact of MCLS node location on the number of required wavelengths in the WRMD mesh network is assessed. Additionally, the effect of optical carrier reuse is evaluated. In addition, I give a discussion on the heuristic

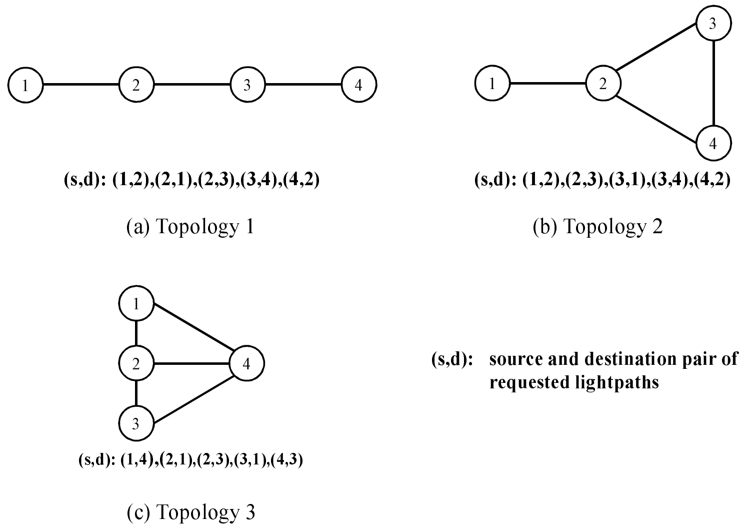


Figure 4.1: Network topologies for comparison of ILP approach and heuristic RWA scheme.

RWA scheme in the last subsection. In the evaluation, I assume that each link contains 8 wavelengths, the bandwidth of each request is one wavelength channel, and the duration of the request is infinite. I use a Linux-based computer with Intel®Core™i7-3770 CPU @ 3.40GHz and 32GB of memory.

The RWA problem is to determine both route and wavelength for each lightpath request. Therefore, all routes of optical carrier connections and requested lightpaths are required to be designed to minimize the number of wavelengths. I consider all possible number of MCLS nodes for WRMD networks. Three network topologies presented in [23] are considered, see Fig. 4.1.

Figures 4.2 - 4.10 show the numbers of required wavelengths by the ILP approach for Topology 1, Topology 2, and Topology 3, respectively, for the three different regeneration numbers. Since the ILP approach gives the minimum number of required wavelengths, it is able to provide reference values for further analysis. I observe that the number of required wavelengths decreases as the allowable carrier regeneration number increases. In addition, the number of required wavelengths decreases as the number of MCLS nodes increases.

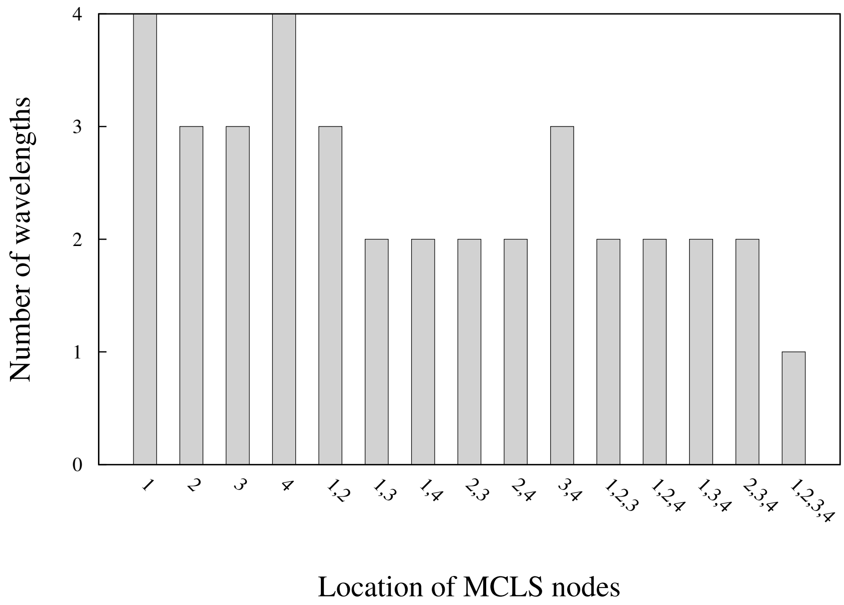


Figure 4.2: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach without regeneration for Topology 1.

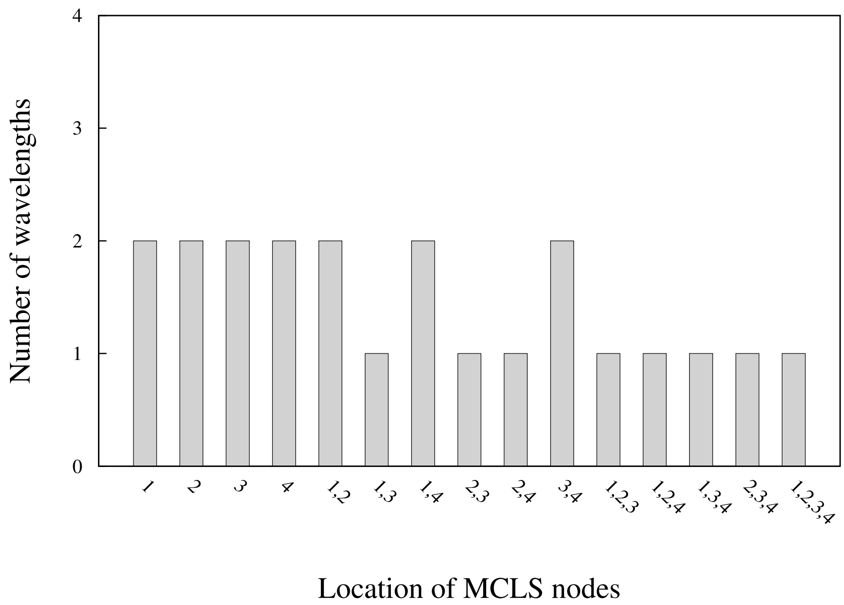


Figure 4.3: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with one regeneration for Topology 1.

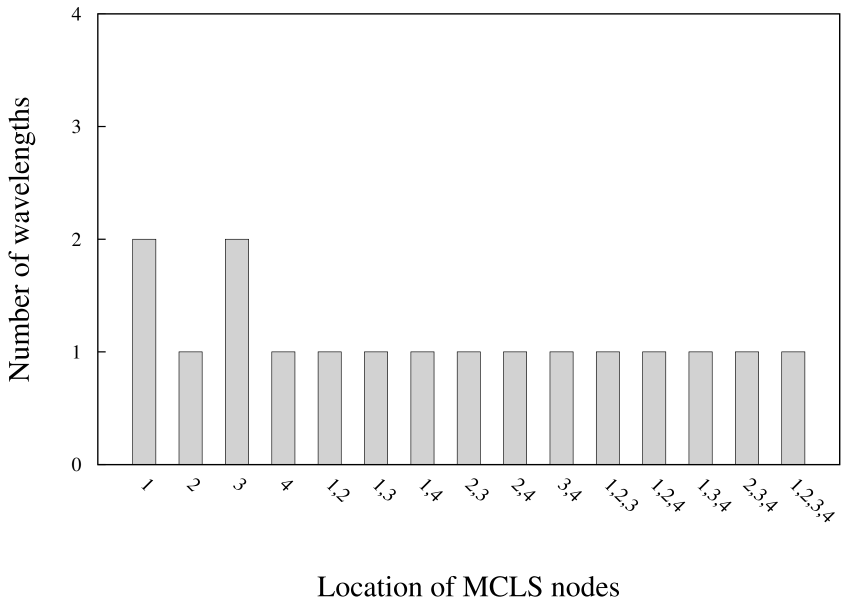


Figure 4.4: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with two regenerations for Topology 1.

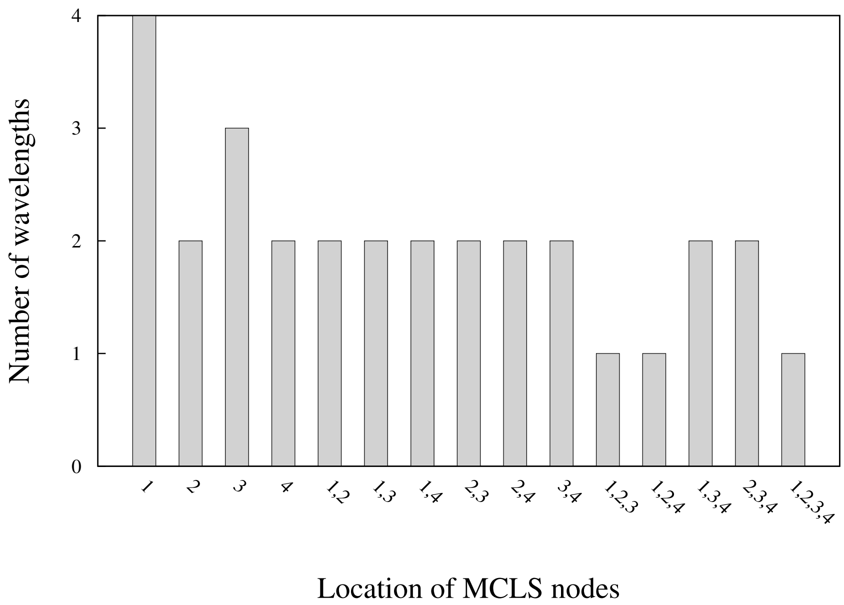


Figure 4.5: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach without regeneration for Topology 2.

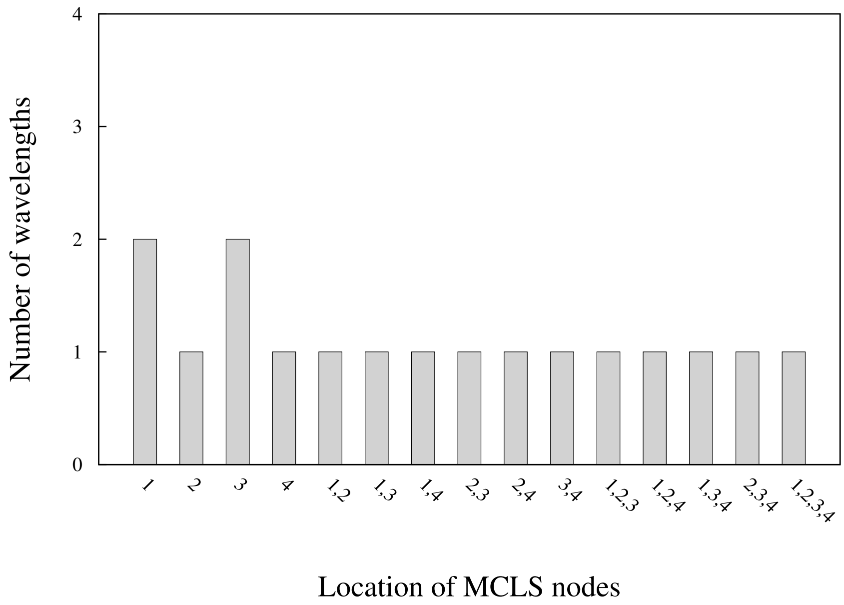


Figure 4.6: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with one regeneration for Topology 2.

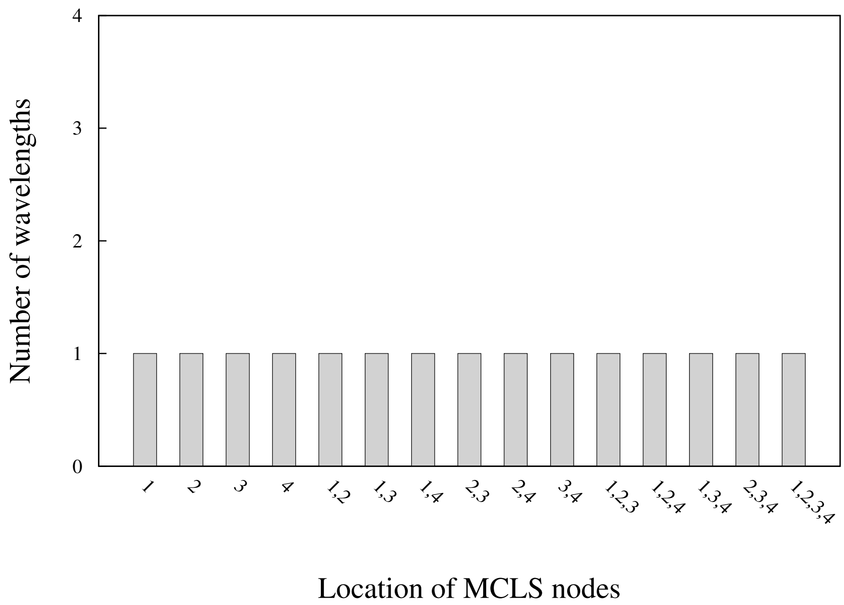


Figure 4.7: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with two regenerations for Topology 2.

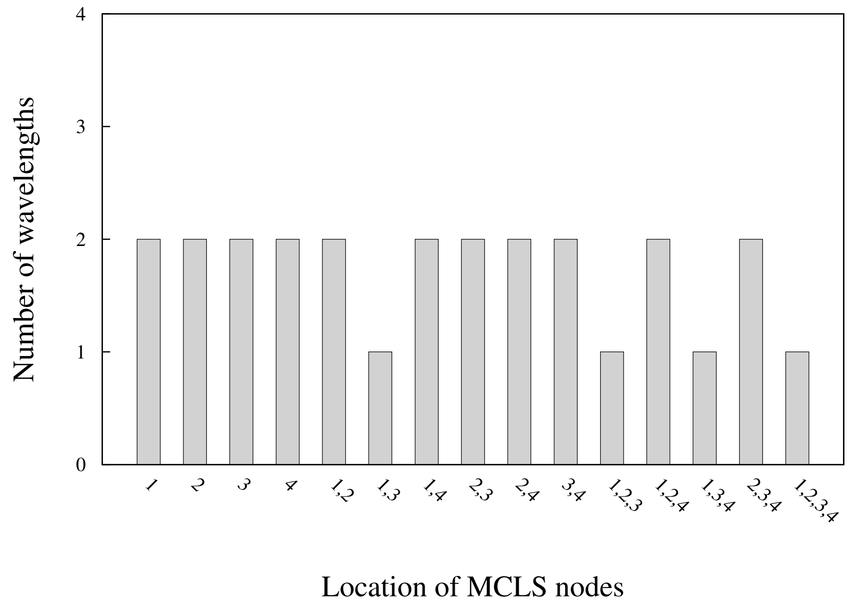


Figure 4.8: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach without regeneration for Topology 3.

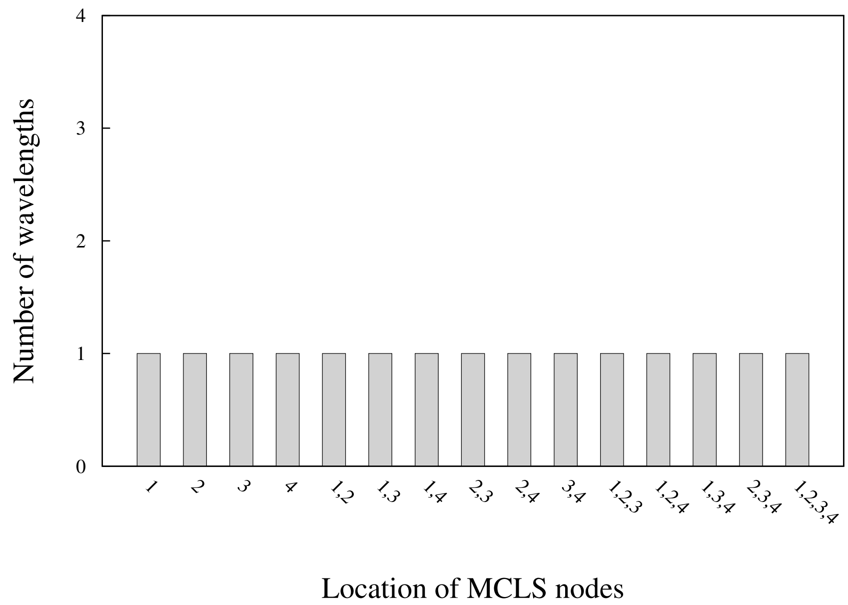


Figure 4.9: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with one regeneration for Topology 3.

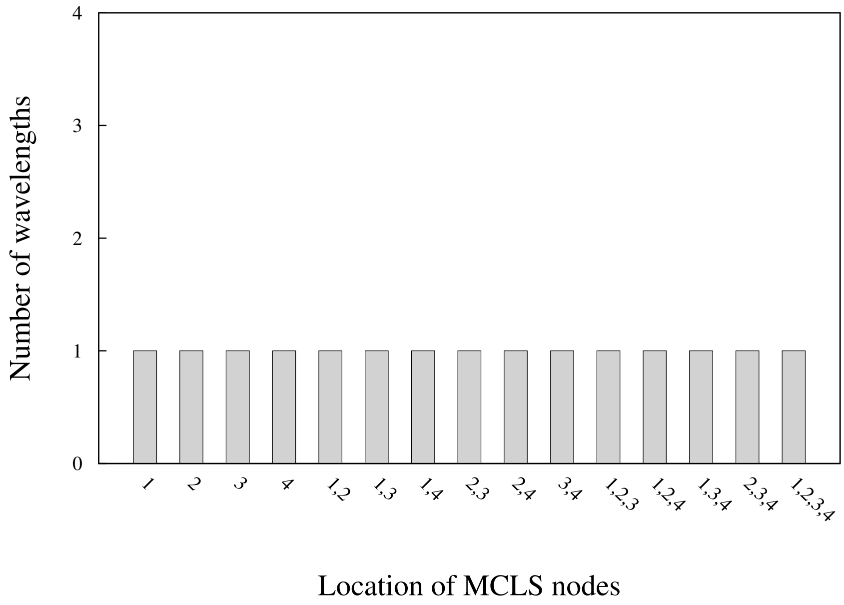


Figure 4.10: Comparison of number of wavelengths in each possible MCLS nodes under the ILP approach with two regenerations for Topology 3.

4.3 Summary

A mathematical model for WRMD mesh networks that support multiple MCLS nodes to minimize the number of wavelengths required for lightpath establishment was proposed. I focused on the static scenario, which assumes that lightpath setup requests are statically given in advance. The number of required wavelengths reduces as the allowable number of carrier regenerations increases. Furthermore, I observe that the number of required wavelengths decreases as the number of MCLS nodes increases.

Chapter 5

Heuristic RWA scheme in WRMD networks with multiple MCLS nodes

This chapter proposes an heuristic RWA scheme that supports multiple light-source nodes to minimize the number of required wavelengths for wavelength-reusable multi-carrier-distributed (WRMD) mesh networks. The heuristic RWA scheme uses the k-shortest path (KSP) algorithm to realize alternate routing. The wavelength assignment algorithm has two steps. The first step is to create chains of lightpaths and the second step is to assign a wavelength to each lightpath chain. Moreover, two lightpath selection policies, nearest optical carrier first (NCF) and less number of required wavelengths first (LWF), are introduced to create the lightpath chains. Simulation results show that the heuristic RWA scheme with the LWF policy achieves better performance than that with the NCF policy if regeneration is not used, while the scheme with the NCF policy outperforms that with the LWF policy in the cases of one and two regenerations.

5.1 Presented heuristic algorithm

5.1.1 Overview

I develop the heuristic RWA scheme to support multiple light-source nodes for overcoming the difficulty of the ILP problem. The heuristic RWA scheme consists of a routing algorithm and a wavelength assignment algorithm, which are performed separately.

The routing algorithm provides the routes of optical carrier connections and requested lightpaths. I employ the alternate routing using the k-shortest path (KSP) algorithm [50] to find the first k shortest paths from the light-source node or regeneration point to source for the optical carrier connection and source to destination for the requested lightpath.

The wavelength assignment algorithm requires the routes before it can be run. There are two steps in the wavelength assignment algorithm. In the first step, chains of lightpaths are created. In this step, a requested lightpath is selected to establish a connection, based on a lightpath selection policy. An optical carrier is generated from the MCLS node, and travels along a carrier lightpath to the selected requested lightpath. The optical carrier is regenerated at the end node of the selected requested lightpath. Another requested lightpath is selected. The optical carrier travels along the other carrier lightpath to the requested lightpath. A path from the MCLS node to the end node of the last requested lightpath, including carrier lightpaths and requested lightpaths, is called a chain of lightpaths. Moreover, due to the property of optical carrier duplication, I also consider the common source node of requested lightpaths. The optical carrier can be split into several copies and each copy is used to establish another requested lightpath. In the second step, each lightpath chain is assigned a wavelength. Wavelength assignment is then solved as a graph coloring problem. I use a heuristic algorithm, called the largest degree first [48], to solve the graph coloring problem, since it is widely used in graph coloring research and its effectiveness has been confirmed.

As shown in Fig. 5.1, the heuristic RWA scheme first decides the routes by the routing algorithm. Wavelengths are then assigned by the wavelength assignment algorithm.

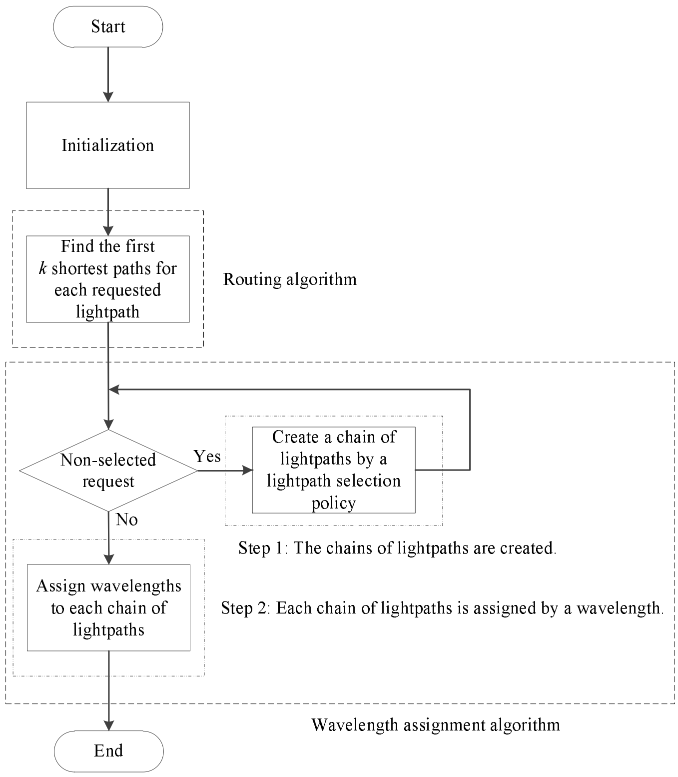


Figure 5.1: Flowchart of heuristic RWA scheme.

5.1.2 Lightpath selection policies to create lightpath chains

In the heuristic RWA scheme, two lightpath selection policies, namely nearest optical carrier first (NCF) and less number of required wavelengths first (LWF), are introduced to create the lightpath chains and to support multiple light-source nodes. To describe the heuristic RWA scheme, additional terms are defined. Let $T = \{t_1, t_2, \cdots, t_N\}$ be a set of light sources, which are defined as MCLS nodes or regeneration points. Let g_t be the nodal degree of light source t. Let $L = \{l_1, l_2, \cdots, l_P\}$ be a set of lightpaths. Let f_l^t be the distance from light source t to lightpath l, and f_l be the length of lightpath l. I define an optical connection as a lightpath associated with an optical carrier. Let $O = \left\{o_{l_1}^{t_1}, o_{l_2}^{t_1}, o_{l_1}^{t_2}, \cdots, o_{l_P}^{t_N}\right\}$ be a set of optical connections, where $o_{l_j}^{t_i}$ is an optical connection from light source $t_i \in T$ to lightpath $l_j \in L$.

The two lightpath selection policies are described as follows. At the beginning, each MCLS node and requested lightpath are indexed.

5.1.2.1 Nearest optical carrier first (NCF) policy

The NCF policy aims to create each chain of lightpaths with the shortest length, since a longer transmission length has larger transmission loss and results in stricter limits being placed on optical carrier regeneration [49]. This policy first selects the requested lightpaths that are the nearest to any MCLS node in case regeneration is not used. In case of carrier regeneration, it selects the remaining requested lightpaths that are possibly nearest to the regeneration point to fulfill both carrier regeneration and wavelength resources. The lightpath selection process is as follows.

- Step 1: Set $r \in R$ to 0.
- Step 2: Add MCLS node $m \in M$ that is the nearest to lightpath $p \in P$ to T.
- Step 3: Select a light source $t \in T$.
- Step 4: If $r = 0$, then add lightpath $p \in P$ that is the nearest to light source t to L. Otherwise, add lightpath $p \in P$ to L.
- Step 5: Select lightpath $l \in L$.
- Step 6: Add an optical connection from light source $t \in T$ to $l \in L$ to O and then remove lightpath l from L.
- Step 7: If L is not empty, then repeat from step 5. Otherwise, remove light source t from T.
- Step 8: If T is not empty, then repeat from step 3. Otherwise, sort O on g_t in descending order as the first key, f_l^t in ascending order as the second key, and f_l in ascending order as the third key.
- Step 9: Select the optical connection $o \in O$ that has the highest rank.

- Step 10: If the selected optical connection from light source t to lightpath l does not collide with each other, then set up this optical connection, add destination node of lightpath l to T as well as remove optical connection o with lightpath l from O, and lightpath l from P. Otherwise, remove optical connection o from O.

- Step 11: If O is not empty, then repeat from step 9. Otherwise, increase r by one.

- Step 12: If $r \leq R_{max}$, then go to step 3. Otherwise, a chain of lightpaths is created; reset T and L to empty.

- Step 13: If P is not empty, then go to step 1. Otherwise, the lightpath selection process is finished.

5.1.2.2 Less number of required wavelengths first (LWF) policy

The LWF policy aims to create each lightpath chain to avoid unnecessary carrier regeneration while minimizing the number or required wavelengths. This policy selects the requested lightpaths that do not collide with each other regardless of the number of transmission spans and transmission length if regeneration is not used. If carrier regeneration is used, it selects the requested lightpaths that are the nearest to any regeneration point to minimize the transmission length. The lightpath selection process is as follows.

- Step 1: Set $r \in R$ to 0.

- Step 2: Add MCLS node $m \in M$ to T.

- Step 3: Select light source $t \in T$.

- Step 4: If $r = 0$, then add lightpath $p \in P$ to L. Otherwise, add lightpath $p \in P$ that is nearest to light source t to L.

- Step 5: Select lightpath $l \in L$.

- Step 6: Add an optical connection from light source $t \in T$ to $l \in L$ to O and then remove lightpath l from L.

- Step 7: If L is not empty, then repeat from step 5. Otherwise, remove light source t from T.

- Step 8: If T is not empty, then repeat from step 3. Otherwise, sort O on g_t in descending order as the first key, f_l^t in ascending order as the second key, and f_l in ascending order as the third key.

- Step 9: Select the optical connection $o \in O$ that has the highest rank.

- Step 10: If the selected optical connection from light source t to lightpath l does not collide with each other, then set up this optical connection, add destination node of lightpath l to T as well as remove optical connection o with lightpath l from O, and lightpath l from P. Otherwise, remove optical connection o from O.

- Step 11: If O is not empty, then repeat from step 9. Otherwise, increase r by one.

- Step 12: If $r \leq R_{max}$, then go to step 3. Otherwise, a chain of lightpaths is created; reset T and L to empty.

- Step 13: If P is not empty, then go to step 1. Otherwise, the lightpath selection process is finished.

5.1.3 Example of lightpath selection policies

Figures 5.2 and 5.3 show examples of the two lightpath selection policies. There are six requested lightpaths: first, requested lightpath $i = 1$ travels on route 1 $\rightarrow$ 3; second, requested lightpath $i = 2$ travels on route 5 $\rightarrow$ 1; third, requested lightpath $i = 3$ travels on route 3 $\rightarrow$ 1; fourth, requested lightpath $i = 4$ travels on route 2 $\rightarrow$ 4; fifth, requested lightpath $i = 5$ travels on route 3 $\rightarrow$ 2; and finally, requested lightpath $i = 6$ travels on route 5 $\rightarrow$ 6. I assume that node 1 and node 6 are the MNs, which are named as $MN1$ and $MN2$, respectively. Moreover, the allowable carrier regeneration number is one and the alternate routing algorithm considers the maximum number of paths with $k = 1$.

In the NCF policy, as in Fig. 5.2(a), the policy first sets r to 0 for initialization. Next, the policy adds the MCLS node that is the nearest to each requested lightpath to T. As a result, T includes MN1 (step 2). Next, the policy selects $MN1$ and then adds the requested lightpath $i = 1$ that is the nearest to $MN1$ to L (step 4). The requested lightpath $i = 1$ is processed in steps 5-10. T is then set with the destination node of requested lightpath $i = 1$, which is node 3 (step 10). Next, r is increased by one in step 11. The policy selects the regeneration point (node 3) and then adds all requested lightpaths $i = 2, 3, 4, 5$, and 6. The requested lightpaths are processed to add optical connections to O in steps 5-7. The policy sorts O on nodal degree of regeneration point in descending order as the first key, distance from regeneration point to requested lightpath in ascending order as the second key, and length of requested lightpath in ascending order as the third key (step 8). The sorted O is related to the requested lightpaths $i = 5, 3, 4, 6$, and 2. However, only the requested lightpaths $i = 5, 6$, and 2 can be selected, since the requested lightpaths $i = 3$ and 4 conflict with wavelength assignment rule 3 presented in Section 1. The first chain of lightpaths is then created on route $1 \rightarrow 2 \rightarrow 3$, $3 \rightarrow 2$, $3 \rightarrow 5 \rightarrow 6$, and $5 \rightarrow 4 \rightarrow 1$ (step 12), as shown in Fig. 5.2(b). After that, step 2 is executed, and T includes $MN1$ and $MN2$. Next, the policy selects $MN1$ and adds $i = 4$, the requested lightpath that is nearest to $MN1$, to L. Next, it selects $MN2$ and adds $i = 3$, the requested lightpath that is nearest to $MN2$, to L. Both of them are processed in steps 5-10. The second chain of lightpaths is created on route $1 \rightarrow 2 \rightarrow 4$ and $6 \rightarrow 3 \rightarrow 2 \rightarrow 1$ (step 12), as shown in Fig. 5.2(c). After the chains of lightpaths are created, a wavelength is assigned to each chain. λ_1 is assigned to the first lightpath chain. λ_2 is assigned to the second lightpath chain, as shown in Fig. 5.2(d).

In the LWF policy, as shown in Fig. 5.3(b), the policy first sets r to 0 for initialization. Next, all MNs are first added to T (step 2). Next, the policy selects $MN1$ and then adds all requested lightpaths to L. Next, it selects $MN2$ and adds all the requested lightpaths to L. Notice that the policy adds all combinations between the MNs and the requested lightpaths to O in steps 3-7. Next, the policy sorts O on nodal degree of regeneration point in descending order as the first key, distance from regeneration point to requested lightpath in ascending order as the second key, and length of requested lightpath in ascending order

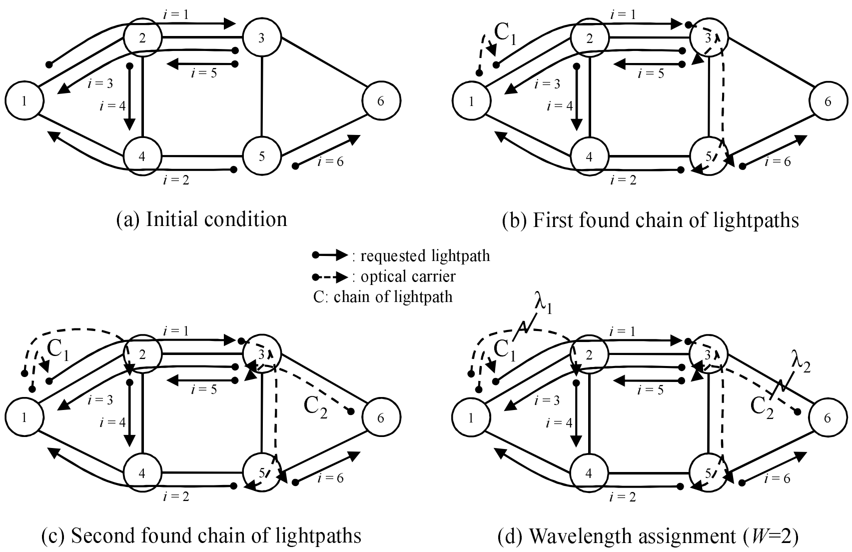


Figure 5.2: Example of NCF policy.

as the third key (step 8). Next, it selects an optical connection from $MN1$ to the requested lightpath $i = 1$ and selects optical connections from $MN2$ to the requested lightpaths $i = 5, 6$, and 2. The requested lightpaths $i = 1, 5, 6$, and 2 are processed in steps 5-10. The destination nodes of requested lightpaths $i = 1, 5, 6$, and 2, which are node 3, node 2, node 6, and node 1, respectively, are then added to T (step 10). Next, r is increased by one in step 11. Next, it adds all combinations between the regeneration points and the remaining requested lightpaths. The policy selects an optical connection from node 2 to requested lightpath $i = 4$. The remaining requested lightpath is not selected, since it conflicts with wavelength assignment rule 3. The first chain of lightpaths is then created on route $1 \to 2 \to 3$, $6 \to 3 \to 2$, $6 \to 5 \to 6$, and $5 \to 4 \to 1$ (step 12), as shown in Fig. 5.3(b). After that, the policy adds all combinations between the MNs and the requested lightpaths. Next, it selects an optical connection from $MN2$ to requested lightpath $i = 3$. The second chain of lightpaths is then created on route $6 \to 3 \to 2 \to 1$ (step 12), as shown in Fig. 5.3(c). After the chains of lightpaths are created, a wavelength is assigned to each chain. λ_1 is assigned to the first lightpath chain. λ_2 is assigned to the second lightpath chain, as shown in Fig. 5.3(d).

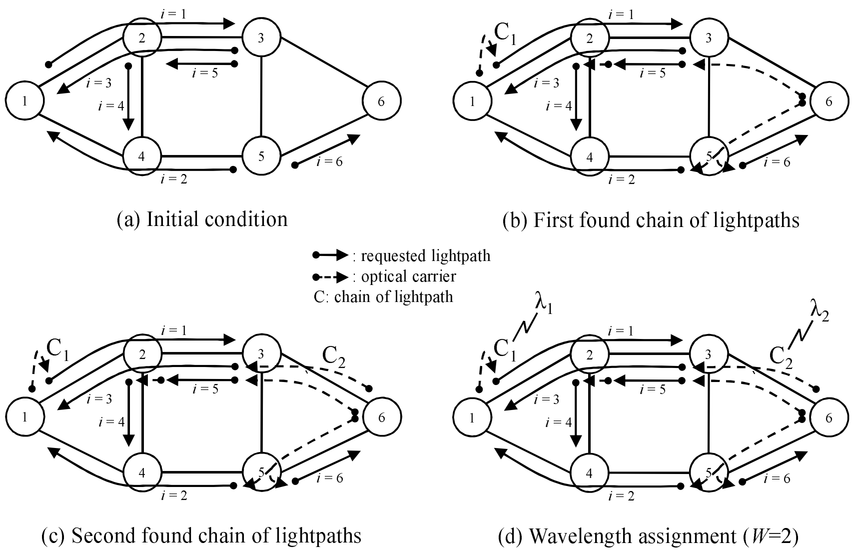


Figure 5.3: Example of LWF policy.

5.2 Results and discussions

I evaluate the performance of the heuristic RWA scheme from three points. First, the number of required wavelengths in the mathematical model is compared with that demanded by the heuristic RWA scheme. Second, the number of required wavelengths by the heuristic RWA scheme is determined under different parameters. Finally, the impact of MCLS node location on the number of required wavelengths in the WRMD mesh network is assessed. Additionally, the effect of optical carrier reuse is evaluated. In addition, I give a discussion on the heuristic RWA scheme in the last subsection. In the evaluation, I assume that each link contains 8 wavelengths for small networks and 256 wavelengths for large-scale networks, the bandwidth of each request is one wavelength channel, and the duration of the request is infinite. I use a Linux-based computer with Intel®Core$^{\text{TM}}$i7-3770 CPU @ 3.40GHz and 32GB of memory.

5.2.1 Comparison of ILP approach and heuristic RWA scheme

The RWA problem is to determine both route and wavelength for each lightpath request. Therefore, all routes of optical carrier connections and requested lightpaths are required to be designed to minimize the number of wavelengths. In order to evaluate the effectiveness of the heuristic RWA scheme, the number of required wavelengths is investigated. The number of wavelengths required under the ILP approach is compared with that under the heuristic RWA scheme, which takes into account all possible shortest paths of optical carrier connections and requested lightpaths in the WRMD mesh network. I consider the three network topologies presented in [23], see Fig. 4.1. The alternate routing algorithm considers the maximum number of paths with $k = 1$, $k = 2$, and $k = 3$ paths for Topology 1, Topology 2, and Topology 3, respectively.

Figures 5.4 - 5.6 show the numbers of required wavelengths by the ILP approach and heuristic RWA scheme for Topology 1 for the three different regeneration numbers. The ILP approach gives the minimum number of required wavelengths. Therefore, the ILP approach is able to provide reference values for further analysis. I observe that the heuristic RWA scheme approaches the optimal number of required wavelengths. The heuristic RWA scheme with LWF policy outperforms that with NCF policy in the no-regeneration case, while the heuristic RWA scheme with NCF policy outperforms that with LWF policy in the cases of one and two regenerations. In addition, I observe that the number of required wavelengths decreases as the number of MCLS nodes increases.

Figures 5.7 - 5.9 show the numbers of wavelengths required under the ILP approach and heuristic RWA scheme for Topology 2 for the three different regeneration numbers. The heuristic RWA scheme with NCF and LWF policies approaches the optimal number of required wavelengths for all regeneration numbers.

Figures 5.10 - 5.12 plot the numbers of wavelengths required under the ILP approach and heuristic RWA scheme for Topology 3 for the three different regeneration numbers. The results show that the heuristic RWA scheme with NCF

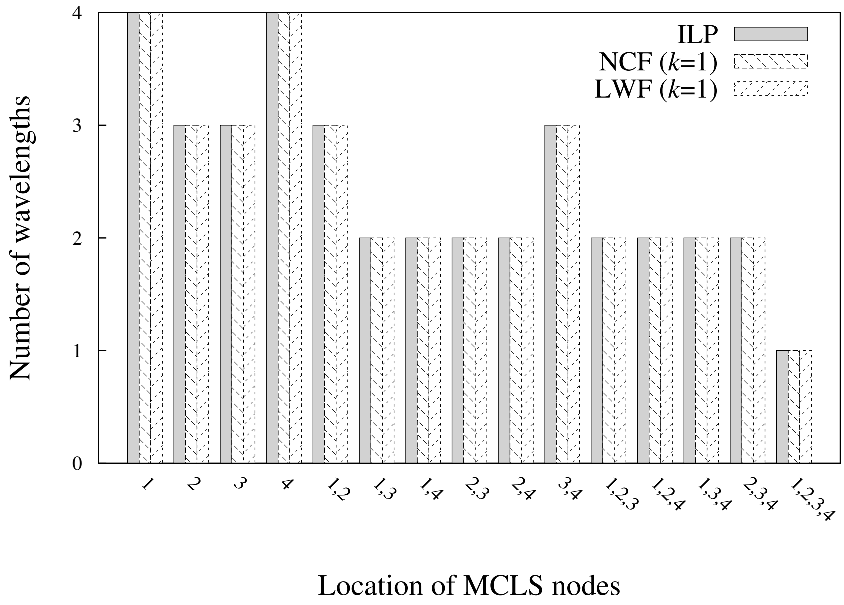


Figure 5.4: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme without regeneration for Topology 1.

and LWF policies approaches the optimal number of wavelengths as the maximum number of paths, k, increases.

However, the ILP approach is hard to solve in any practical time, especially when the network topology is large. Therefore, I investigate the performance of the heuristic RWA scheme for large-scale networks in the next subsection.

5.2.2 Effectiveness of heuristic RWA scheme

I evaluate the effectiveness of the heuristic RWA scheme using the two lightpath selection policies for large-scale networks, namely Synthetic network, European COST239 network, and U.S. long distance network as shown in Fig. 5.13. The number of requested lightpaths is set to 200 and 300. I average the values over the numbers of required wavelengths for 100 randomly generated, different sets of requested lightpaths. The allowable number of carrier regenerations is two and the alternate routing algorithm considers the maximum number of paths with $k = 3$.

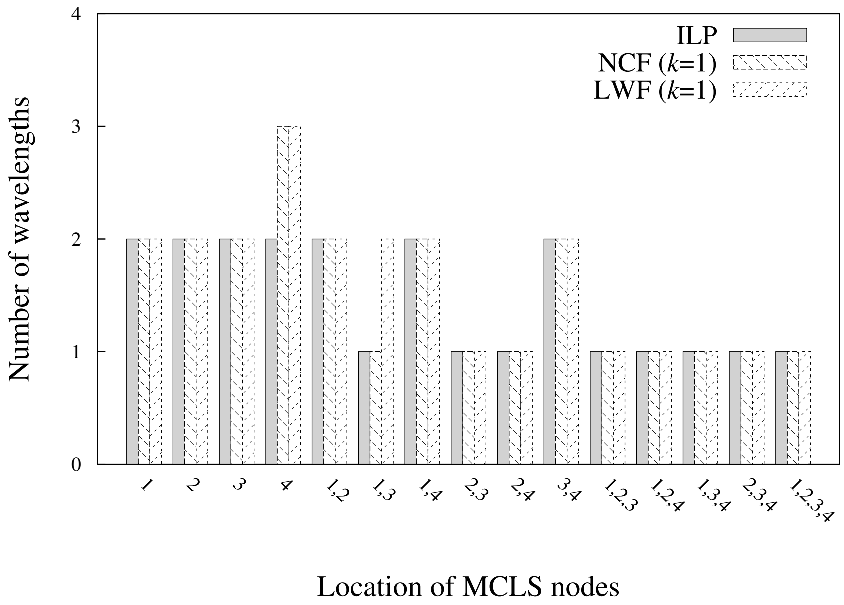


Figure 5.5: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with one regeneration for Topology 1.

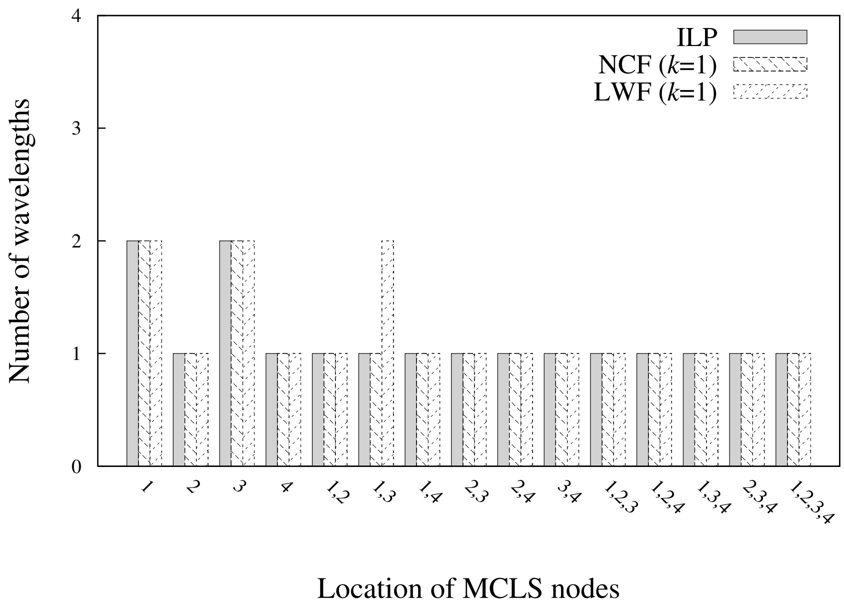


Figure 5.6: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with two regenerations for Topology 1.

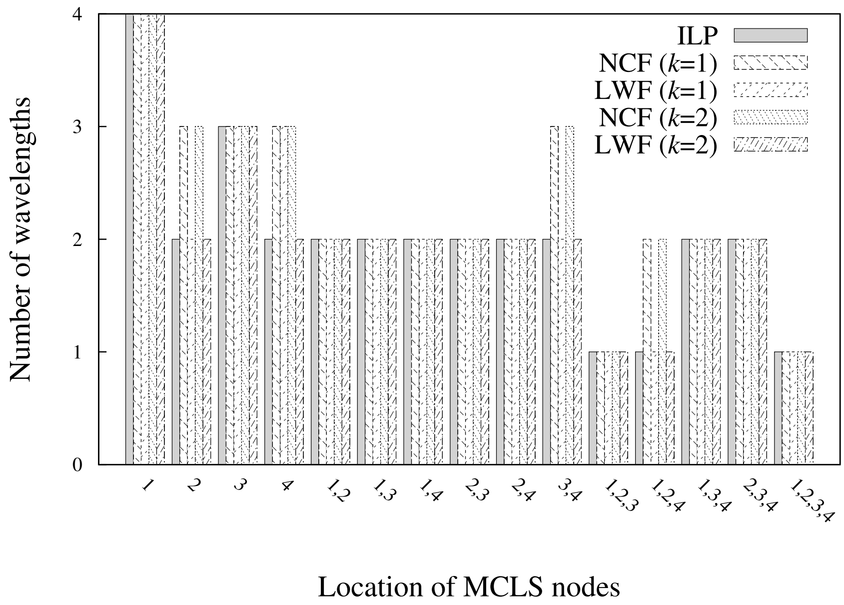


Figure 5.7: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme without regeneration for Topology 2.

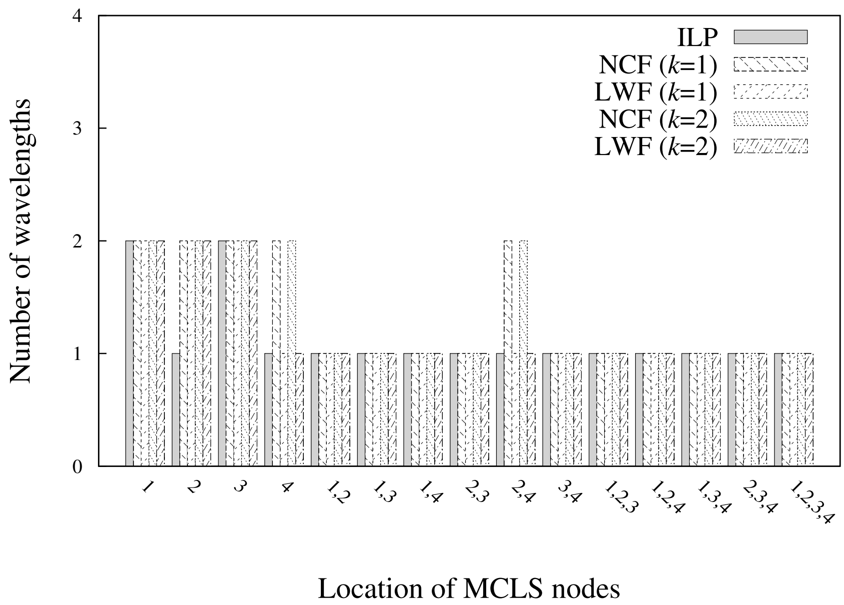


Figure 5.8: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with one regeneration for Topology 2.

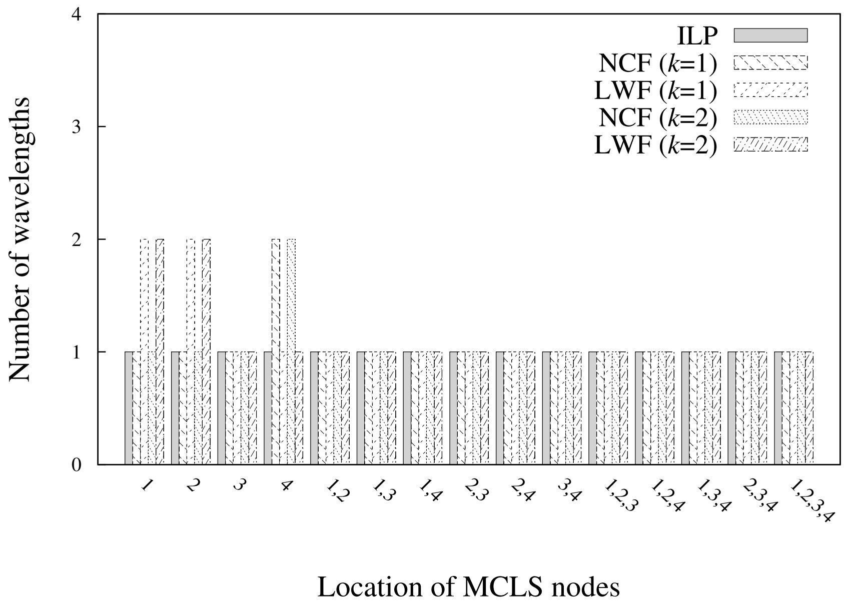


Figure 5.9: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with two regenerations for Topology 2.

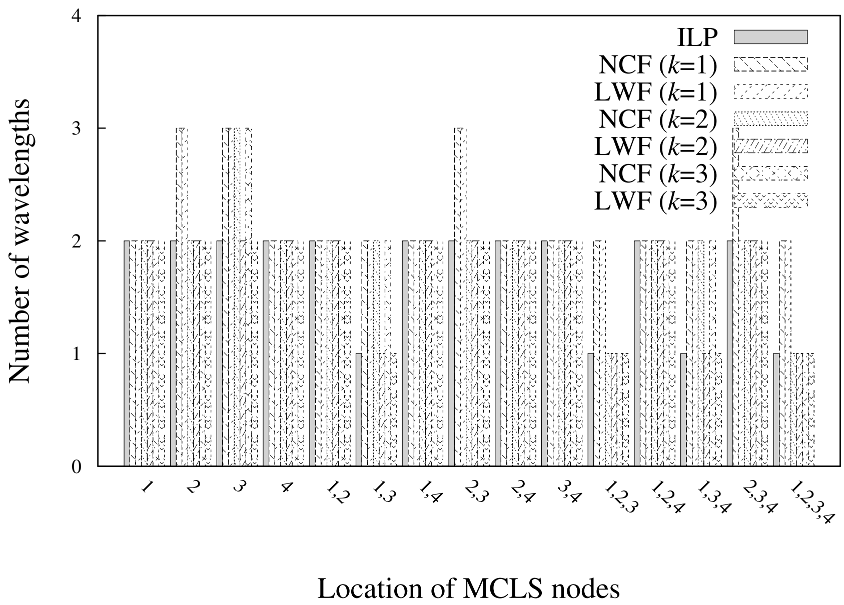


Figure 5.10: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme without regeneration for Topology 3.

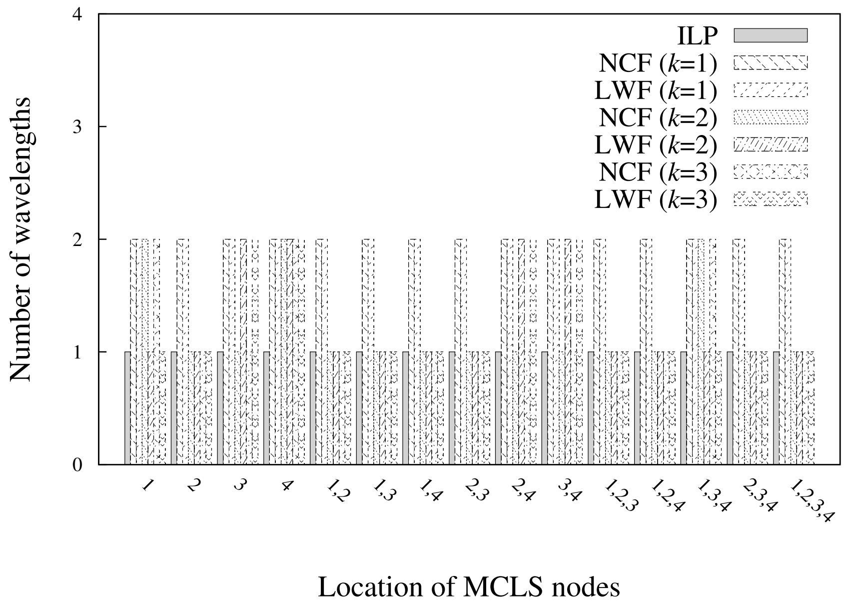


Figure 5.11: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with one regeneration for Topology 3.

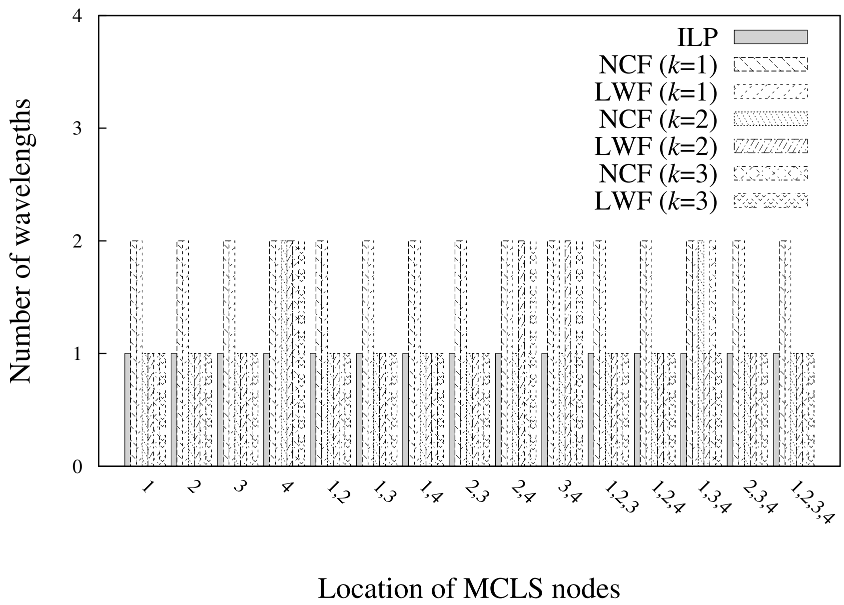
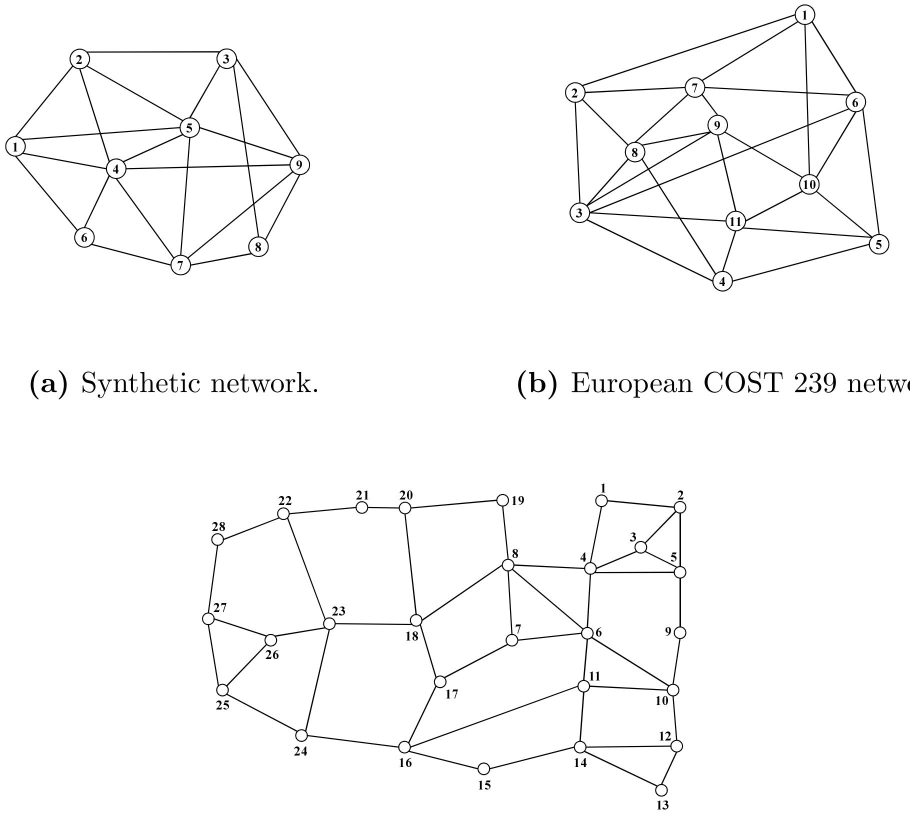


Figure 5.12: Comparison of the number of wavelengths required under the ILP approach and heuristic RWA scheme with two regenerations for Topology 3.



(a) Synthetic network.

(b) European COST 239 network.

(c) U.S. long distance network.

Figure 5.13: Network topologies examined.

Tables 5.1 and 5.2 show the number of required wavelengths of the heuristic RWA scheme with the two different policies for the three different topologies with 200 and 300 requested lightpaths, respectively. I observe similar behavior with regard to the number of required wavelengths. The heuristic RWA scheme without regeneration demands a large number of required wavelengths; the number decreases as the allowable carrier regeneration number increases. The heuristic RWA scheme with one regeneration reduces the number of required wavelengths by at least 44%, 46%, and 44% from that without regeneration for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. Furthermore, the heuristic RWA scheme with two regenerations reduces the number of required wavelengths by at least 48%, 51%, and 54% from that without regeneration for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. In addition, the heuristic RWA scheme is able to reduce the number of required wavelengths when the number of MCLS nodes increases. The results show that the heuristic RWA scheme with two MCLS nodes reduces the number of required wavelengths by at least 24%, 24%, and 27% from that with one MCLS node for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. On the other hand, the heuristic RWA scheme with three MCLS nodes reduces the number of required wavelengths by at least 35%, 35%, and 41% from that with one MCLS node for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. Additionally, the number of required wavelengths decreases under the heuristic RWA scheme as the maximum number of paths, k, increases.

Figures 5.14 - 5.31 show the number of required wavelengths of the heuristic RWA scheme in the different policies and the different maximum number of paths, k, for the Synthetic network, European COST 239 network, and U.S. long distance network with 200 and 300 requested lightpaths, respectively. From the network designer's point of view, it is important to observe that the reduction ratio of the number of required wavelengths over the number of carrier regenerations is better than that over the number of MCLS nodes. Moreover, the reduction ratio of the number of required wavelengths over the maximum number of paths, k, is relatively high.

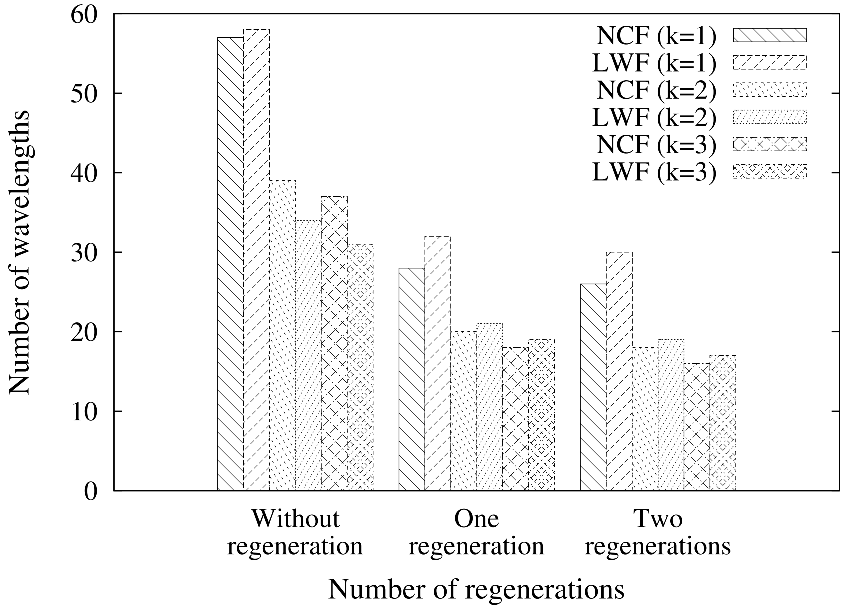


Figure 5.14: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for Synthetic network with 200 requested lightpaths.

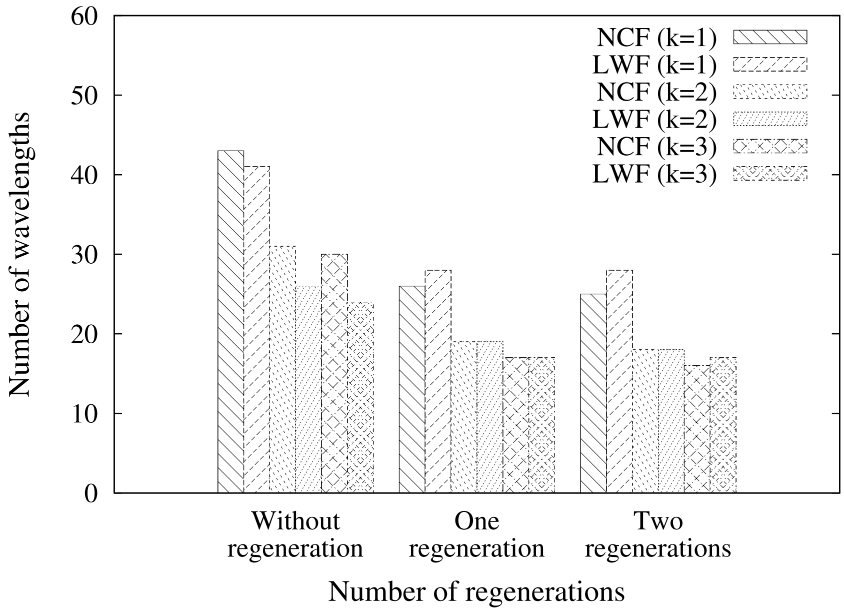


Figure 5.15: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for Synthetic network with 200 requested lightpaths.

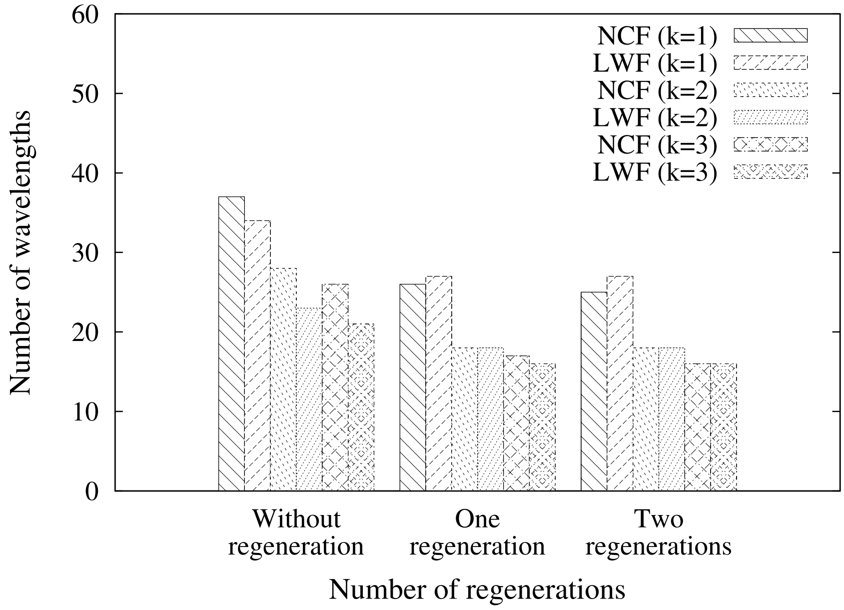


Figure 5.16: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for Synthetic network with 200 requested lightpaths.

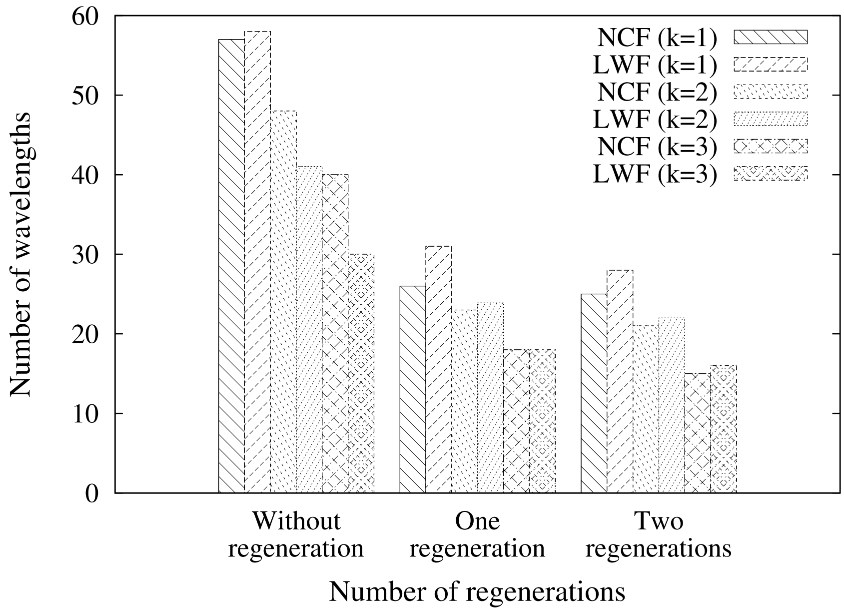


Figure 5.17: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for European COST 239 network with 200 requested lightpaths.

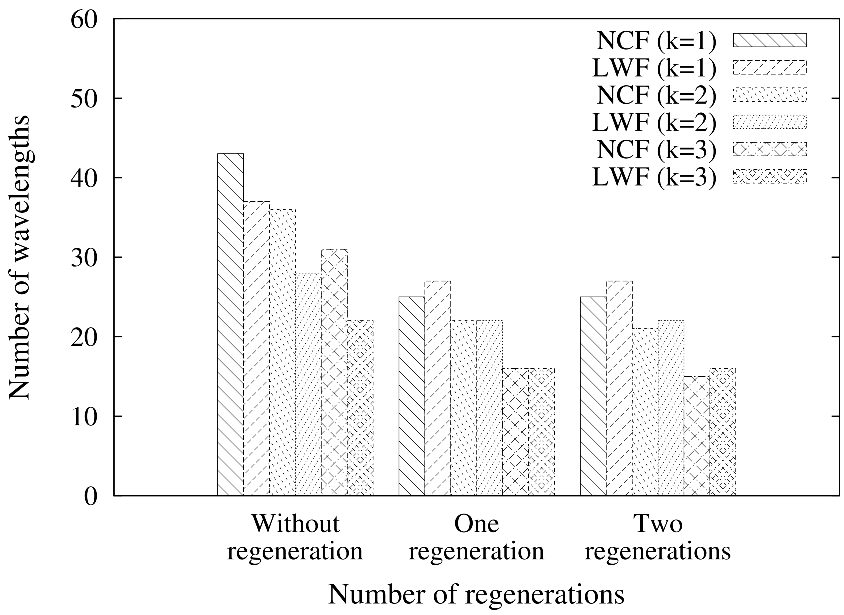


Figure 5.18: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for European COST 239 network with 200 requested lightpaths.

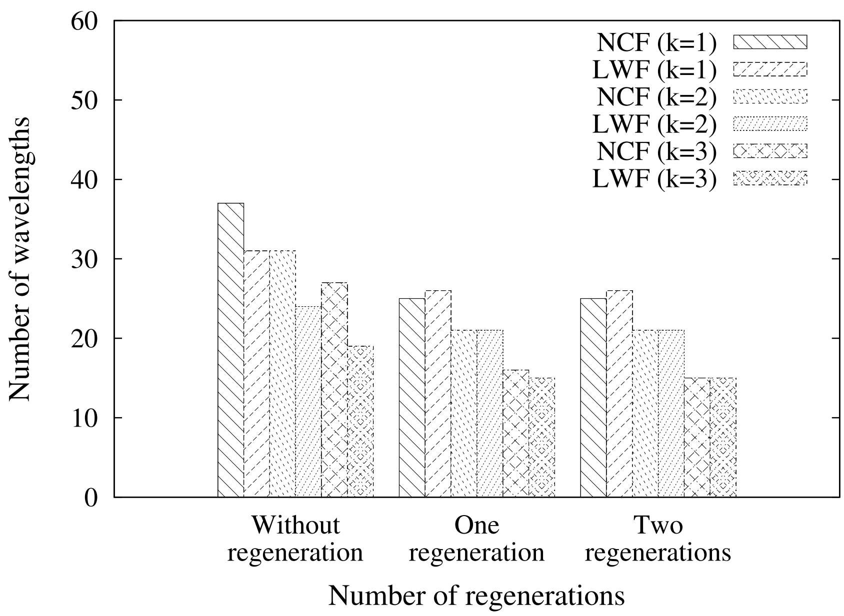


Figure 5.19: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for European COST 239 network with 200 requested lightpaths.

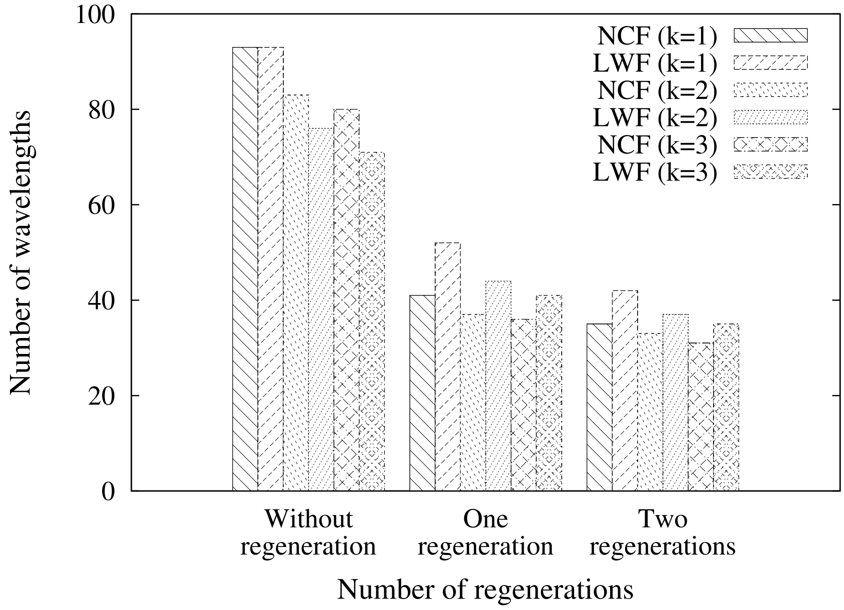


Figure 5.20: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for U.S. long distance network with 200 requested lightpaths.

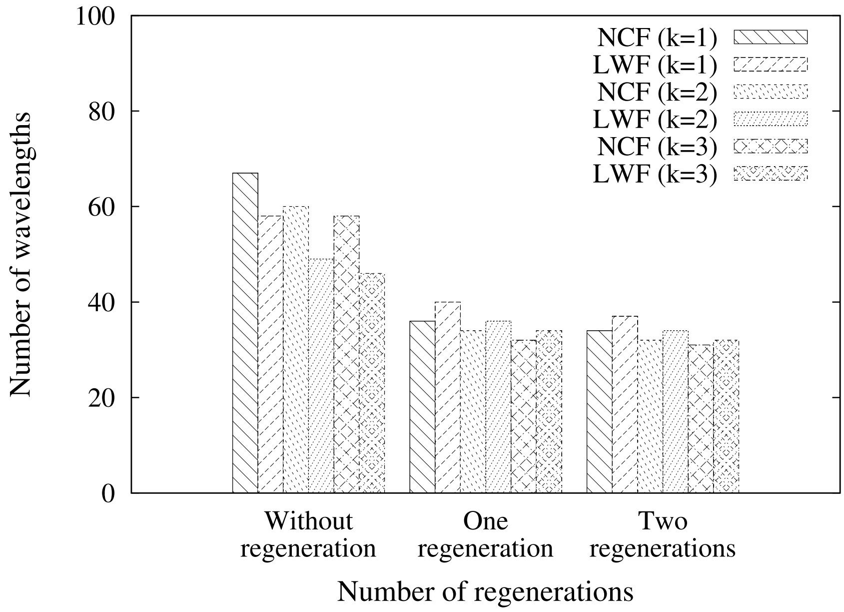


Figure 5.21: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for U.S. long distance network with 200 requested lightpaths.

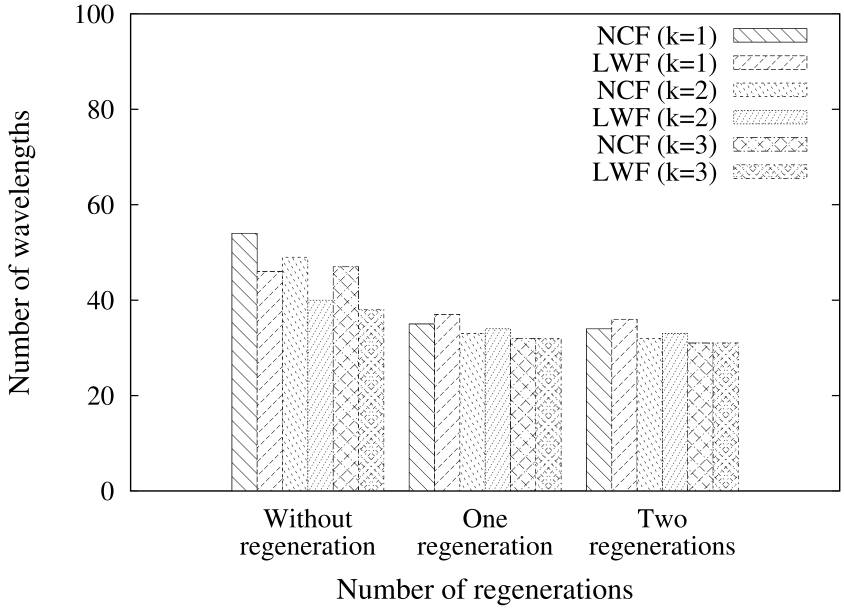


Figure 5.22: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for U.S. long distance network with 200 requested lightpaths.

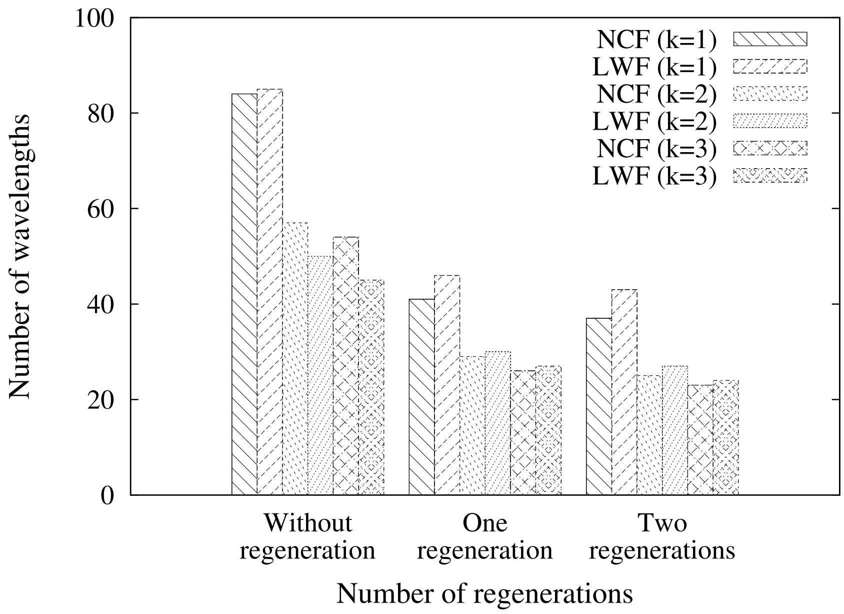


Figure 5.23: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for Synthetic network with 300 requested lightpaths.

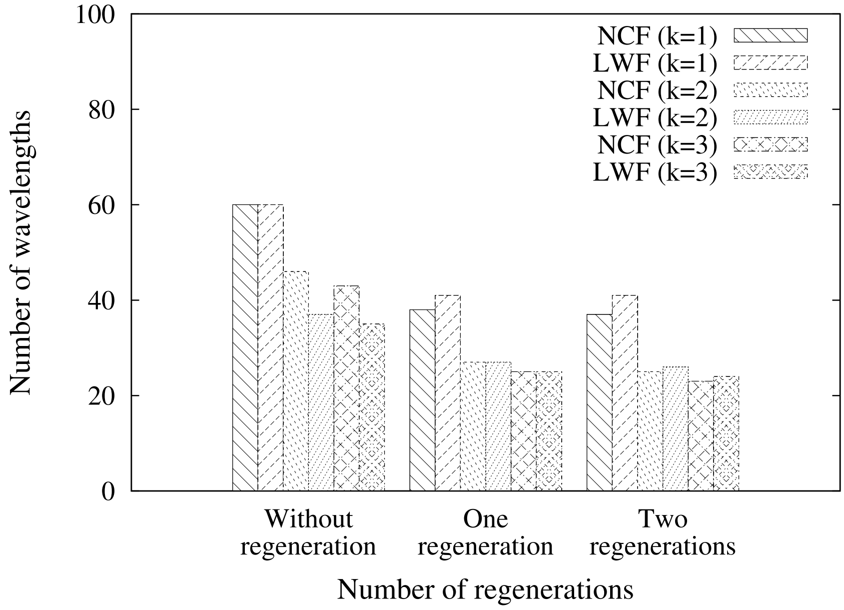


Figure 5.24: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for Synthetic network with 300 requested lightpaths.

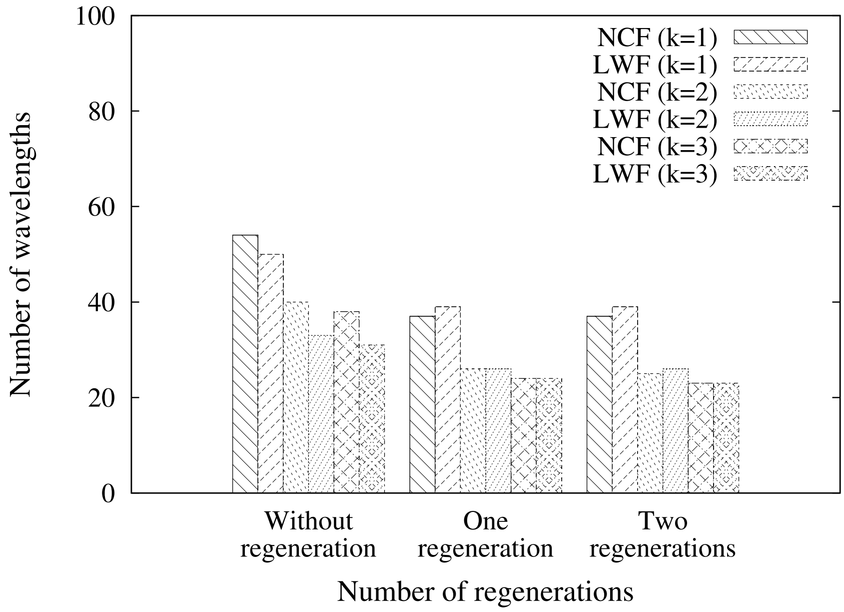


Figure 5.25: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for Synthetic network with 300 requested lightpaths.

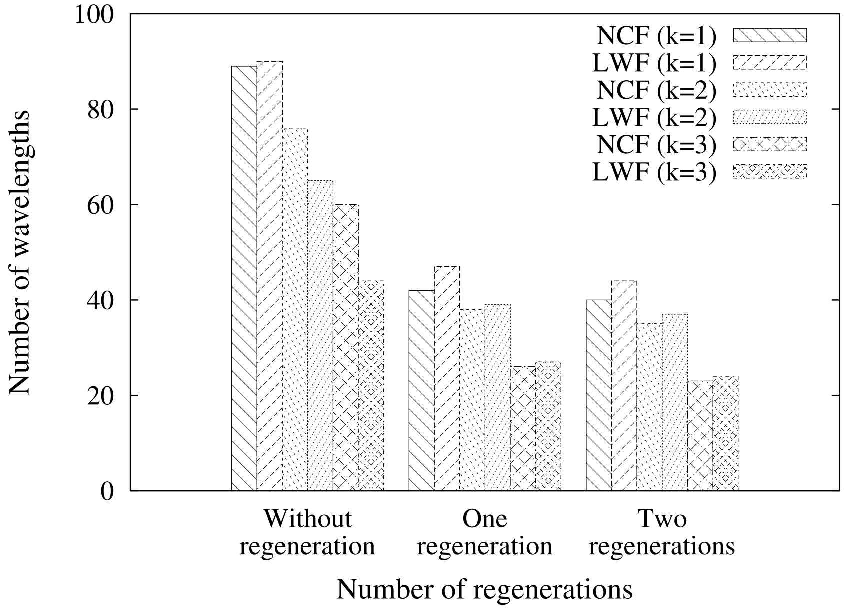


Figure 5.26: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for European COST 239 network with 300 requested lightpaths.

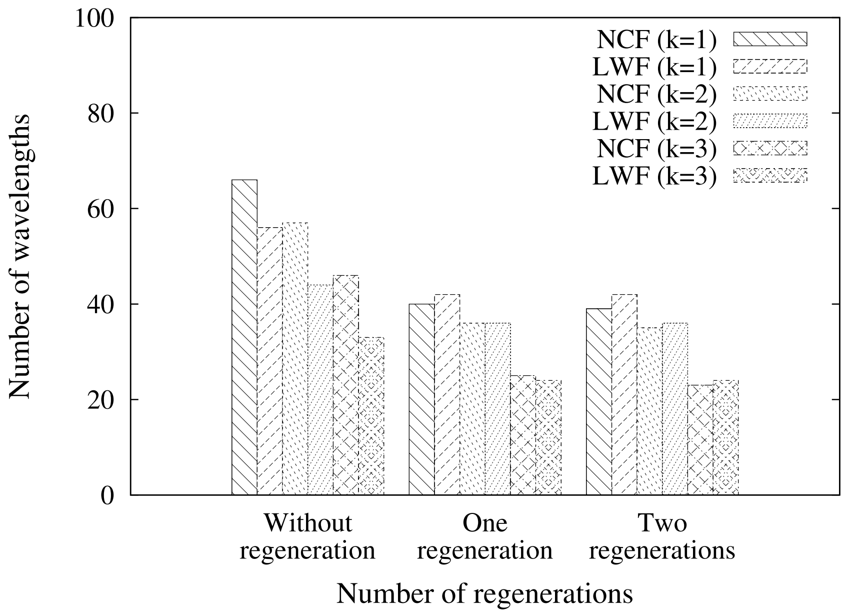


Figure 5.27: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for European COST 239 network with 300 requested lightpaths.

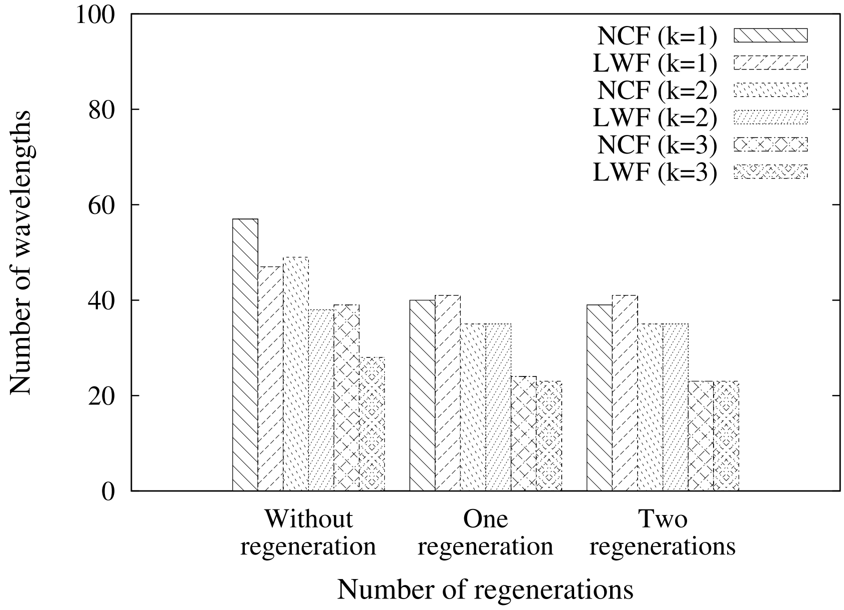


Figure 5.28: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for European COST 239 network with 300 requested lightpaths.

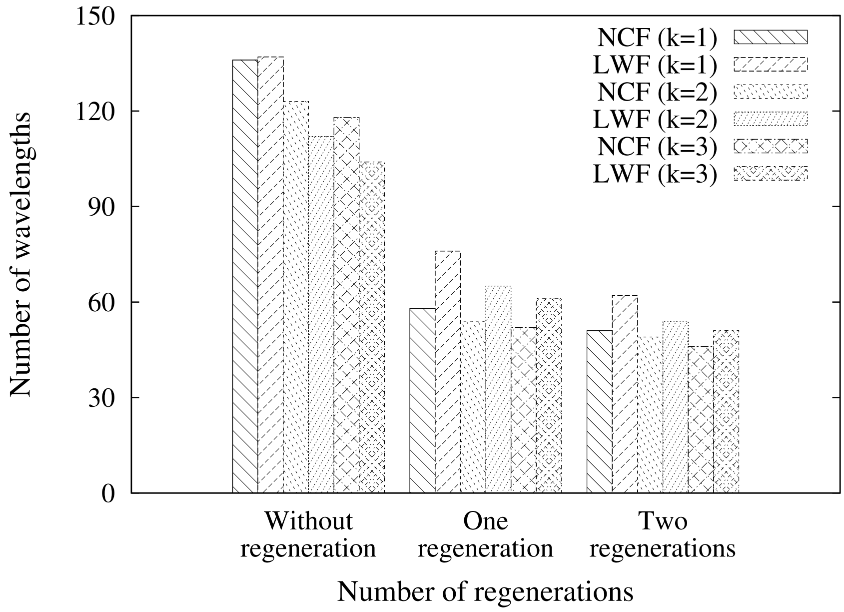


Figure 5.29: Number of required wavelengths of the heuristic RWA scheme with one MCLS node for U.S. long distance network with 300 requested lightpaths.

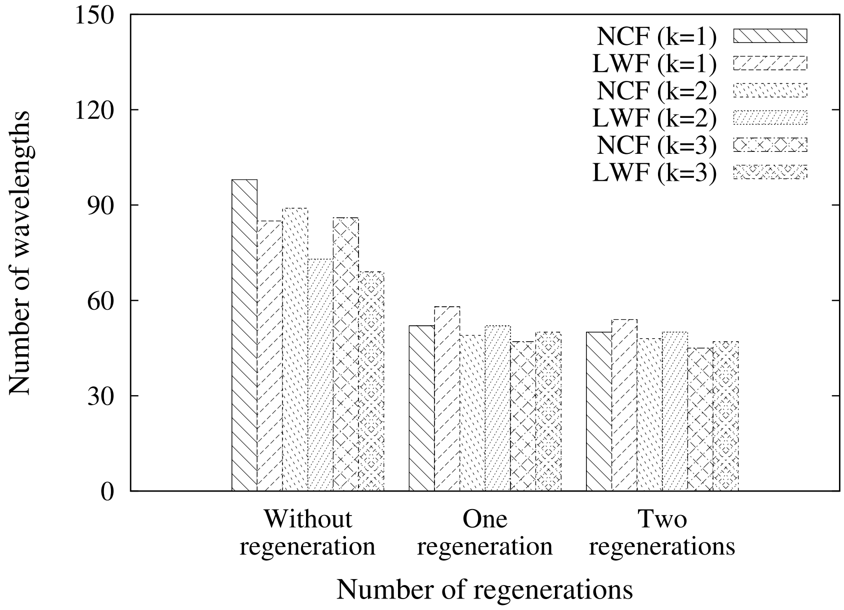


Figure 5.30: Number of required wavelengths of the heuristic RWA scheme with two MCLS nodes for U.S. long distance network with 300 requested lightpaths.

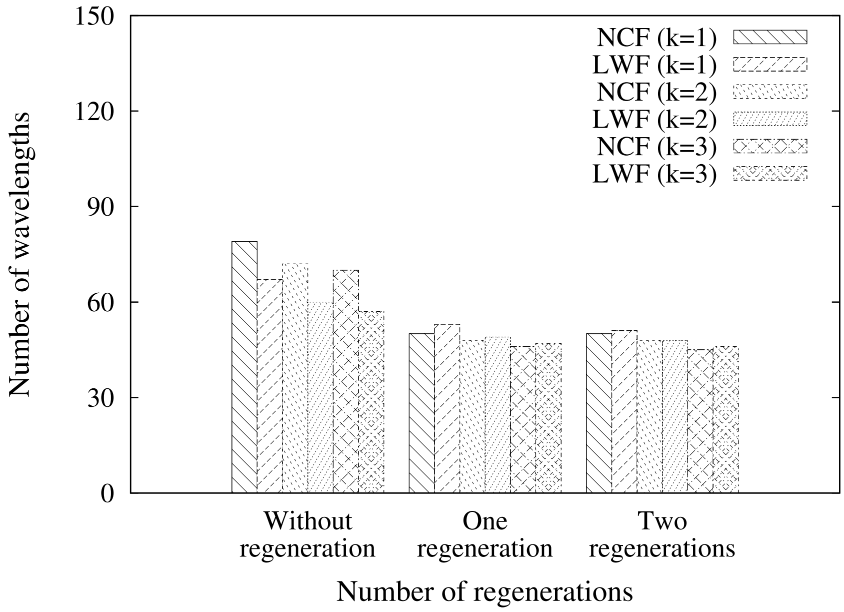


Figure 5.31: Number of required wavelengths of the heuristic RWA scheme with three MCLS nodes for U.S. long distance network with 300 requested lightpaths.

Table 5.1: Comparison between NCF and LWF policies with 200 requested light-paths.

Network topology	Number of MCLS nodes	Policy	Without regeneration	With one regeneration	With two regenerations
Synthetic network	1	NCF (k=1)	57	28	26
		LWF (k=1)	58	32	30
		NCF (k=2)	39	20	18
		LWF (k=2)	34	21	19
		NCF (k=3)	37	18	16
		LWF (k=3)	31	19	17
	2	NCF (k=1)	43	26	25
		LWF (k=1)	41	28	28
		NCF (k=2)	31	19	18
		LWF (k=2)	26	19	18
		NCF (k=3)	30	17	16
		LWF (k=3)	24	17	17
	3	NCF (k=1)	37	26	25
		LWF (k=1)	34	27	27
		NCF (k=2)	28	18	18
		LWF (k=2)	23	18	18
		NCF (k=3)	26	17	16
		LWF (k=3)	21	16	16
European COST 239 network	1	NCF (k=1)	57	26	25
		LWF (k=1)	58	31	28
		NCF (k=2)	48	23	21
		LWF (k=2)	41	24	22
		NCF (k=3)	40	18	15
		LWF (k=3)	30	18	16
	2	NCF (k=1)	43	25	25
		LWF (k=1)	37	27	27
		NCF (k=2)	36	22	21
		LWF (k=2)	28	22	22
		NCF (k=3)	31	16	15
		LWF (k=3)	22	16	16
	3	NCF (k=1)	37	25	25
		LWF (k=1)	31	26	26
		NCF (k=2)	31	21	21
		LWF (k=2)	24	21	21
		NCF (k=3)	27	16	15
		LWF (k=3)	19	15	15
U.S. long distance network	1	NCF (k=1)	93	41	35
		LWF (k=1)	93	52	42
		NCF (k=2)	83	37	33
		LWF (k=2)	76	44	37
		NCF (k=3)	80	36	31
		LWF (k=3)	71	41	35
	2	NCF (k=1)	67	36	34
		LWF (k=1)	58	40	37
		NCF (k=2)	60	34	32
		LWF (k=2)	49	36	34
		NCF (k=3)	58	32	31
		LWF (k=3)	46	34	32
	3	NCF (k=1)	54	35	34
		LWF (k=1)	46	37	36
		NCF (k=2)	49	33	32
		LWF (k=2)	40	34	33
		NCF (k=3)	47	32	31
		LWF (k=3)	38	32	31

Table 5.2: Comparison between NCF and LWF policies with 300 requested light-paths.

Network topology	Number of MCLS nodes	Policy	Without regeneration	With one regeneration	With two regenerations
Synthetic network	1	NCF (k=1)	84	41	37
Synthetic network	1	LWF (k=1)	85	46	43
Synthetic network	1	NCF (k=2)	57	29	25
Synthetic network	1	LWF (k=2)	50	30	27
Synthetic network	1	NCF (k=3)	54	26	23
Synthetic network	1	LWF (k=3)	45	27	24
Synthetic network	2	NCF (k=1)	64	38	37
Synthetic network	2	LWF (k=1)	60	41	41
Synthetic network	2	NCF (k=2)	46	27	25
Synthetic network	2	LWF (k=2)	37	27	26
Synthetic network	2	NCF (k=3)	43	25	23
Synthetic network	2	LWF (k=3)	35	25	24
Synthetic network	3	NCF (k=1)	54	37	37
Synthetic network	3	LWF (k=1)	50	39	39
Synthetic network	3	NCF (k=2)	40	26	25
Synthetic network	3	LWF (k=2)	33	26	26
Synthetic network	3	NCF (k=3)	38	24	23
Synthetic network	3	LWF (k=3)	31	24	23
European COST 239 network	1	NCF (k=1)	89	42	40
European COST 239 network	1	LWF (k=1)	90	47	44
European COST 239 network	1	NCF (k=2)	76	38	35
European COST 239 network	1	LWF (k=2)	65	39	37
European COST 239 network	1	NCF (k=3)	60	26	23
European COST 239 network	1	LWF (k=3)	44	27	24
European COST 239 network	2	NCF (k=1)	66	40	39
European COST 239 network	2	LWF (k=1)	56	42	42
European COST 239 network	2	NCF (k=2)	57	36	35
European COST 239 network	2	LWF (k=2)	44	36	36
European COST 239 network	2	NCF (k=3)	46	25	23
European COST 239 network	2	LWF (k=3)	33	24	24
European COST 239 network	3	NCF (k=1)	57	40	39
European COST 239 network	3	LWF (k=1)	47	41	41
European COST 239 network	3	NCF (k=2)	49	35	35
European COST 239 network	3	LWF (k=2)	38	35	35
European COST 239 network	3	NCF (k=3)	39	24	23
European COST 239 network	3	LWF (k=3)	28	23	23
U.S. long distance network	1	NCF (k=1)	136	58	51
U.S. long distance network	1	LWF (k=1)	137	76	62
U.S. long distance network	1	NCF (k=2)	123	54	49
U.S. long distance network	1	LWF (k=2)	112	65	54
U.S. long distance network	1	NCF (k=3)	118	52	46
U.S. long distance network	1	LWF (k=3)	104	61	51
U.S. long distance network	2	NCF (k=1)	98	52	50
U.S. long distance network	2	LWF (k=1)	85	58	54
U.S. long distance network	2	NCF (k=2)	89	49	48
U.S. long distance network	2	LWF (k=2)	73	52	50
U.S. long distance network	2	NCF (k=3)	86	47	45
U.S. long distance network	2	LWF (k=3)	69	50	47
U.S. long distance network	3	NCF (k=1)	79	50	50
U.S. long distance network	3	LWF (k=1)	67	53	51
U.S. long distance network	3	NCF (k=2)	72	48	48
U.S. long distance network	3	LWF (k=2)	60	49	48
U.S. long distance network	3	NCF (k=3)	70	46	45
U.S. long distance network	3	LWF (k=3)	57	47	46

5.2.3 Dependency of location of MCLS nodes

I examine the impact of MCLS node location since their placement in the WRMD mesh network affects the number of required wavelengths. I observe the most and fewest number of required wavelengths, which are averaged over those with 100 randomly generated and different sets of requested lightpaths, for all combinations of MCLS node locations in each network. I use the heuristic RWA scheme with both policies with k, the maximum number of paths, set to 3 for the three different topologies with 300 requested lightpaths, as shown in Fig. 3.4.

Table 5.3 shows the number of required wavelengths of the heuristic RWA scheme with the two different locations of MCLS nodes for the three different topologies with 300 requested lightpaths. Moreover, the number of required wavelengths of the heuristic RWA scheme with the average of all combinations of MCLS nodes from Table 5.2 is also included for easy comparison in Table 5.3. The heuristic RWA scheme with both policies and the best MCLS node locations achieves the least number of required wavelengths, while that with both policies and the worst MCLS node locations achieves the most number of required wavelengths. In the case of no-regeneration, the heuristic RWA scheme with the LWF policy, which demands fewer required wavelengths than the NCF policy, is considered. The heuristic RWA scheme with the LWF policy and the best MCLS node locations reduces the number of required wavelengths by at least 32%, 28%, and 60% from that with the LWF policy and the worst MCLS node locations for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively. If regeneration is used, the heuristic RWA scheme with the NCF policy and two regenerations, which demands fewer required wavelengths than the LWF policy, is investigated. The heuristic RWA scheme with the NCF policy and the best MCLS node locations reduces the number of required wavelengths by at least 12%, 19%, and 10% from that with the NCF policy and the worst MCLS node locations for the Synthetic network, European COST 239 network, and U.S. long distance network, respectively.

From Table 5.3 I present the best locations, where a suitable policy is employed with each regeneration condition. In the case of no-regeneration, the best MCLS node locations in the Synthetic network are node 7 for one MCLS node, nodes 3 and 4 for two MCLS nodes, and nodes 4, 5, and 8 for three MCLS nodes. For the European COST 239 network, the best MCLS node locations are node 3 for one MCLS node, nodes 2 and 5 or nodes 5 and 7 for two MCLS nodes, and nodes 2, 4, and 10 for three MCLS nodes. Additionally, the best MCLS node locations in the U.S. long distance network are node 8 for one MCLS node, nodes 6 and 28 for two MCLS nodes, and nodes 2, 17, and 27 or nodes 5, 17, and 27 or nodes 7, 12, and 27 or nodes 8, 10, and 27 or nodes 10, 17, and 27 for three MCLS nodes.

If regeneration is used, the best MCLS node locations in the Synthetic network are node 8 for one MCLS node, nodes 6 and 8 for two MCLS nodes, and nodes 4, 6, and 8 for three MCLS nodes. For the European COST 239 network, the best MCLS node locations are node 2 for one MCLS node, nodes 2 and 7 for two MCLS nodes, and nodes 1, 2, and 10 for three MCLS nodes. Additionally, the best MCLS node locations in the U.S. long distance network are node 27 for one MCLS node, nodes 26 and 28 or nodes 27 and 28 for two MCLS nodes, and nodes 25, 27, and 28 for three MCLS nodes.

5.2.4 Comparison of NCF and LWF policies

As shown in Table 5.4, if the maximum number of paths is set at $k = 1$, the NCF policy achieves better performance than the LWF policy for the networks with one MCLS node and without carrier regeneration, since the LWF policy may sometimes lose the benefit of optical carrier duplication during lightpath selection. For the networks with multiple MCLS nodes and without carrier regeneration, the LWF policy outperforms the NCF policy, since it has more chance to avoid the overlapping of optical carrier connections while the NCF policy wastes fiber for optical carrier connections when the location of MCLS nodes is not suitable. For the networks with carrier regeneration, the NCF policy outperforms the other policy, since it creates lightpath chains with the shortest length. For this reason, it has more chance to avoid the overlapping of optical connections when the number of carrier regenerations increases. Due to the overlapping of optical connections, the LWF policy has also less chance to reuse optical carriers. In addition, since the LWF policy yields lightpath chains whose average length is longer than that

Table 5.3: Comparison of locations of MCLS nodes with 300 requested lightpaths.

Network topology	Number of MCLS nodes	Policy	Worst location	Best location	Average of combinations
Synthetic network	1	LWF without regeneration (k=3)	56	38	45
		NCF with two regenerations (k=3)	24	21	23
	2	LWF without regeneration (k=3)	42	27	35
		NCF with two regenerations (k=3)	26	21	23
	3	LWF without regeneration (k=3)	40	26	31
		NCF with two regenerations (k=3)	26	20	23
European COST 239 network	1	LWF without regeneration (k=3)	49	35	44
		NCF with two regenerations (k=3)	26	21	23
	2	LWF without regeneration (k=3)	44	27	33
		NCF with two regenerations (k=3)	27	21	23
	3	LWF without regeneration (k=3)	38	23	28
		NCF with two regenerations (k=3)	27	20	23
U.S. long distance network	1	LWF without regeneration (k=3)	171	68	104
		NCF with two regenerations (k=3)	60	43	46
	2	LWF without regeneration (k=3)	150	46	69
		NCF with two regenerations (k=3)	48	43	45
	3	LWF without regeneration (k=3)	128	44	57
		NCF with two regenerations (k=3)	48	43	45

Table 5.4: Comparison between NCF and LWF policies when maximum number of paths is one, $k = 1$.

Number of regenerations \ Number of MCLS nodes	1	2	3
0	NCF	LWF	LWF
1	NCF	NCF	NCF
2	NCF	NCF	NCF

under than the NCF policy when the number of carrier regenerations increases, it has less chance to avoid lightpath chain overlap.

In the case of $k > 1$, the LWF policy achieves better performance than the NCF policy for the networks without carrier regeneration, since it has more chance to avoid optical connection overlap when selecting the requested lightpaths that do not collide with each other. For the networks with carrier regeneration, the NCF and LWF policies with KSP have similar effectiveness, since both policies with KSP have more chance to avoid optical connection overlap.

5.3 Summary

The heuristic RWA scheme for WRMD mesh networks that support multiple MCLS nodes to minimize the number of wavelengths required for lightpath establishment was proposed. It consists of a routing algorithm and a wavelength assignment algorithm; they are run separately to solve the RWA problem. I use the KSP algorithm to realize alternate routing. The wavelength assignment algorithm has two steps. The first step is to create chains of lightpaths and the second step is to assign a wavelength to each lightpath chain. Moreover, two lightpath selection policies, NCF and LWF, are introduced to create the lightpath chains. The results showed that the heuristic RWA scheme with one regeneration and either of the lightpath selection policies reduces the number of required wavelengths by at least 44% from that without regeneration. The scheme with the

LWF policy achieves better performance than that with the NCF policy if regeneration is not used, while the scheme with the NCF policy outperforms that with the LWF policy in the cases of one and two regenerations. Furthermore, the heuristic RWA scheme with multiple MCLS nodes reduces the number of required wavelengths by at least 35% from that with one MCLS node. From the network designer's point of view, the number of carrier regenerations is more valuable than the number of MCLS nodes. In addition, I observed that optimizing MCLS node location also reduces the number of required wavelengths.

Chapter 6

Optimization approach in multi-domain optical networks

This chapter first presents an Integer Linear Programming (ILP) model for survivable lightpath provisioning, called two-phase lightpath provisioning, to handle dated or inaccurate routing information as well as to support various types of traffic demands in multi-domain optical networks. The optimization approach employs an ILP formulation for survivable lightpath provisioning in multi-domain optical networks to minimize the cumulative cost of a set of paths, and the full-mesh topology abstraction approach for handling dated or inaccurate routing information. Therefore, I formulate the survivable lightpath provisioning problem as a two-phase hierarchical ILP problem based on hierarchical path computation with the full-mesh topology abstraction and a priori knowledge of requests. All wavelength division multiplexing (WDM) domains are assumed to be all-optical with full wavelength conversion at optical cross-connect (OXC) nodes at borders. Furthermore, three different protection strategies are considered with varying degrees of primary and backup route separation. The proposed approach works in two phases, as shown in Fig. 6.1. In the first phase, I solve the ILP problem to obtain the optimal solution on an inter-domain topology and then feed the results as intra-domain requests and solve the ILP problem to obtain the optimal solution on each related domain in the second phase. Finally, I concatenate all the intra-domain solutions along routing sequences. Therefore, the optimal cumulative cost of a set of paths is obtained.

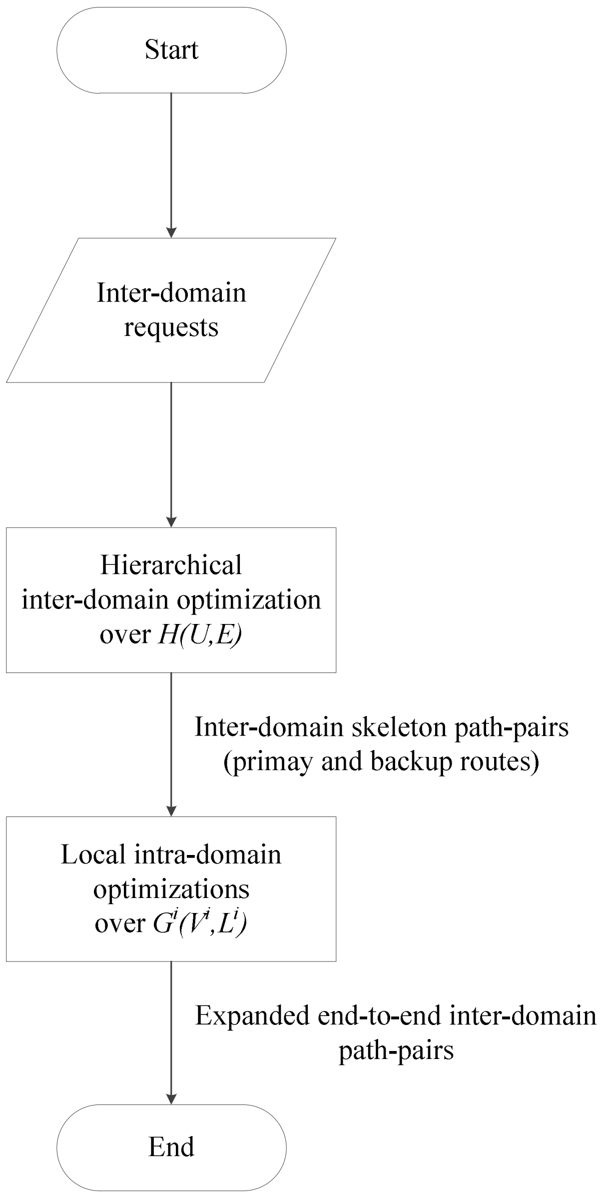


Figure 6.1: Flowchart of two-phase lightpath provisioning.

6.1 Mathematical model

6.1.1 Terminologies

The requisite notation and ILP formulation are presented below. Consider an optical WDM network with D domains where the i-th domain has n^i OXC nodes and b^i border OXC nodes. This network is represented by a set of domain subgraphs, $G^i(V^i, L^i)$, where $V^i = \{v_1^i, v_2^i, \ldots\}$ is the set of OXCs in domain i and $L^i = \{l_{jk}^{ii}\}$ $(1 \leq i \leq D, 1 \leq j, k \leq n^i)$ is the set of physical intra-domain links between node v_j^i and v_k^i with capacity $C_{i,jk}^L$. $\{c_{jk}^{ii}\}$ is the set of physical intra-domain link cost. The set of physical inter-domain links $\{l_{km}^{ij}\}$ $(1 \leq i, j \leq D, 1 \leq k \leq b^i, 1 \leq m \leq b^j)$ is defined between border nodes in separate domains, i.e., v_k^i and $v_m^j, i \neq j$. $\{c_{km}^{ij}\}$ is the set of physical inter-domain link cost.

For a hierarchical routing setup, a global abstract topology is defined using domain abstraction. This graph is denoted by $H(U, E)$, where U is the set of all border nodes and E is the set of global links. E comprises all physical inter-domain links as well as abstract intra-domain links, i.e., topology abstraction reduces a domain to a mesh of abstract links between border OXC pairs. Capacity of link in $H(U, E)$ is denoted by $C_{ij,km}^G$.

Requests for inter-domain and intra-domain networks are defined as follows. Let N be the number of multi-domain requests; the n-th multi-domain request is given by the 3-tuple (s_n, d_n, r_n), where s_n is the source, d_n is the destination, and r_n is the number of requested wavelengths. Similarly, let N' be the number of intra-domain requests; the n'-th intra-domain request is given by the 3-tuple $({s'}_{n'}, {d'}_{n'}, {r'}_{n'})$, where ${s'}_{n'}$ is the source, ${d'}_{n'}$ is the destination, and ${r'}_{n'}$ is the number of requested wavelengths.

Decision variables in survivable lightpath provisioning problems to represent routing states are defined as follows. The variable x_{km}^{nij} denotes the number of wavelengths routed over link l_{km}^{ij} for primary routes of request n, y_{km}^{nij} denotes the number of wavelengths routed over link l_{km}^{ij} for backup routes of request n, p_{km}^{nij} is a binary variable, where it is set to 1 if the link l_{km}^{ij} is passed by the primary routes of request n, and zero otherwise. b_{km}^{nij} is a binary variable, where, it is set to 1 if the link l_{km}^{ij} is passed by the backup routes of request n, and zero otherwise. Note that p_{km}^{nij} and b_{km}^{nij} are used only in the hierarchical abstract graph, $H(U, E)$. a_{jk}^{nii} is a binary variable, where, it is set to 1 if the link l_{jk}^{ii} is passed by the intra-domain routes of request n', and zero otherwise.

6.1.2 Inter-domain lightpath provisioning

The first phase of the proposed approach is implemented over the hierarchical abstract graph, $H(U, E)$. Namely, the objective (6.1) is the minimization of the cumulative cost of a set of paths, which includes the primary and backup routes.
Objective function

$$\min \sum_{n \in N} \sum_{l_{km}^{ij} \in E} \left(c_{km}^{ij} x_{km}^{nij} + c_{km}^{ij} y_{km}^{nij} \right) \tag{6.1}$$

To evaluate the cumulative cost of a set of paths, three different protection strategies, namely same domain sequence, link disjoint, and domain disjoint, are considered with varying levels of primary and backup route separation. All protection strategies ensure full protection against single link failures.

6.1.2.1 Same domain sequence (SDS) strategy

This strategy selects the primary and backup routes along the same domain sequence. This strategy is shown in Fig. 1.2 for the backup route 1. The constraints of the SDS strategy are defined as follows.
Constraints

$$\sum_{(j,m):l_{km}^{ij} \in E} x_{km}^{nij} - \sum_{(j,m):l_{mk}^{ji} \in E} x_{mk}^{nji} = \begin{cases} r_n, & \text{if} \quad v_k^i = s_n, \\ -r_n, & \text{if} \quad v_k^i = d_n, n \in N \\ 0, & \text{otherwise,} \end{cases} \tag{6.2}$$

$$\sum_{(j,m):l_{km}^{ij} \in E} y_{km}^{nij} - \sum_{(j,m):l_{mk}^{ji} \in E} y_{mk}^{nji} = \begin{cases} r_n, & \text{if} \quad v_k^i = s_n, \\ -r_n, & \text{if} \quad v_k^i = d_n, n \in N \\ 0, & \text{otherwise,} \end{cases} \tag{6.3}$$

$$\sum_{n \in N} \left(x_{km}^{nij} + y_{km}^{nij} \right) \leq C_{ij,km}^{G}, l_{km}^{ij} \in E \tag{6.4}$$

$$p_{km}^{nij} + b_{km}^{nij} \leq 1, n \in N, l_{km}^{ij} \in E \tag{6.5}$$

$$\begin{gathered}\sum_{(k,m):l_{km}^{ij} \in E} p_{km}^{nij} = \sum_{(k,m):l_{km}^{ij} \in E} b_{km}^{nij}, \\ n \in N, i \in D, j \in D, i \neq j\end{gathered} \tag{6.6}$$

$$\sum_{l_{km}^{ij} \in E} p_{km}^{nij} \leq \sum_{l_{km}^{ij} \in E} b_{km}^{nij}, n \in N \tag{6.7}$$

$$x_{km}^{nij} \leq p_{km}^{nij} C_{ij,km}^{G}, n \in N, l_{km}^{ij} \in E \tag{6.8}$$

$$x_{km}^{nij} \geq p_{km}^{nij}, n \in N, l_{km}^{ij} \in E \tag{6.9}$$

$$y_{km}^{nij} \leq b_{km}^{nij} C_{ij,km}^{G}, n \in N, l_{km}^{ij} \in E \tag{6.10}$$

$$y_{km}^{nij} \geq b_{km}^{nij}, n \in N, l_{km}^{ij} \in E \tag{6.11}$$

$$x_{km}^{nij} \in \{0, 1, 2, \ldots\}, n \in N, l_{km}^{ij} \in E \tag{6.12}$$

$$y_{km}^{nij} \in \{0, 1, 2, \ldots\}, n \in N, l_{km}^{ij} \in E \tag{6.13}$$

$$p_{km}^{nij} \in \{0, 1\}, n \in N, l_{km}^{ij} \in E \tag{6.14}$$

$$b_{km}^{nij} \in \{0, 1\}, n \in N, l_{km}^{ij} \in E \tag{6.15}$$

Constraints (6.2) and (6.3) represent the flow conservation constraint between the incoming and outgoing flows at each (border) node in the abstract graph for primary and backup routes, respectively. Constraint (6.4) restricts the total relative traffic load carried on an inter-domain link to under the capacity, i.e., less than $C_{ij,km}^{G}$. Constraint (6.5) sets up the link-disjoint restriction. Constraint (6.6) ensures that both primary and backup routes traverse the same sequence of domains. Constraint (6.7) ensures that the primary route is always shorter than the backup route. Constraints (6.8)-(6.11) determine whether a link is supporting any primary and backup routes, respectively. Constraints (6.12)-(6.15) represent integrality constraints.

6.1.2.2 Link-disjoint (LD) strategy

This strategy allows the primary and backup route sequences to traverse common intermediate domains as long as the inter-domain links are unique. In other words, this strategy allows the primary and backup routes to use partially overlapped domain sequences, i.e., mixed domain sequences. This is shown in Fig. 1.2 for backup route 2. The constraints of the LD strategy are based on the same constraints as the SDS strategy except for constraint (6.6).

Constraints

Constraints (6.2)-(6.5)

Constraints (6.7)-(6.15)

6.1.2.3 Domain-disjoint (DD) strategy

This strategy selects the primary and backup routes without any common physical inter-domain links and intermediate domains. This is shown in Fig. 1.2 for backup route 3. Note that the constraints of the DD strategy is also based on the same SDS strategy except for constraint (6.6), which is replaced by constraint (6.16). Constraint (6.16) forces the backup routes to be domain-joint.

Constraints

Constraints (6.2)-(6.5)

$$\sum_{(k,m):l_{km}^{ij} \in E} \left(p_{km}^{nij} + b_{km}^{nij}\right) \leq 1, \quad n \in N, i \in D, j \in D, i \neq j \tag{6.16}$$

Constraints (6.7)-(6.15)

6.1.3 Intra-domain lightpath provisioning

After solving an ILP problem associated with each protection strategy, presented in Subsection 3.3, I can obtain a set of skeleton inter-domain routes for the requested connections over the abstract topology, $H(U, E)$. This information can then be used to determine the required number of all-optical sub-path segments that must be computed between all border node pairs in each related domain, i.e., by simply counting the number of skeleton lightpaths traversing the respective abstract links. Therefore, the second phase of the lightpath provisioning performs domain expansion by optimizing the domain-traversing sub-paths over the local domain graphs, $G^i(V^i, L^i)$. The primary and backup routes are treated in the same way since both routes obtained from the abstract topology are disjoint. To achieve this, I utilize the following ILP.

Objective function

$$\min \sum_{n' \in N'} \sum_{l_{jk}^{ii} \in L^i} c_{jk}^{ii} x_{jk}^{n'ii} \tag{6.17}$$

Constraints

$$\sum_{k:l_{jk}^{ii} \in L^i} x_{jk}^{n'ii} - \sum_{k:l_{jk}^{ii} \in L^i} x_{kj}^{n'ii} = \begin{cases} r'_{n'}, & \text{if} \quad v_j^i = s'_{n'}, \\ -r'_{n'}, & \text{if} \quad v_j^i = d'_{n'}, n' \in N' \\ 0, & \text{otherwise}, \end{cases} \tag{6.18}$$

$$\sum_{n' \in N'} a_{jk}^{n'ii} \leq 1, l_{jk}^{ii} \in L^i \tag{6.19}$$

$$x_{jk}^{n'ii} \leq a_{jk}^{n'ij} C_{i,jk}^{L}, n' \in N', l_{jk}^{ii} \in L^i \tag{6.20}$$

$$x_{jk}^{n'ii} \geq a_{jk}^{n'ij}, n' \in N', l_{jk}^{ii} \in L^i \tag{6.21}$$

$$x_{jk}^{n'ii} \in \{0, 1, 2, \ldots\}, n' \in N', l_{jk}^{ii} \in L^i \tag{6.22}$$

$$a_{km}^{n'ii} \in \{0, 1\}, n' \in N', l_{jk}^{ii} \in L^i \tag{6.23}$$

Objective (6.17) is to minimize the cost of the path. Constraint (6.18) represents the flow conservation constraint between the incoming and outgoing flows at each OXC node in a domain. Constraint (6.19) sets up the link-disjoint restriction. Constraints (6.20)-(6.21) determine whether a link is supporting any routes. Constraints (6.22)-(6.23) represent integrality constraints.

Finally, the complete end-to-end lightpath route sequences are then identified by concatenating all intra-domain segments (with the same flow index) with their respective inter-domain links in $H(U, E)$.

6.2 Results and discussions

I investigate the cumulative cost, the hop counts, and the ratio of successful and unsuccessful requests for the three different protection strategies in two points: the effect of traffic demands and the effect of link capacity.

The evaluation environment and conditions are described as follows. The two-phase lightpath provisioning scheme is solved by the CPLEX Interactive Optimizer 12.6.1.0 [51]. I consider a small 6-node network, an NSFNET network, and a Grid network, as shown in Fig. 6.2. Each node represents a domain consisting of 7 to 10 nodes, which include 2 to 4 border nodes. In addition to these networks, I compare these protection strategies on an augmented 6-node network and an augmented NSFNET network in order to analyze the performance in a more connected multi-domain network. Each node represents a domain consisting of 7 to 10 nodes, which include 4 to 8 border nodes. All nodes in each domain are connected in a mesh topology. The inter-domain links are randomly generated according to the number of border nodes in the corresponding domains. The costs on the intra-domain links are randomly generated with a uniform distribution from 1 to 10, and the costs on the inter-domain links are randomly generated with a uniform distribution from 20 to 30. I average the values over the cumulative cost and hop counts for requests generated between all pairs of border nodes. All tests are performed for equivalent inter-domain and intra-domain link capacities, i.e., $C^G_{ij,km} = C^L_{i,jk} = 8$. Overall, the results show that the LD strategy gives notably better performance than the other strategies.

6.2.1 Effect of traffic demands

I examine the effect of traffic demands in two cases: (i) the number of requested wavelengths is less than link capacity, and (ii) the number of requested wave-

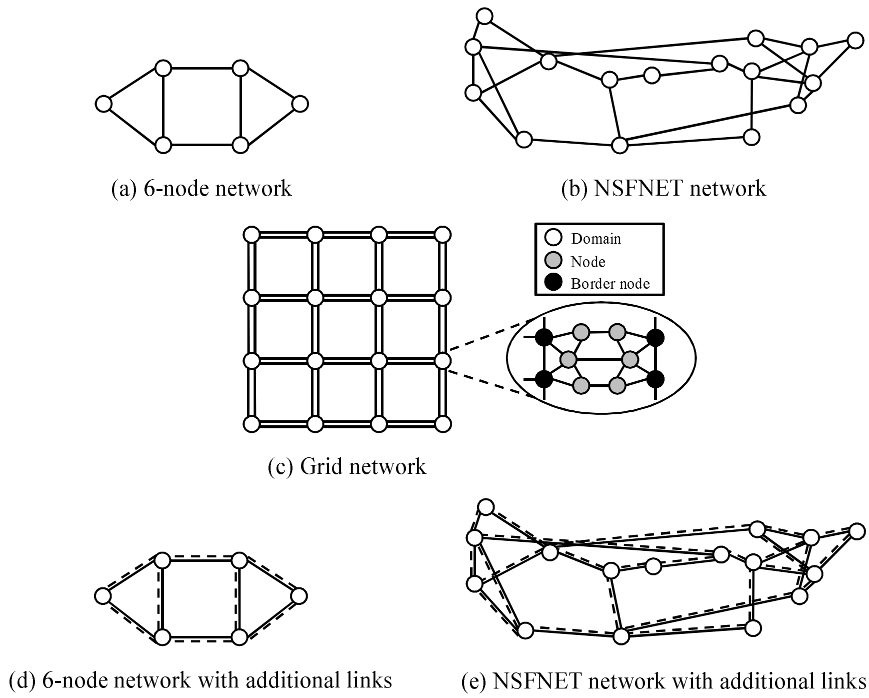


Figure 6.2: Examined networks.

lengths is greater than link capacity. The numbers of requested wavelengths are 1 for the first case and 16 for the second case.

Figure 6.3 shows the average cumulative cost for the three different protection strategies when the number of requested wavelengths is less than link capacity. It notes that the average cumulative cost of the SDS strategy in 6-node and NSFNET networks has no feasible solution. Since each domain pair has only one inter-domain link, the SDS strategy is not able to find any primary and backup routes along the same domain sequence. The average cumulative cost of the LD and DD strategies have, for the 6-node network, the same value because all requests are served on the same primary and backup routes. In the NSFNET network, the LD strategy has slightly lower average cumulative cost than the DD strategy. The DD strategy has, for the Grid network, greater average cumulative cost than the others because the DD strategy chooses the primary and backup routes such that there is a greater chance to include inter-domain links than is true with the other strategies. For augmented 6-node and augmented NSFNET networks, the SDS strategy is able to find the primary and backup routes along the same domain sequence since there are more connected links. However, the LD strategy has lower average cumulative cost than the other strategies.

The resource usage rates are estimated by measuring the average hop counts. Figure 6.4 shows the average hop counts for the three different protection strategies when the number of requested wavelengths is less than link capacity. It notes that the average hop counts of the SDS strategy in 6-node and NSFNET networks have no feasible solution. The average hop counts of the LD and DD strategies have, for the 6-node network, the same value, while those of the LD strategy are slightly less in the NSFNET network than the DD strategy. Moreover, the average hop counts of the SDS strategy are, for the Grid network, greater than those of the others because this strategy generates longer intra-domain routes when the primary and backup paths traverse same domains. In addition, the average hop counts of the LD strategy are, for augmented 6-node and augmented NSFNET networks, less than those of the others.

Figure 6.5 shows the ratio of successful requests for the three different protection strategies when the number of requested wavelengths is less than link capacity. The ratios of successful requests of the LD and DD strategies in 6-node and NSFNET networks have the same value, while the SDS strategy has no feasible solution. The Grid and augmented 6-node networks allow all connection requests to be established. For the augmented NSFNET network, the ratios of successful requests of all the strategies decrease, since they are not able to find any primary and backup sub-paths.

Unsuccessful requests can be caused by the inter-domain lightpath provisioning process in the first phase or the intra-domain lightpath provisioning process in the second phase. Figure 6.6 shows the ratio of unsuccessful requests for the three different protection strategies when the number of requested wavelengths is less than link capacity. The ratio of unsuccessful requests of the SDS strategy in 6-node and NSFNET networks derives from the inter-domain lightpath provisioning process, while those of all the strategies in augmented NSFNET network derive from the intra-domain lightpath provisioning process.

Figure 6.7 shows the average cumulative cost for the three different protection strategies when the number of requested wavelengths is greater than link capacity.

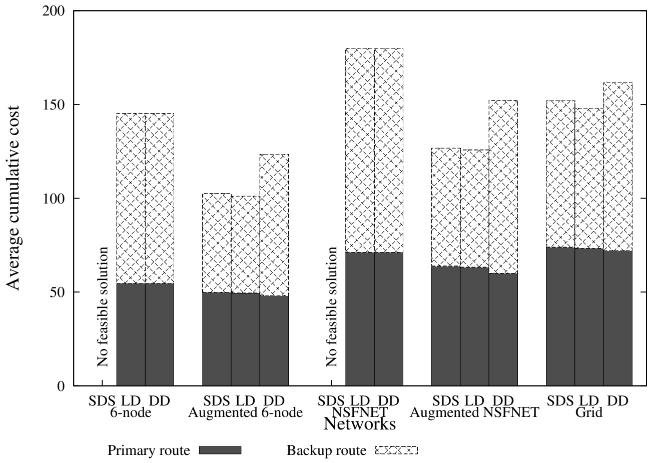


Figure 6.3: Average cumulative cost ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 1$).

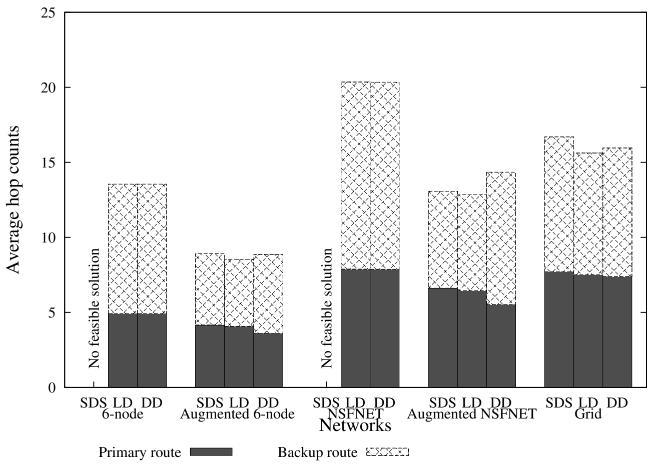


Figure 6.4: Average hop counts ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 1$).

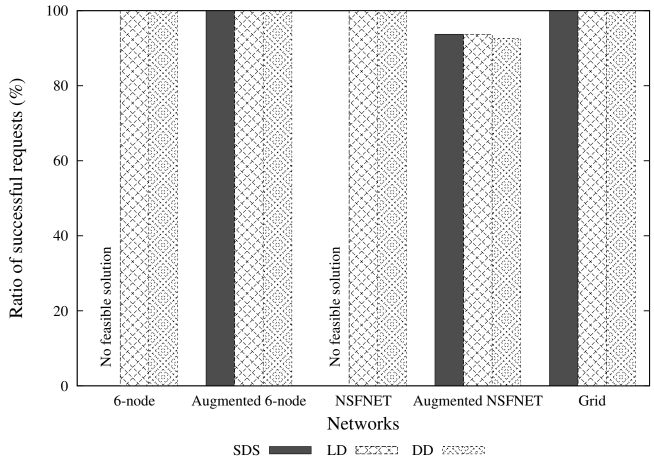


Figure 6.5: Successful request ratio ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 1$).

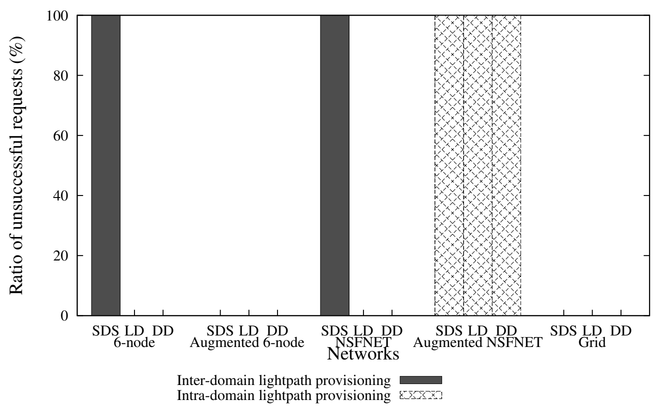


Figure 6.6: Unsuccessful request ratio ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 1$).

If the number of requested wavelengths is greater than link capacity, the proposed approach allows traffic to be split among feasible primary and backup routes. It is noted that the average cumulative cost of the SDS, LD, and DD strategies in 6-node network have no feasible solution due to the lack of inter-domain links. For the NSFNET network, the LD and DD strategies have slightly different average cumulative costs. For the Grid network, the DD strategy has greater average cumulative cost than the others because the DD strategy chooses primary and backup routes such that they have a greater chance to include inter-domain links than the other strategies. For the augmented 6-node network, the SDS and LD strategies have the same average cumulative cost while the DD strategy has no feasible solution due to the lack of disjoint aggregated links. For the augmented NSFNET network, the LD and DD strategies have slightly different average cumulative costs while the DD strategy has greater average cumulative cost than the others.

Figure 6.8 shows the average hop counts for the three different protection strategies when the number of requested wavelengths is greater than link capacity. It is noted for the 6-node network that the average hop counts of the SDS, LD, and DD strategies have no feasible solution, while those of the LD and DD strategies are slightly different for the NSFNET network. For the Grid network, the DD strategy has lower average hop counts than others because the SDS and LD strategies generate longer intra-domain routes when the primary and backup paths traverse the same domains. Moreover, only a few connection requests can be established under the DD strategy. For the augmented 6-node network, the average hop counts of the SDS and LD strategies are slightly different. The average hop counts of the LD strategy are, for the augmented NSFNET network, less than those of the others.

Figure 6.9 shows the ratio of successful requests for the three different protection strategies when the number of requested wavelengths is greater than link capacity. The ratios of successful requests of the SDS, LD, and DD strategies have no feasible solution for the 6-node network. The LD and DD strategies have, for the NSFNET network, the same ratio of successful requests, while the SDS strategy has no feasible solution. For the Grid network, the SDS and LD strategies have greater ratios of successful requests than the other strategy because the DD strategy needs to have more domain-disjoint routes. The SDS and LD strategies have, for the augmented 6-node network, the same ratio of successful requests, while the DD strategy has no feasible solution. For the augmented NSFNET network, the LD strategy has greater ratio of successful requests than the others, while the DD strategy has lower ratio of successful requests than the others.

Figure 6.10 shows the ratio of unsuccessful requests for the three different protection strategies when the number of requested wavelengths is greater than link capacity. The ratios of unsuccessful requests of all the strategies in 6-node network derive from the inter-domain lightpath provisioning process. For the NSFNET network, the ratio of unsuccessful requests of the SDS strategy derives from the intra-domain lightpath provisioning process, while those of the LD and DD strategies derive from both inter-domain and intra-domain lightpath provisioning processes. The ratios of unsuccessful requests of all the strategies, for the Grid network, derive from both inter-domain and intra-domain lightpath provisioning processes. For the augmented 6-node network, the ratios of unsuccessful requests of the SDS and LD strategies derive from the intra-domain lightpath provisioning process, while that of the DD strategy derives from the inter-domain lightpath provisioning process. For the augmented NSFNET network, the ratios of unsuccessful requests of the SDS and LD strategies derive from the intra-domain lightpath provisioning process, while that of the DD strategy derives from both inter-domain and intra-domain lightpath provisioning processes.

6.2.2 Effect of link capacity

As tests are performed earlier, the inter-domain links have same the number of wavelengths as intra-domain links. In this subsection, I examine the effect of link capacity. The inter-domain links have twice the number of wavelengths as intra-domain links, i.e., $C^G_{ij,km} = 2C^L_{i,jk} = 16$.

Figures 6.11 - 6.14 show the average cumulative cost, average hop counts, ratio of successful requests, and ratio of unsuccessful requests for the three different protection strategies, respectively, when the inter-domain links have twice the

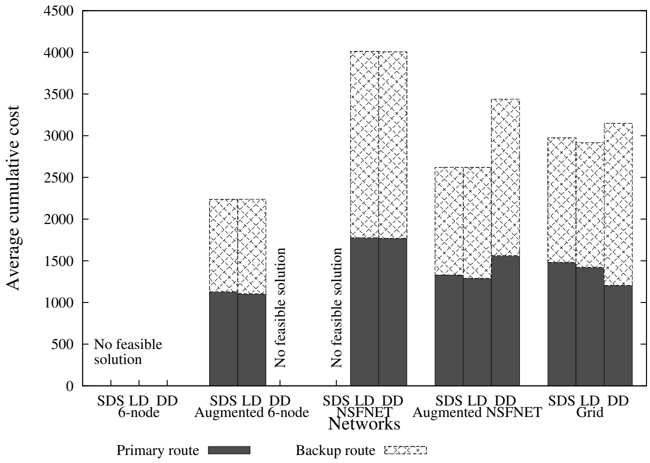


Figure 6.7: Average cumulative cost ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 16$).

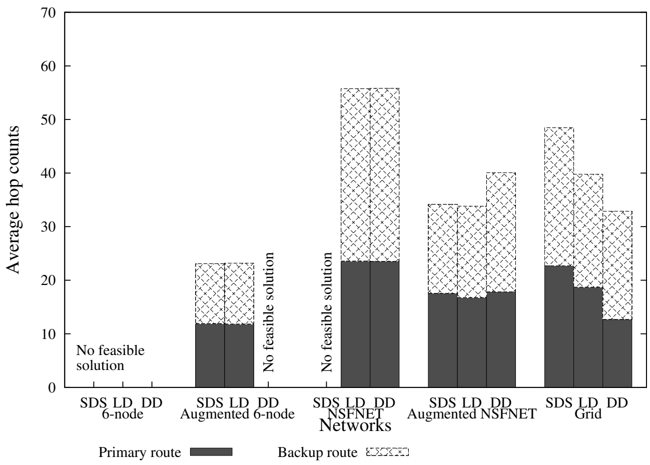


Figure 6.8: Average hop counts ($C^G_{ij,km} = C^L_{i,jk} = 8$ and $r_n = 16$).

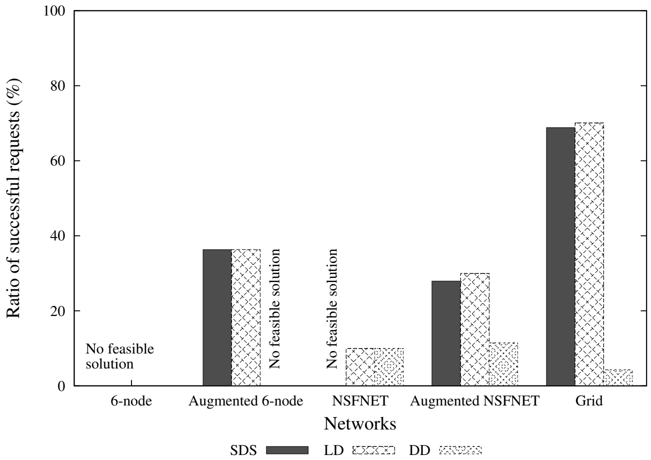


Figure 6.9: Successful request ratio ($C^{G}_{ij,km} = C^{L}_{i,jk} = 8$ and $r_n = 16$).

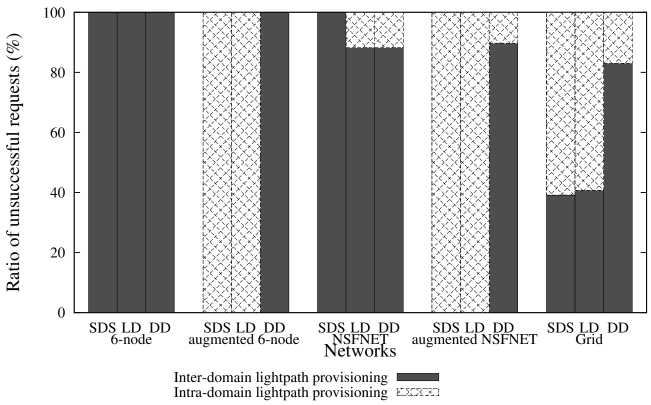


Figure 6.10: Unsuccessful request ratio ($C^{G}_{ij,km} = C^{L}_{i,jk} = 8$ and $r_n = 16$).

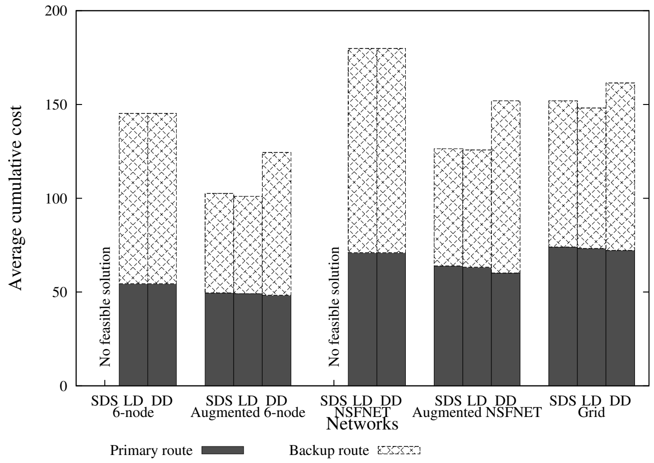


Figure 6.11: Average cumulative cost ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 1$).

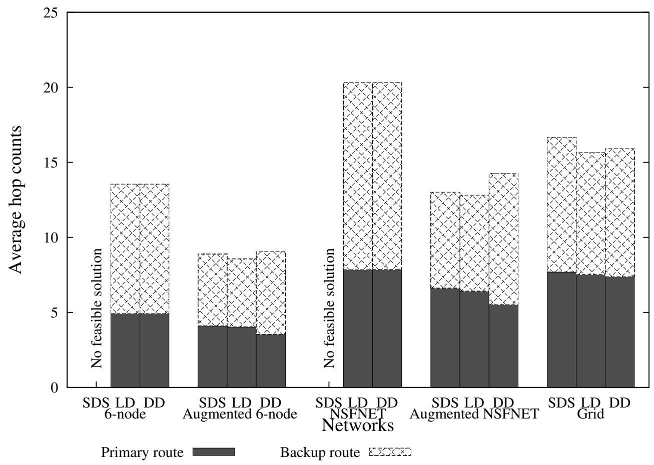


Figure 6.12: Average hop counts ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 1$).

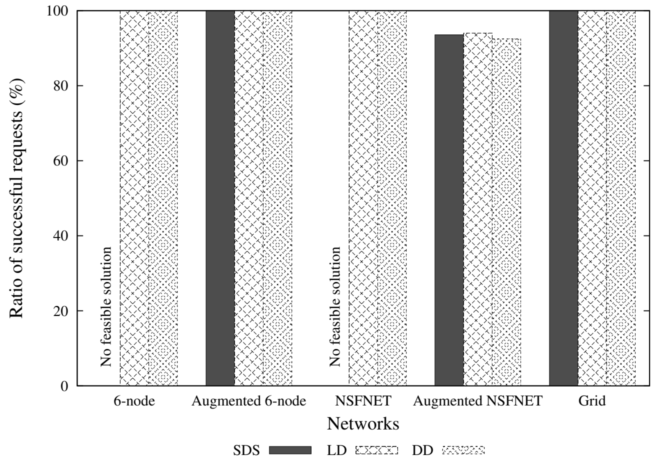


Figure 6.13: Successful request ratio ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 1$).

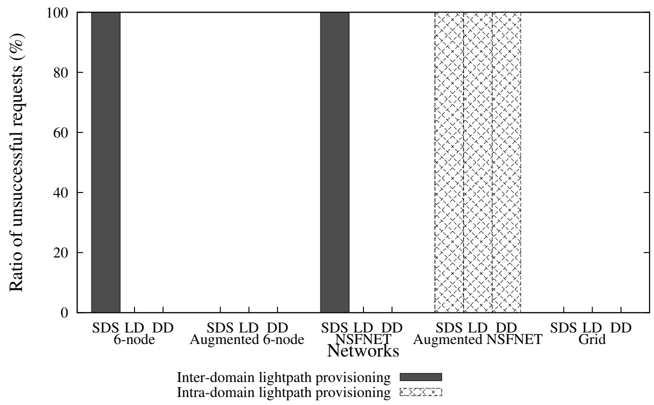


Figure 6.14: Unsuccessful request ratio ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 1$).

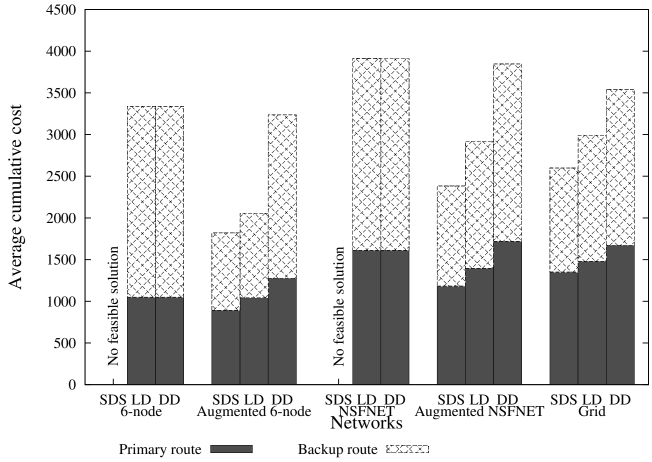


Figure 6.15: Average cumulative cost ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 16$).

number of wavelengths as intra-domain links and the number of requested wavelengths is less than link capacity. I observe similar behavior of them when the inter-domain links have the same number of wavelengths as intra-domain links, since the number of requested wavelengths is less than link capacity.

Figure 6.15 shows the average cumulative cost for the three different protection strategies when the inter-domain links have twice the number of wavelengths as intra-domain links and the number of requested wavelengths is greater than link capacity. It is noted that the average cumulative cost of the LD and DD strategies are found in 6-node network, while those of both strategies have no feasible solution when the inter-domain links have the same number of wavelengths as intra-domain links. Similarly, the average cumulative cost of the DD strategy is found in augmented 6-node network. Overall, the average cumulative cost of all the strategies reduce as the number of used inter-domain links decreases. However, for the Grid network, the average cumulative cost of the DD strategy increases as the ratio of successful requests increases.

Figure 6.16 shows the average hop counts for the three different protection strategies when the inter-domain links have twice the number of wavelengths as intra-domain links and the number of requested wavelengths is greater than link capacity. It is noted that the average hop counts of the SDS and LD strategies increase slightly since these strategies generate longer intra-domain routes when

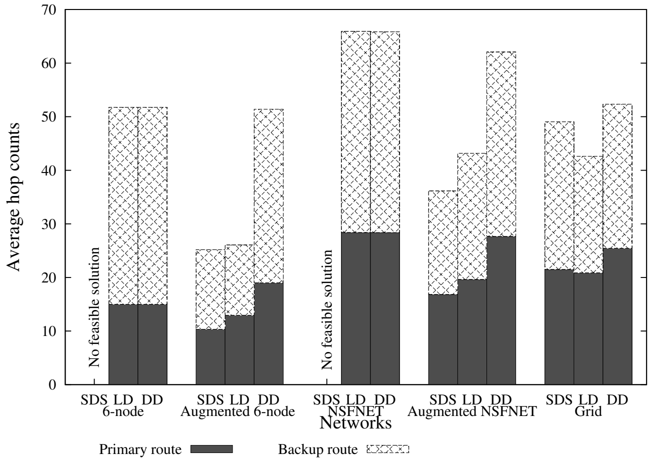


Figure 6.16: Average hop counts ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 16$).

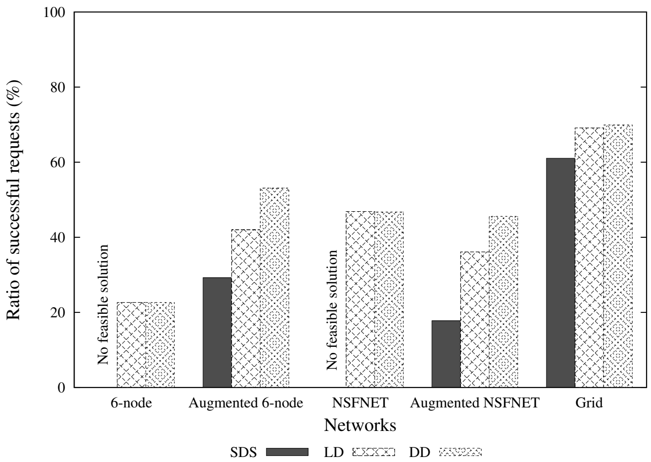


Figure 6.17: Successful request ratio ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 16$).

the primary and backup paths traverse the same domains. The average hop counts of the DD strategy decrease as the number of used inter-domain links decreases.

Figure 6.17 shows the ratio of successful requests for the three different protection strategies when the inter-domain links have twice the number of wavelengths as intra-domain links and the number of requested wavelengths is greater than link capacity. Overall, the ratios of successful requests of the LD and DD strate-

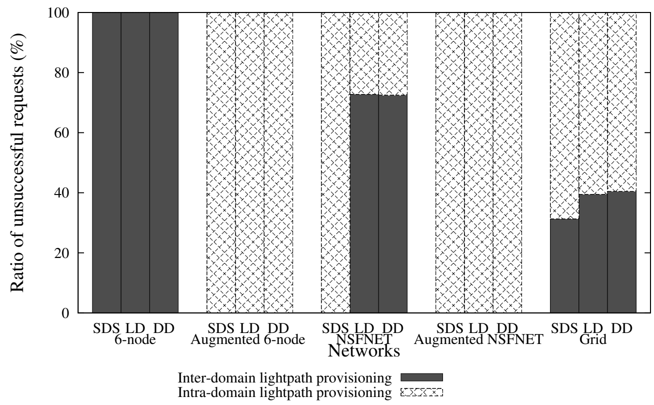


Figure 6.18: Unsuccessful request ratio ($C^G_{ij,km} = 2C^L_{i,jk} = 16$ and $r_n = 16$).

gies increase while that of the SDS strategy decreases.

Figure 6.18 shows the ratio of unsuccessful requests for the three different protection strategies when the inter-domain links have twice the number of wavelengths as intra-domain links and the number of requested wavelengths is greater than link capacity. It is noted that the ratios of unsuccessful requests deriving from the inter-domain provisioning process decrease, especially the DD strategy.

6.3 Summary

The two-phase lightpath provisioning approach that allows the traffic of multi-domain optical networks to be split so as to minimize the cumulative cost of a set of paths was proposed. The proposed approach employs an ILP formulation based on hierarchical path computation with full-mesh topology abstraction. The proposed approach consists of two phases. The first phase solves the ILP problem on an inter-domain topology and then feeds the results as intra-domain requests. The second phase solves the ILP problem on each related domain. Finally, I concatenate all intra-domain solutions along routing sequences. Three protection strategies, the SDS, LD, and DD strategies, were considered with varying levels of primary and backup route separation. In addition, I evaluated my approach from two points: the effect of traffic demands and the effect of link capacity. The results showed that the LD strategy gives notably better performance than the other strategies in both points. Therefore, the proposed approach can provide reference values to gauge the existing distributed heuristics.

Chapter 7

Conclusions and future works

7.1 Conclusions

This thesis introduces resource allocation schemes in optical networks. Two kinds of optical networks, which are WRMD network and multi-domain optical network, are considered.

First, a routing and wavelength assignment scheme for the WRMD mesh network that minimizes the number of required wavelengths for lightpath establishment is proposed. I focused on the static scenario, which assumes that lightpath setup requests are statically given in advance. The heuristic RWA scheme consists of a routing algorithm and a wavelength assignment algorithm, which are performed separately to solve the RWA problem. The shortest path routing policy is adopted in the routing decision. The wavelength assignment algorithm has two steps. The first step is to create chains of lightpaths and the second step is to assign a wavelength to each lightpath chain. In addition, three requested lightpath selection policies, random, NE, and NM policies, are introduced to create the lightpath chains. The results showed that the heuristic RWA scheme with one regeneration and the three requested lightpath selection policies reduces the number of required wavelengths by more than 30%. Moreover, the scheme with the NM policy and two regenerations reduces the number of required wavelengths by at least 50%, compared to that without carrier regeneration. In addition, I noted that suitable selection of the MCLS node location also reduces the number of required wavelengths. The number of required wavelengths in the WRMD network approaches that in the conventional OADM network if the allowable number of carrier regenerations is increased and the MCLS node location is optimum.

Nevertheless, for large-scale networks that must support increasing numbers of lightpaths, there may be a need to have more than one MCLS node to use wavelength resources efficiently. I proposed a routing and wavelength assignment scheme for WRMD mesh networks that support multiple MCLS nodes to minimize the number of wavelengths required for lightpath establishment. I use the KSP algorithm to realize alternate routing. The wavelength assignment algorithm has two steps. The first step is to create chains of lightpaths and the second step is to assign a wavelength to each lightpath chain. Moreover, two lightpath selection policies, NCF and LWF, are introduced to create the lightpath chains. The results showed that the heuristic RWA scheme with one regeneration and either of the lightpath selection policies reduces the number of required wavelengths by at least 44% from that without regeneration. The scheme with the LWF policy achieves better performance than that with the NCF policy if regeneration is not used, while the scheme with the NCF policy outperforms that with the LWF policy in the cases of one and two regenerations. Furthermore, the heuristic RWA scheme with multiple MCLS nodes reduces the number of required wavelengths by at least 35% from that with one MCLS node. In addition, I observed that optimizing MCLS node location also reduces the number of required wavelengths.

Second, I proposed a two-phase lightpath provisioning approach that allows the traffic of multi-domain optical networks to be split so as to minimize the cumulative cost of a set of paths. The proposed approach employs an ILP formulation based on hierarchical path computation with full-mesh topology abstraction. The proposed approach consists of two phases. The first phase solves the ILP problem on an inter-domain topology and then feeds the results as intra-domain requests. The second phase solves the ILP problem on each related domain. Finally, I concatenate all intra-domain solutions along routing sequences. Three protection strategies, the SDS, LD, and DD strategies, were considered with varying levels of primary and backup route separation. In addition, I evaluated my approach from two points: the effect of traffic demands and the effect of link capacity. The results showed that the LD strategy gives notably better performance than the other strategies in both points. Therefore, the proposed approach can provide reference values to gauge the existing distributed heuristics.

7.2 Future works

Future research and application trends of WRMD network architectures focus on performance and operation parameters such as channel number, channel spacing, etc. Currently, MCLS is still in the research/experimental stage. I expect that the number of optical carriers generated by the MCLS will vary from 100 to 10000 in the near future. The narrow channel spacing of optical carriers not only introduces physical impairments such as crosstalk, but also impacts on the transmission speed of each wavelength. Therefore, the development of narrow channel spacing presents challenges for MCLS in the future. Furthermore, since carrier quality is degraded after regeneration, the optical carrier reuse number must be further considered and improved to prevent excessive degradation of optical signal quality in future research.

In this thesis, I focused on the static scenario, which assumes that lightpath setup requests are statically given in advance. For the dynamic scenario, the complexity of dynamically managing the wavelengths increases in the WRMD network. That makes it difficult to design the RWA scheme, which becomes a challenging issue. This would be considered as the future work. Furthermore, since my RWA scheme only focuses on optical carriers from MCLS nodes or regeneration points, an RWA scheme considering the duplication of optical carriers along the route is needed to reduce the number of required wavelengths. Therefore, in the implementation of the RWA scheme considering the duplication of optical carriers along the route, the route of optical carrier connection not only starts from MCLS node or regeneration point, but also starts from a node along another route of optical carrier connection. That is, in the ILP model, the flow conservation constraints between the incoming and outgoing flows at each node for optical carrier connections must be reformulated.

Moreover, current optical networks strictly follow the fixed and coarse wavelength grids and channel spacings, which results in low spectrum utilizations and poor supports of high-speed transmission signals such as 400 Gb/s and beyond.

Therefore, MCLS is applicable for an elastic optical network (EON). Optical carriers are distributed to network nodes on demand as light sources through elastic reconfigurable optical add-drop multiplexers designed with the carrier-drop function. For this reason, researches on routing and spectrum allocation for EONs with MCLS must be conducted in future work.

For multi-domain optical networks, I addressed the survivable lightpath provisioning to resolve complete end-to-end primary and backup path pairs. However, the ILP approach does not offer practical computation times for large-scale networks. A heuristic scheme is needed to solve the survivable lightpath provisioning. Furthermore, since spare capacity allocation serves as one of the most critical tasks in optical networks, survivable lightpath provisioning based on shared backup path protection is needed in the future. Note that the survivable lightpath provisioning can be extended with non-linear provisions to handle disaster recovery scenarios with probabilistic multi-failure events. In addition, it is also applicable for regular bandwidth provisioning multi-domain networks and emerging EONs.

In current multi-domain optical networks relying on the path computation element (PCE) architecture, domain sequence computation can be performed through mechanisms. PCEs provides an evolutionary approach to software defined networking (SDN) enabling seamless inter-domain routing, flexible/customizable path computation, improved price/performance, and simplified operations in future networks. Therefore, the development of multi-domain SDN network is a key challenge to be further addressed and validated in the future.

Appendix A

Cost analysis

Cost calculation

For cost-effectiveness analysis [47], the cost of the single laser diode (LD), C_{LD}, is defined to equal c cost units. The costs of the wavelength selective switch (WSS), all-optical carrier extraction (ACE), and multi-carrier light source (MCLS) are defined as C_{WSS}, C_{ACE}, and C_{MCLS}, respectively. The cost of the MCLS includes the additional functions such as WSS and wavelength converters (WCs), while the cost of the optical carrier regenerator (OCR) consists of C_{WSS} and C_{ACE}. The coupler, multiplexer (MUX), and demultiplexer (DMUX) are common optical devices, which are employed in both wavelength-reusable multi-carrier-distributed (WRMD) and conventional optical add-drop multiplexer (OADM) networks, and their costs are not counted. The WRMD network becomes cost effective if the following conditions are true:

$$N \times c \times (K_1 + W) > N \times c \times (2K_1 + K_2) + K_3 \times c + N \times \Delta C \times W, \tag{A.1}$$

where N is the number of nodes in the network and W is the required number of wavelengths. K_1, K_2, and K_3 are the cost ratios of WSS, ACE, and MCLS to LD, respectively. ΔC is an incremental cost factor of WSS related to the number of wavelengths. In analysis, the values of K_1, K_2, K_3, and ΔC are set to 10, 10, 30, and 0.1, respectively. The WRMD network has lower cost than the conventional OADM network when W is larger than 30.

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Publications

List of Publications related to the dissertation

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