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Path Protection in Translucent WDM Optical Networks

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Path Protection in Translucent WDM Optical Networks

By

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Declaration of Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis incorporates the outcome of a joint research undertaken in collaboration with Mr. Quazi Rahman under the supervision of Dr. Subir Bandyopadhyay. The collaboration is covered in Chapter 3 of the thesis. The author was responsible for developing a new technique for solving the Routing with Regenerators Problem, to improve an algorithm developed by Mr. Quazi Rahman. In all cases, the key ideas, primary contributions, experimental designs, data analysis and interpretation for eta factorization were performed by the author and the contribution of co-authors was primary through the provision of constructive comments.

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ABSTRACT

Optical noise, chromatic dispersion, nonlinear effects, polarization mode dispersion (PMD) and cross-talk cause the quality of an optical signal to degrade as it propagates through the fibers in wavelength division multiplexed (WDM) optical networks. In a translucent network, regenerators are placed ay appropriate intervals to carry out 3R regeneration (*re-amplify, re-shape and re-time*). Translucent WDM networks are receiving attention as long-haul back bone networks. One important aspect of such networks that has not received attention is the possibility of cycles in the path of a translucent network. This research studies how we implement path protection in translucent networks, considering the possibility of cycles. We are developing a new scheme for dynamic lightpath allocation using the idea of shared path protection. We propose to study the performance of the scheme using a number of well known networks.

Dedication

This thesis is dedicated to my beloved wife, Yingnan Du, and my parents, Prof Baochang Wang and Prof Butong Zhang for their endless support, as well as my son Ryan Wang and my daughter Maggie Wang.

Also, it is dedicated to my supervisor, Sean Moriarty, Director of ITS, University of Windsor, Roger Lauzon (formal Director of ITS, University of Windsor) and other co-workers for their great support.

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I also thank to my external reader, Dr. Kevin Li from School of Business, University of Windsor and my internal reader, Dr. Jessica Chen, as well as the chair of my graduate committee, Dr. Robert Kent for their time and efforts to help to finish the writing of this thesis.

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Chapter 1

INTRODUCTION

A computer network is an interconnection of a group of computers or electronic devices for data communication. Computer networks are widely used for data communication. Optical networks have been arising as a key technology for fast communication because of its high bandwidth [1]. Modern optical networks take into account some important issues such as optimizing the use of optical network resources, using the same fibre for carrying multiple optical signals simultaneously. Optical networks are widely used as back-bone networks or Wide Areas Networks (WAN) since they have very high bandwidths compared to regular copper networks and wireless networks. Within a WAN, the distance the signal travels over optical fibers is becoming a key issue and translucent optical networks are being used for long-haul data communication.

Wavelength Division Multiplexing (WDM) [1] is the major technology of carrying multiple optical signals with different optical wavelengths using a single fibre. A lightpath is an optical connection from one end-node to another and is used to carry data in the form of encoded optical signals [1]. WDM optical networks provide a way to handle multiple lightpaths simultaneously on the same fibre and maintain the required speed for communication. To maximizing the utilization of a WDM optical network is a very common objective for optimization. When optical signals are sent over a long distance, the signal degrades due to the optical noise, chromatic dispersion, nonlinear effects, polarization mode dispersion (PMD), and/or cross talk, etc [1]. To compensate for this, 3R (Re-shape, Re-time, Re-amplify) regenerators are placed at selected nodes in a long-haul WDM optical network that divides the translucent network into transparent segments to enable the signals to travel for long distances. In a translucent WDM optical network, Regenerator Placement Problem (RPP) and Routing with Regenerator Problem (RRP) are two major optimization problems.

Linear Programming (LP) is one important tool to solve this kind of optimization problems. An LP formulation includes a linear objective function and a number of linear constraints to define the problem. In our problem, the linear objective function is minimizing the number of regenerators used for each traffic demand. We have to use an Integer Linear Program (ILP) where some of the variables are constrained to be integers.

Solving the ILP is a NP-Hard problem which means that the time complexity of the algorithm is exponentially high. Therefore, for a medium size or large scale of network, the ILP may take an unacceptably long time return the results. Using a heuristic algorithm is another alternative solution to handle such problems. The heuristic algorithms usually return the result in an acceptable time frame, even though the effectiveness of optimization may be the trade-off from ILP.

Since a single fibre in a WDM optical network carries multiple optical signals, a failure of a fibre can cause lots of communication to be disrupted. Thus, fault tolerance is an important consideration in network design and/or data routing. The backup path [1] for data routing is one important approach for fault tolerance in a WDM optical network, translucent or transparent. The strategies of fault tolerance are protection scheme (using either dedicated backup paths or shared backup paths) and restoration scheme, [1]. For maximizing the benefits of fault tolerance, dynamic allocation with shared backup path in protection scheme are the best solution in a survivable translucent WDM optical network [1].

There exists an algorithm for solving the shortest path pair (primary path and backup path) problem of a WDM optical network. This has been introduced by Reid Andersen, et al, which we will discuss in Section 2.2.3 in detail. An Integer Linear Programming (ILP) function of optimization of minimizing the 3R regenerators in translucent WDM optical networks has been implemented in our lab by Mr. Quazi Rahman, a candidate of the Ph.D degree in Computer Science of University of Windsor. Then a heuristic algorithm called Active Path First Enhanced (APFE) which was introduced by Anderson [3] can be repeatedly performed to find the shortest path pairs in all possible segments in a translucent network. Finally an ILP to will solve the RWA problem in each segment.

1.1 Objective of this thesis

In this thesis, our objective is to propose a heuristic algorithm to find a “near optimal” scheme for path protection from any given source to any given destination in a translucent network. We will discuss how to implement the heuristic, so that it consists of the algorithm proposed by Reid Anderson, etc the Integer Linear Program (ILP) implemented by Mr. Quazi Rahman.

After discussing the implementation of our proposed algorithm, we will describe the experiments to simulate the algorithm and compare it to the ILP solution implemented by Mr. Quazi Rahman. In this thesis, we will describe the simulation results to analyze the improvement of performance.

1.2 Motivation

In translucent WDM optical networks, RPP problem addresses the problem of placing a minimum number of regenerators in the network to realize the physical topology of such networks using the lowest cost. The RRP problem needs to address the minimum number of regenerators used to handle each traffic demand during deployment of each request for communication with path protection. The RRP problem minimize the number of regenerators on each translucent lightpaths in order to free up the limited regenerator resources in a translucent WDM optical network. This allows the network to handle more requests for communication and speed up the traffic demands since regeneration is relatively expensive and increases the latency of the signal travelling in the optical fibre.

The ILP function performs well on translucent WDM optical network of small size. However, for larger networks, the ILP is unacceptably slow and it is not possible to have the result in an acceptable time, even for the medium size network. The ILP function searches the optimal solution in the entire network presented as a graph G(V,E) with *n* nodes and *m* edges , such that V is the set of vertices to represent nodes in the network and E is the set of edges to represent fibres in the network. To simplify the search by the ILP, we can reduce the search space in advance to speed up the performance of ILP.

An efficient ILP has been implemented by Mr. Quazi Rahman which, however, has poor performance. Our approach is to use APFE to build up a new graph G'(V',E') from G(V,E) with relevant nodes and edges to efficiently handle the request for communication from source node S to destination node D in the presence of ongoing communication in response to previous requests for communication. The ILP will solve the RRP and RWA problems on the graph G' in an optimal manner.

Using this approach we have implemented our algorithm in C and tested our algorithm on various network sizes with different traffic loads.

1.3 Organization of thesis

This thesis is organized as follows. In Chapter 2, we have given a background review in the area of translucent WDM networks and path protection schemes. We have also reviewed some topics relevant to our problem. In Chapter 3, we have outlined the proposed algorithm and the simulation algorithm. In Chapter 4, we have given the experimental results we obtained, after implementing our simulator. In Chapter 5, we have drawn some conclusions and made some suggestions for future research in this area.

Chapter 2

REVIEW OF LITERATURE AND BACKGROUND

2.1 Background

In this chapter, we review some relevant background material including WDM Networks, Translucent WDM Networks, schemes to handle faults in WDM networks, and linear program-based solutions for routing in translucent WDM networks.

2.1.1 WDM Network

Optical network uses optical signals carried by optical fibres to encode the information for the communication between computers. It has been widely deployed in modern networks with significant improvements in the technology in the last twenty years. Optical networks have found widespread use because the bandwidth of such networks using current technology is 50 tera-bits per second [1]. But most communication requests do not need that much bandwidth. To handle this, concurrency is introduced among multiple user transmissions into the optical network architectures and protocols.

Concurrency among multiple user transmissions is needed to make use of the vast bandwidth available without experiencing any electronic bottleneck. This concurrency may be provided either in wavelength or frequency, called WDM (Wavelength Division Multiplexing), in time slots, called TDM (Time Division Multiplexing), or wave shape (spread spectrum), called CDMA (Code Division Multiple Access). WDM network is currently the favourite multiplexing technology in optical networks since all of the end-user equipment needs to operate only at bit rate of a WDM channels, which can be chosen arbitrarily. [26].

WDM increases the information capacity of a fibre by transmitting information on several different wavelengths simultaneously. By using multiplexers (MUX) and de-multiplexers (DEMUX), the system is able to achieve this simultaneous transmission without experiencing significant interference between the information channels [GR00].

[CGK92] first proposed an architectural approach based on light paths on WDM networks. Before this paper, existing network architectures could not efficiently utilize the light bandwidth of optical signals in wide area networks.

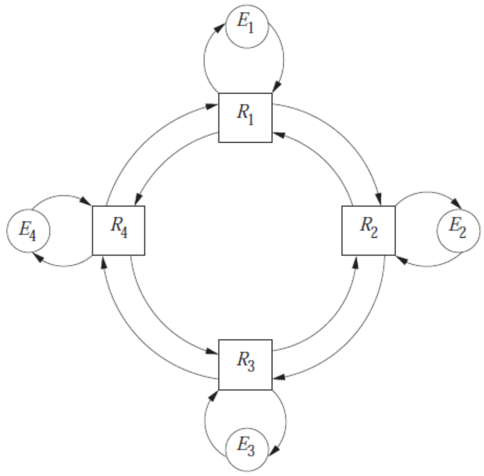


Figure 2.1 The physical topology of the typical WDM network with 4 nodes $E_1 \ldots E_4$ and 4 routers $R_1 \ldots R_4$.

2.1.1.1 Optical Networks

Before discussing WDM network, the concept of optical network is briefly introduced in this section. Three generations of networks based on the physical technology have been developed [4][5]. First generation networks are based on copper-wire or microwave-radio technology. Second generation networks use optical fibres in traditional architectures, in which the fibre is used simply as a replacement for copper. Because of the advantages of optical fibre, the second generation networks can achieve performance improvements over the first generation networks. However, the performance of second generation networks is limited by the maximum speed of electronics employed in the switches and end-nodes. In third generation systems, all-optical networks use the unique properties in order to meet the needs of high bandwidth applications. Totally new approaches are employed to exploit the vast bandwidth (50 tera bits/second which may be divided to give up to 200 channels) available in the fibres. In the third generation networks, all-optical property provides the benefits as that the information is transferred in the optical domain (without facing any electro-optical conversions) through the network until it is delivered to its destination.

2.1.1.2 Categorization of WDM Networks

Optical networks can be classified either as transparent optical networks or as translucent optical networks according to the distance that the data traverses until it reaches its destination node.

All-optical transparent networks carry the data from source to destination by using optical signals without any Optical-Electronic-Optical (O-E-O) conversion or any wavelength conversion. This type of network takes full advantage of the vast bandwidth of optical networks.

Translucent optical networks allow optical networks to communicate over long distances and consider the optical reach for a long-haul network. 3R regenerators are placed into the optical networks to have data transmission over long distances by re-amplifying, re-shaping and re-timing the optical signal.

2.1.1.3 Physical Topology vs. Logical Topology

A simple model of the physical topology of the WDM network includes the set of routing/end-nodes and the fibre-optical links connecting them. [9] Each physical link may have multiple lightpaths that must use different wavelengths. A lightpath is acting as a pipe between a selected pair of end nodes with a bandwidth between 10-40 GHz. The set of lightpaths that have been set up between end nodes constitutes the logical topology. [9] We usually use G(V,E) to represent a physical topology of a WDM network, where V is the set of end nodes and router nodes and E is the set of links (fibres).

The logical topology is a graph with nodes corresponding to the end nodes with a directed edge from a source to a destination of each lightpath in the network.

2.1.1.4 Static and dynamic lightpath allocation

There are two approaches for deciding a strategy for data communication in a wavelength routed network [1]. The straight forward idea is to set up lightpaths on a semi-permanent basis, so that, once the lightpaths are established to handle the data from a source node to a destination node, the lightpaths will exist for a relatively long period of time. This approach is called static lightpath allocation. In this approach, we can see that the strategy is designed for a “fixed” communication request with relatively high volume of data transport and this approach requires knowing the requests when setting up the network.

Another approach is to set up the lightpaths on demand and once the communication is over, the lightpath will be taken down. This approach is called dynamic lightpath allocation, and is applicable if there are frequent changes of communication requests in a WDM network. This technique frees up the resource on the WDM network to handle more requests.

2.1.2 Translucent WDM Networks

2.1.2.1 Introduction

In Section 2.1.1, we have discussed that all-optical transparent network takes advantage of the large bandwidth of WDM networks, but it does not consider some factors, which degrade the optical signal quality in long-reach optical transmission systems to make the data unrecognizable at the receiver [6].

In such a long-haul optical transmission system, the concept of optical reach is useful to researchers. Optical reach is the distance an optical signal can travel before the signal quality degrades to a level that necessitates regeneration [7]. Within the optical reach, the data is transmitted on a transparent network, before the signal quality degrades. When the travel distance exceeds the optical reach, a 3R regenerator is necessary to Re-shape, Re-time and Re-amplify the signal [1]. Such networks with 3R regenerators are called Translucent Networks.

2.1.2.2 Categorization of Translucent Networks

Obviously, translucent networks extends the distance that signal can travel. The translucent network is broadly classified into three categories, namely [6]

- Translucent networks made up of transparent islands[13,16]
- Translucent networks with sparsely placed opaque nodes [14,15]
- Translucent networks made up of translucent nodes [16]

A translucent network can made up of several subdomains (termed islands) of optical transparency [13,16]. The optical transparency means in a given island, all nodes are transparent, so that no node has regeneration capacity in any island. The Optical Cross-Connect (OXC) nodes are located on the island boundary [6]. Figure 2.2 illustrates a translucent network made up of three transparent islands and nodes 4, 7, 8 and 9 are boundary nodes acting as regenerators for lightpaths crossing neighboring transparent islands.

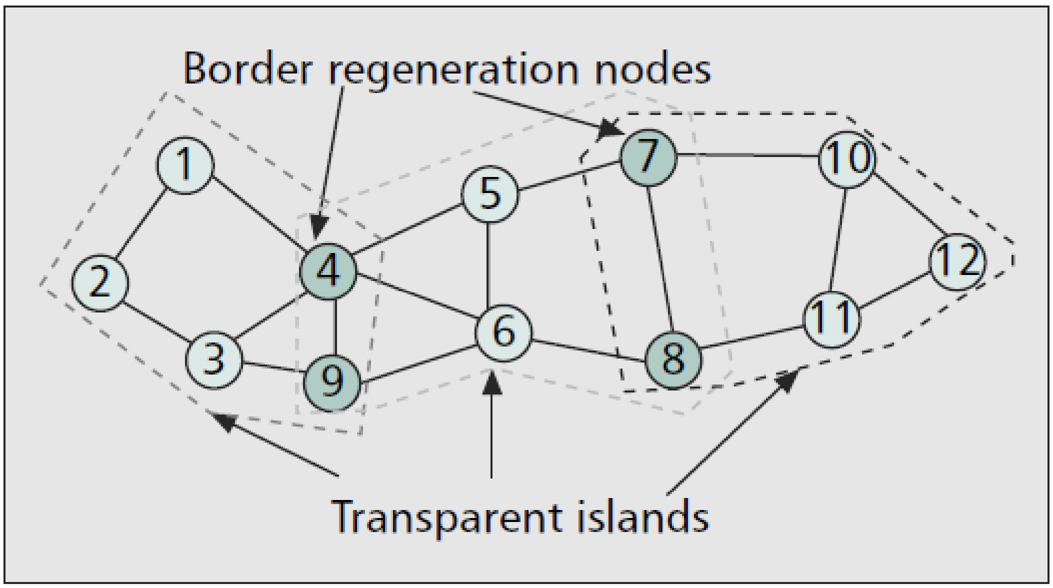


Figure 2.2 An example of a translucent network with multiple transparent optical islands

A translucent network can be more general than one with regeneration nodes only at islands boundaries. We can have some switches with regeneration function that can be shared by all lightpaths in the network as a whole. One such type of implementation is based on sparse placement of opaque switches [14, 15]. Thus we can have small number of electronic nodes, at which wavelength conversion and regeneration is possible. All other nodes are lower-cost optically transparent OXCs [6]. Figure 2.3 shows an example of a translucent network with sparsely placed opaque nodes, where node 1 and node 3 are opaque, and as the rest of the nodes are transparent.

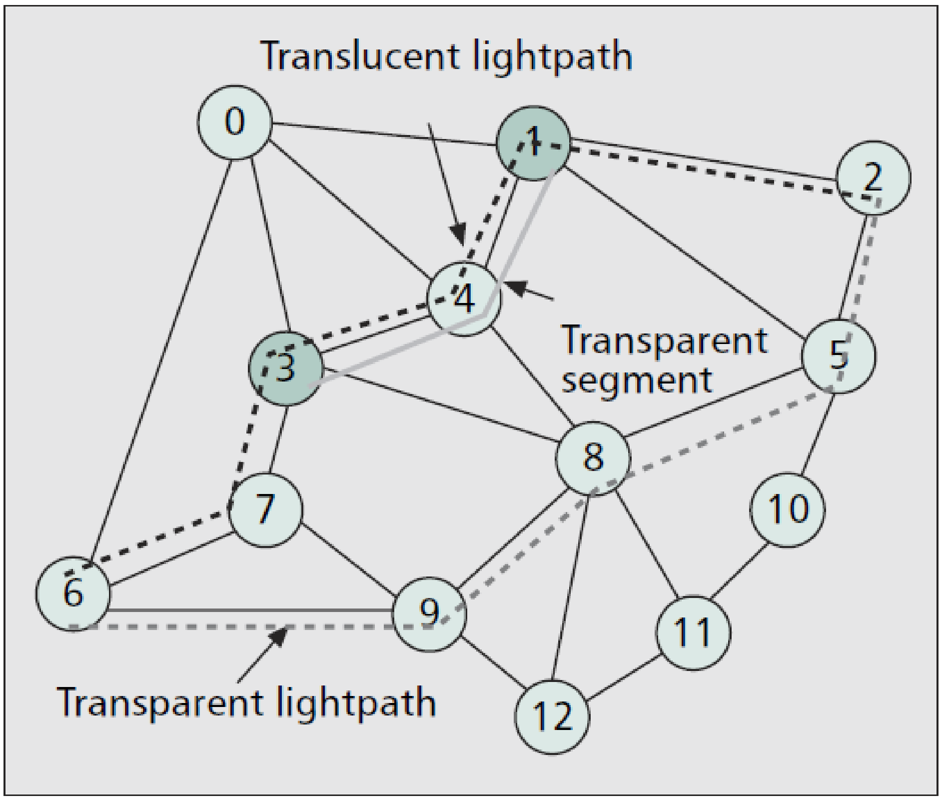


Figure 2.3 Example of a translucent network with sparsely placed opaque nodes (adapted from [15])

Another distributed regeneration approach is to deploy hybrid optical switches at some or all of the nodes in an optical network [17]. Each of those switches contains an optical switch core and electronic core as shown in Figure 2.4. This type of switch can pass the optical signal without O-E-O conversion. If the O-E-O conversion if not necessary when the signal travels to this switch, then this type of switch is acting as normal optical node, thus the OXC nodes only act as regenerators when necessary.

In Figure 2.4, if the O-E-O conversion is necessary, then the optical signal received by the optical core first, then the signal is transmitted to the electronic core, after the signal is being converted to the electronic signal, then it is transmitted back to become an optical signal to the optical core and it is switched out. In this conversion, the optical signal is re-amplified and re-shaped by the O-E-O conversion.

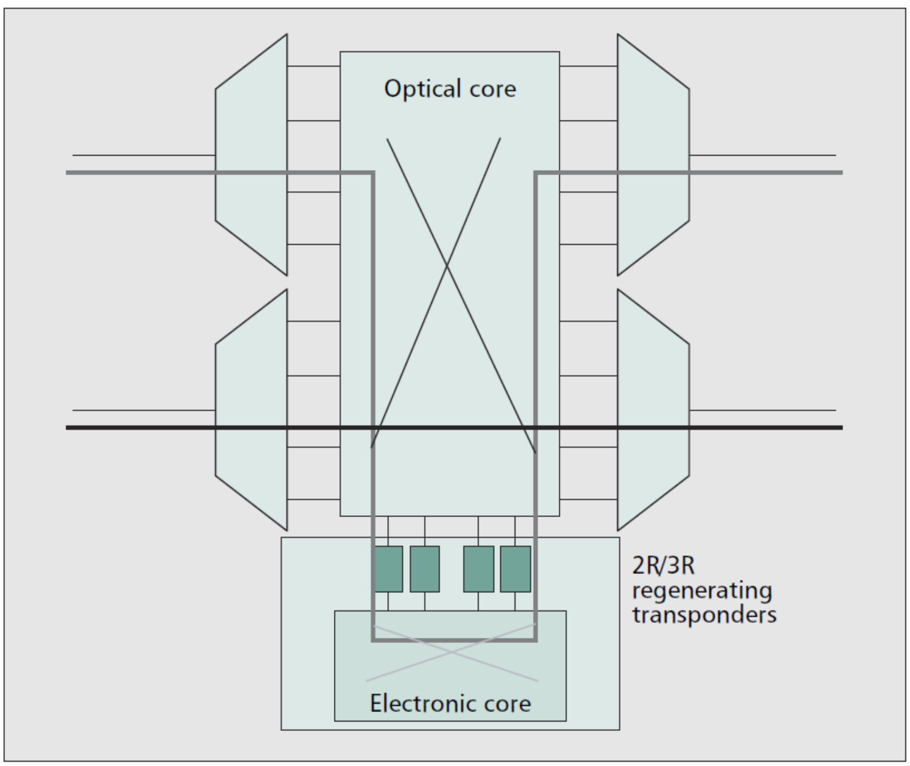


Figure 2.4 Architecture of a translucent OXC node.

In this type of a translucent network, the network provides more flexibility and it is easy to deploy such a long-haul optical network.

In a translucent network, a logical path may contain several transparent lightpaths. Such a transparent lightpath is called a segment. For example in Figure 2.5, from the source node to a regenerator, from a regenerator to another regenerator, and from a regenerator to the destination node are segments in the translucent WDM networks. In other words, S-1-2-R1, R1-3-4-5-R2, R2-6-7-D are three segments in this translucent network.

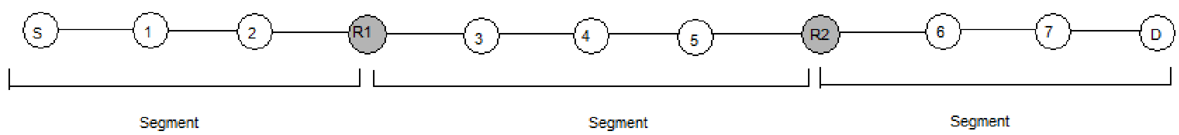


Figure 2.5 Translucent WDM Networks with 3R regenerators

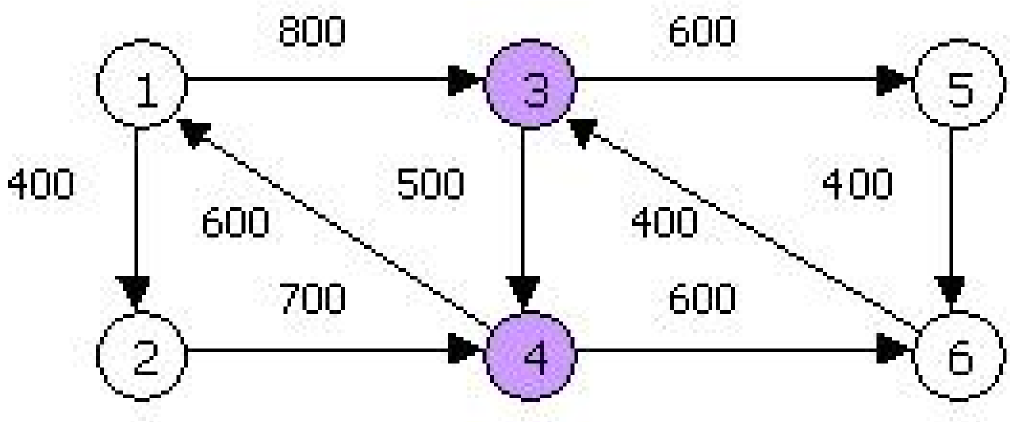
According to the categories of translucent optical networks discussed above, translucent network made up of translucent nodes are broadly implemented in the long-haul WDM optical networks. However, the OXC nodes with 3R regeneration capacities are fairly higher-cost than pure optical switch nodes. Thereafter, minimizing the number of 3R regenerators and finding their locations can significantly save the cost for long-haul networks. In the next section, we are going to introduce this problem which is named Regenerator Placement Problem (RRP).

2.1.2.3 RPP PROBLEM & RRP PROBLEM

Based on the characteristics of translucent optical networks, two problems have attracted attention from researchers: the Regenerator Placement Problem (RPP) and the Routing with Regenerators Problem (RRP).

RPP is to find i) the minimum number of regenerators and ii) their locations, so that a communication path can be established between every pair of source-destination nodes in the network [2]. This problem is determined at the network design stage. Before the problem is defined, the optical reach *r* needs to be known in order to have a regenerator placement, with the overall cost as low as possible. Many factors affect the optical reach: the type of amplification, the power of the signal at source, the modulation format of the signal, etc [7]. Obviously, the longer the optical reach, the fewer regeneration nodes are required in the network. However, longer optical reach also requires more expensive transmitters to get a powerful signal which imply expensive amplifiers. Therefore, balancing the cost of transmitters, amplifiers and the number of regenerators is a major topic for many researchers in that field. Additionally, the network routing cost is also an important consideration of determining the optical reach. In summary the RPP problem is as follows,

- Given a network topology, Identify the minimum numbers of nodes and their locations that should have regenerating capacity to establish connections between every node-pair within the optical reach.



Optical Reach = 1000

Figure 2.6 An example of a translucent network

In RRP, the locations of the regenerators are known and the objective is to compute a path between a source-destination node pair using as few regenerators as possible [18]. Since the RPP problem addresses the minimum number of regenerators and their locations in the network for a given optical reach *r*, the RRP problem has to determine how to use the minimum number of regenerators. This frees up the limited resources so that the network has ability to handle as many traffic requirements as possible. As we discussed, O-E-O conversion is the higher cost component of the signal transmission in a translucent network, compared to the pure optical switch in a transparent network, thus, reducing the number of regenerators in a translucent lightpath can also help reduce the cost of an optical network.

Figure 2.6 shows an example, where there is a request to communicate from node 1 to node 6. There are three possible paths as follows:

- P1=1-3-5-6

- P2=1-3-4-6
- P3=1-2-4-6

The idea is to select the lightpath with the fewest regenerators on the path. For instance the selected path is P1 or P3, both requiring one regenerator node.

2.1.3 Path Protection in WDM Networks

The huge bandwidth of optical network provides the ability to carry 10 or 40 giga-bits data per second on a lightpath, especially for translucent networks where the data is passing through many nodes and links in long-haul networks. Thereafter, any failure of a node or a link can cause the loss of a huge amount of data and the impact of a fault is considerable high. The survivability of WDM networks is therefore an important factor when designing such networks.

According to the location of fault, two types of failures are defined: Node Failure and Link Failure. For a long haul-network, the Node Failure is fairly easy to locate and repair. However, the Link Failure is not easy to locate and repair, since every link in the network represents a long distance fibre which is usually hundreds of km. Thus the research of most of fault-free WDM networks mainly focus on path protection to handle edge failures.

2.1.3.1 Protection Scheme vs. Restoration Scheme

A broad categorization of the main schemes for the management of edge failure (an edge failure in a graph represents a link failure in a network), following [12], is given in Figure 2.7. In a protection scheme, for every primary lightpath L_i^P, a backup lightpath L_i^B is determined at the same time as L_i^P [1]. Either both the primary lightpath and the backup lightpath in a pair of lightpaths are operational in the WDM network or the backup lightpath is set up quickly when L_i^P fails. In the protection scheme, the search for a route and channel assignment for a backup path for each primary path has been done when determining the primary lightpath. Thus, when a fault occurs, restoration of the communication is quick and it is guaranteed that there will be a backup lightpath to carry the data originally communicated using the primary lightpath.

In a restoration scheme, only after a fault occurs, for every lightpath L_i^p that become inoperative, the search for a route and channel assignment for a backup lightpath L_i^B is carried out [1]. Compared with the protection scheme, the restoration scheme frees up more resources of network for deploying more request for communication since during deployment in response to each request for communication, the backup path is not used. However it takes a longer time to search for a backup path, once the fault occurs. Once the fault occurs, there is no guarantee that the search for a backup lightpath to avoid the faulty node will be successful.

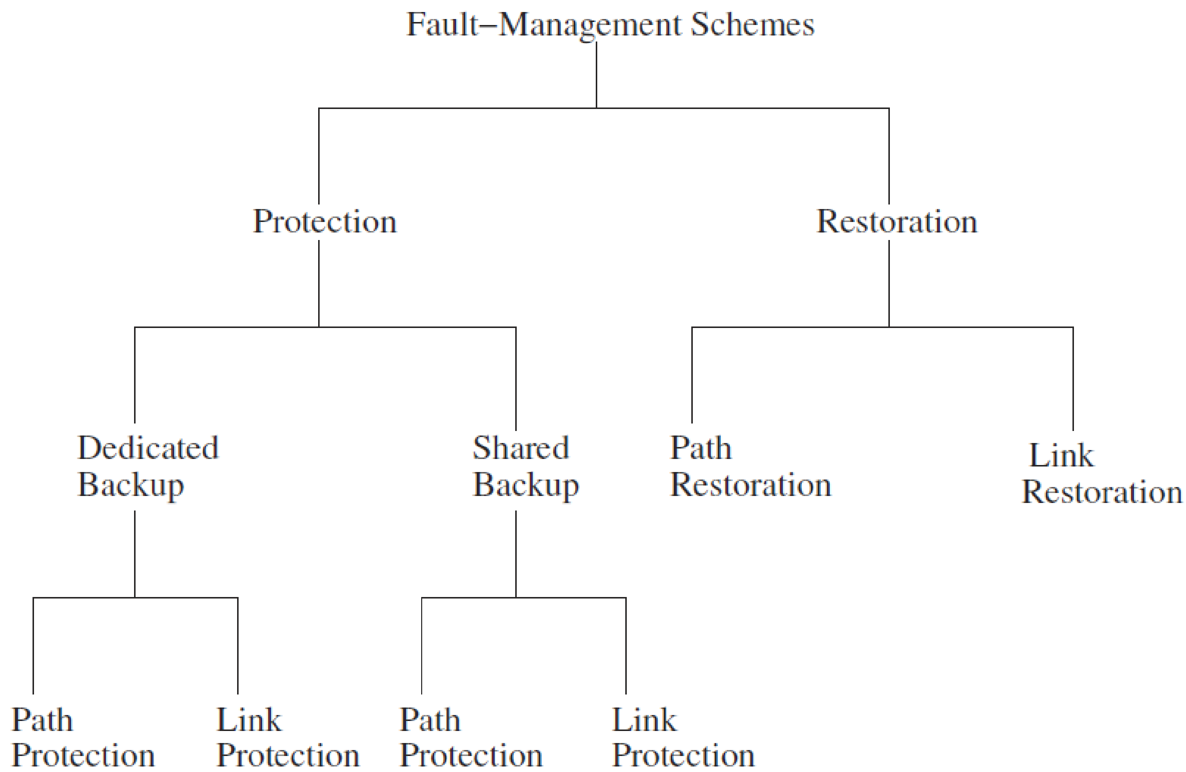


Figure 2.7 A categorization of fault management schemes

2.1.3.2 Dedicated Backup Path vs. Shared Backup Path

Dedicated backup path is a scheme in which the backup path uses a dedicated channel on each fibre in its path. The problem of dedicated path protection is that the resources are exclusively allocated to handle the faults and some of the resources of network are not utilized to carry the traffic demands, until a fault occurs.

In most cases, the failure of multiple components in a WDM network is rare and we can ignore the multiple failures scenario. Therefore, shared protection which allows multiple backup lightpaths to shared one channel on same lightpath is often used for fault tolerance. In this strategy, if a failure occurs on one link (one physical fibre), all ongoing primary traffic on all wavelength channels on the failed fibre need to be re-routed to the corresponding backup lightpath. Thus, link failure protection in shared protection scheme is the most effective fault tolerance strategy in our research. The important property of this strategy is "edge-disjoint" for primary and backup lightpath pair.

2.1.4 Route and Wavelength Assignment Problem

In this section, we discuss the logical topology problem with wavelength continuity constraint. The wavelength continuity constraint means that only one channel number is assigned to a lightpath on all edges on its route, so that there is no wavelength conversion taking place. In WDM networks with wavelength converters at some nodes, the wavelength continuity constraint is not required. Depending on the technology used, a fibre in a network can support a certain number of channels, so that the routes assigned to the lightpaths sharing a fibre should be less or equal to the maximum number of channels that the fibre can support. This problem is called Route and Wavelength Assignment Problem (RWA).

2.1.4.1 Introduction

On each link in a WDM network, the traffic can be categorized as directed, undirected and bi-directed. Directed link means all traffic on this link has to be in one direction. Undirected link is the fibre which allows both directions of traffic flow. Bi-directed link is the link with half channels in one direction and another half in the reversed direction.

To simplify the problem in our research topic, we consider the 3R regenerators are acting as router nodes in translucent networks. Thus the wavelength continuity constraint is satisfied in all segments in a translucent network. It also means all general nodes without 3R capacity are not wavelength convertible. Also, we assume the same number of channels on all links in all segments.

2.1.4.2 Integer Linear Programming for RWA

The Integer Linear Programming (ILP) is a common method to solve the RWA problem to get an optimal result. Maximizing the number of lightpaths or minimizing the congestion are popular objectives of ILP formulations. Certain constraints need to be given to define the problem in an ILP formulation.

For instance, if the problem is to find the shortest path from a source *s* to a destination *d*, the following constraint must besatisfied:

$$\sum_{j:(i,j)\epsilon E} X_{ij} - \sum_{j:(j,i)\epsilon E} X_{ji} = \begin{cases} 1 & if\ i = s, \\ -1 & if\ i = d, \\ 0 & otherwise \end{cases}$$

X_{ij}: an integer variable having a value of 0 or 1 where

$$X_{ij} = \begin{cases} 1\ if\ the\ path\ is\ routed\ through\ the\ edge\ (i,j) \in Ein\ the\ physical\ topology \\ 0\ otherwise \end{cases}$$

In this constraint,

- If node *i* is the source of the network traffic, then there is no flow into node *i*.
- Otherwise, if node *i* is the destination of the network traffic, then there is no traffic out of node *i*.
- Otherwise, the incoming flow must be balanced by the outgoing flow.

An ILP solution can solve the problem and produce an optimal result; however, the time complexity is very high for a large network and/or complex constraints in the ILP definition. The complexity of an ILP formulation with binary variables (i.e., the integer values are 0 or 1) is $O(2^n)$ of the number of binary variables is *n*.

To reduce the complexity, we often use some heuristic which, in general, works reasonably well but may give suboptimal results.

2.1.4.3 Shortest Path Algorithm – Dijkstra Algorithm

In this chapter, we introduce Dijkstra's algorithm that can be considered to be used in the heuristic algorithms. Dijkstra's algorithm is developed by Dutch computer scientist Edsger Dijkstra in 1959. The algorithm is to find the shortest paths in a graph for a given source vertex and it can find out the shortest paths from the given source node to all other nodes. The time complexity of this algorithm is $O(n^3)$.

```
function Dijkstra(Graph, source):
    for each vertex v in Graph:          // Initializations
        dist[v] := infinity              // Unknown distance function from source to v
        previous[v] := undefined         // Previous node in optimal path from source
    dist[source] := 0                    // Distance from source to source
    Q := the set of all nodes in Graph
    // All nodes in the graph are unoptimized - thus are in Q
    while Q is not empty:                // The main loop
        u := vertex in Q with smallest dist[]
        if dist[u] = infinity:
            break                        // all remaining vertices are inaccessible from source
        remove u from Q
        for each neighbor v of u:        // where v has not yet been removed from Q.
            alt := dist[u] + dist_between(u, v)
            if alt < dist[v]:            // Relax (u,v,a)
                dist[v] := alt
                previous[v] := u
    return dist[]
```

Pseudocode 2.1 Dijkstra algorithm [10-Wiki]

2.2 Review of the Problem

In a translucent network where the RPP problem has been resolved and the network has been deployed, we have to solve the RRP problem with given locations of the 3R regenerators. The objective is to establish, if possible, a path, from the source to the destination of any request for communication, so that a lightpath may be established, using the path that requires the fewest stages of regeneration [11].

Formally, we define the problem as follows:

- Given

- An existing undirected physical topology in which

    1. Each node represents an end-node which has a specified number of transmitters and receivers

    2. Nodes are connected by optical fibres that support a fixed number of carrier wavelengths (channels).

    3. The degree of each vertex in the graph G(V,E) is at least 2 for fault tolerance.

    4. The number of channels on each link represents the number of wavelength on each link in one direction.

- The locations of regenerators in the network are given.

- Details of existing lightpaths are known.

- A new request for data communication has to be accommodated, if possible.

* The problem is to determine a logical path for the new request for data communication such that:

    - A minimum number of regenerators are used on the possible pairs of paths (the primary path and the backup path) for the new traffic request.

    - A feasible RWA can be determined for the new primary and backup lightpath, over the underlying physical network.

2.2.1 ILP-1 Formulations

The authors of [11] present the ILP-1 formulation to solve the problem of RRP which minimize the total number of 3R regenerators used by the traffic demand on both the primary lightpath and the backup lightpath.

2.2.1.1 Introduction

An important property of translucent network is as follows:

if a translucent lightpath involves two segments, S_a and S_b that have one or more common fibre(s), the same wavelength cannot be used for both segments S_a and S_b [18].

This property can be explained by using Figure 2.8 (adopted from [3])

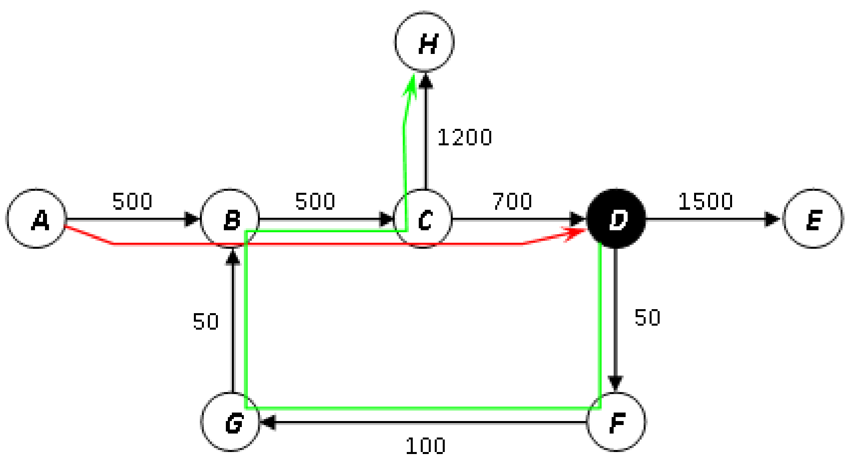


Figure 2.8 Property of translucent networks

The communication request A-H has a lightpath A-B-C-D-F-G-B-C-H, on this lightpath, B-C is the common fibres for both segments S_a (A-D) and S_b (D-H). These segments cannot use same wavelength to avoid the conflict on fibre B-C.

Along with this property, the authors on [11] propose an ILP formulation (which they called ILP-1) that gives an optimal path for a translucent lightpath using a minimum number of regenerators [11].

This objective is to determine the route of the primary and the backup translucent lightpath from a source to a destination, if possible, and allocate a channel number to each segment of the primary and backup lightpath, such that the total number of 3R regenerators on newly established primary and backup lightpaths is minimized.

The formulation is given in Appendix A.

2.2.1.2 Effectiveness

This ILP-1 formulation gives the exact optimal result by search globally. It is good for small sized network. For medium to large size translucent network, the execution time of this formulation is not acceptable.

2.2.1.3 Efficiency

Because this formulation searches the optimal result in the entire translucent network, the time complexity is very high. We will present the comparison between our proposed heuristic algorithms with this ILP-1 formulation in Chapter 4.

2.2.2 ILP-2 Formulation

To address the limitations of formulation ILP-1, the authors in [11] proposed ILP-2 to solve the RRP problem for middle size and/or large size of network.

2.2.2.1 Introduction

In ILP-2, the authors of [11] have reduced the execution time by limiting the search for the routes for any segment of the primary (backup) lightpath to pre-determined edge-disjoint paths. For every pair (x,y) of nodes, such that it is possible to go from x to y without exceeding the optical reach *r*, using at least 2 edge-disjoint paths, we pre-compute, if possible, *m* edge-disjoint paths from x to y [11]. The authors of [11] state that *m* is small fixed number and if it was not possible to find *m* edge-disjoint paths, then we calculate all possible edge-disjoint paths from x to y.

Appendix B gives details of this formulation.

2.2.2.2 Effectiveness and Efficiency

The ILP-2 formulation is able to work on middle size or large size of translucent network to find the solution of RRP problem. The ILP-2 is very efficient compared to ILP-1 with respect to the time required to find a path. However, this formulation frequently fails to find out the solution. That means that, when the solution exists, the ILP-2 returns “cannot deploy” for some requests for communication.

2.2.3 APFE Aalgorithm

In [3], the authors propose an effective heuristic algorithm to find out the primary-backup path pair from source node S to destination node D in a network.

2.2.3.1 Introduction

The APFE [3] algorithm repeatedly use the shortest-path algorithm to find a primary path (in the paper, it is called an Active Path, AP), and then to find a link-disjoint backup path (BP). The authors consider a dynamic scenario, where requests to establish active-backup paths between a specified source-destination node pair arrive sequentially [3]. The authors also claim that the APFE algorithm reduce the number of shared links in a pair of active-backup paths.

By comparing the computational results with ILP formulation proposed in the same paper, the authors show that the APFE algorithm performs much better than the ILP formulations and the execution time is significantly reduced compared with the time required to solve the problem using an ILP formulation.

Algorithm APFE (G, S, D)

step 1 *Find an S-D lightpath AP on free channels using the minimum number of links. Set cost=1.*

step 2 *Let G_0 be a copy of G. For every active or reserved channel, assign a cost of ∞. For every free channel on a link on AP, assign a cost of M. For every other free channel, assign a cost of 1.*

step 3 *Find a minimum cost S-D lightpath BP in G_0.*

step 4 *IF AP and BP are link-disjoint THEN*

AP and BP are the active and backup paths for the connection request; STOP

ELSEIF the cost BP is at least cost THEN

STOP failure

ELSE

Set cost to the cost of BP and let AP represent BP. goto Step 3.

ENDIF

Algorithm 2.3 APFE edge-disjoint path pair finding [3]

2.2.3.2 Benefits to Our Problem

According to the ILP-2 for the solution of RWA problem and RRP problem, APFE can be used to pre-calculate the paths between every node pairs of requests for communication. This result may be used to pre-calculate the result and use it as input to ILP-2 to solve the RWA problem and RRP optimization.

2.3 Related Works

The minimum regenerators path problem has received some attention [7], [17], [18]. In [25], two dynamic routing algorithms have been proposed by authors to minimize the total regeneration hops and the total Bit Error Rate (BER) on the computed route based on the MPLS hierarchy that considers regeneration resources available at each regenerator and link states. In [18], the authors proposed an intra-domain routing algorithm considering the number of optical-layer constraints in a dynamic call arrival setting. However, there may be some difficulties to obtain BER, optical dispersion and other physical impairment factors in real-time. In [7], the researcher indicates that the optical reach r can be used a rough approximation for all of these factors. The author of [8], Simmons suggests some methods to find the minimum regeneration route between a node pair between the source and the destination. Similar to ILP-2 or other heuristics, this method may not always ensure the existence of a solution. In addition, the existing routing techniques do not consider the segments that share fibers. By using the existing technique, the source to destination path may have the edges repeated. Such a path cannot be used in case the overlapping segments have same channel number available for path establishment. There are some routing algorithms (e.g. [8]) that consider capacity constraints, physical impairments and the wavelength continuity constraint in minimizing the cost of the desired route. However, most of them use static computation in which the routes are computed before the requests arrive. The work [2], [11] and [18] are the closest researches to our work. However, since the authors in [18] consider different set of parameters than our problem, there is no way to compare between our solution and their work. In [2], the authors proposed an ILP solution and a heuristic solution to solve the RRP problem. There is no fault tolerance consideration in this research. The research in [11] indicates that the ILP-1 and ILP-2 is a solution to the RRP problem with path protection. Our solution is to improve the performance from ILP-1 by using a new heuristic which adopts ILP-2 as part of heuristic.

Chapter 3

HEURISTIC FOR RRP PROBLEM IN TRANSLUCENT WDM NETWORKS

In this chapter, we introduce the new proposed heuristic algorithm to solve the RRP problem. This algorithm uses APFE algorithm with Dijkstra's algorithm to find pairs of possible edge-disjoint routes for a primary and a backup lightpath to handle future requests for communication from a specified source to a specified destination. These possible route pairs are used as data for an Integer Linear Program, called ILP-2 to find the optimal route from the specified source to the specified destination. The tasks for ILP-2 are as follows:

- Find the pair of paths with fewest regenerators on the paths.
- Assign available wavelengths to each path of the path pair.

We have shown, using simulation, the approach discussed here, in conjunction with formulation ILP-2, fails less frequently compared to another heuristic that has been proposed recently.

3.1 Motivation for a New Heuristic

The existing heuristic, used with the ILP-2 formulation, has an improved efficiency compared to ILP-1, but the effectiveness was not satisfactory. In other words, ILP2 works fast but reports a failure in an unacceptably large number of cases. The idea of the existing heuristic is that a parameter *m* is fixed in advance. Before considering any request for communication, the heuristic pre-computes *m* edge disjoint paths between all source destination pairs where the distance from the source to the destination is less than the optical reach. Subsequently when processing a request for communication from source S to destination D, ILP2 limits the scope of the search by restricting the search to the *m* pre-computed paths between appropriate source destination pairs. Due to this limited scope of the search, formulation ILP-2 works fast. The problem with the existing heuristic is that the same paths are used over and over when considering the requests for communication. These paths quickly become “saturated” meaning that all channels are allocated to support existing communication. Even though there are lots of other edge-disjoint paths that could be used for a request for communication from S to D, the ILP-2 only searches for a solution from the *m* pairs of paths. To avoid this limitation, we propose a heuristic algorithm which re-calculates all available edge-disjoint paths, when the search for a path from S to D fails. The idea is that, very likely, there are other edge disjoint paths in the network. When ILP2 fails, discovering and then using these alternate paths may improve the effectiveness of the RRP algorithm.

3.2 Problem Definition

Before defining the problem, we look at following properties of the problem we are solving:

Property 1: Fault tolerance is mandatory, thus, the degree on each node must be greater than 1. This means if there is only one edge on a node, then there will not have primary-backup path pair if the node is selected on the route and furthermore, the node will not be able to deploy any request for communication including the one which request this node acting as a source or a destination.

Property 2: If the total length of the route is less than the optical reach, even though the route passes through a node with 3R regenerator, 3R regeneration is not triggered, and the entire path is one segment.

Property 3: Since we choose "shared backup path on dynamic edge-disjoint lightpath allocation" as the scheme for fault tolerance, two backup paths of different requests for communication can share the edge with same channel number, provided the corresponding primary paths are disjoint. When the network is fault-free, none of the backup paths has any traffic.

According to the motivation and properties analysis above, we give the formal definition of our problem:

- Given
    - An existing undirected physical topology in which
        1. Each node represents an end-node which has a certain number of transmitters and receivers to support multiple requests for communication.
        2. Nodes are connected by optical fibers that support a fixed number of carrier wavelengths (channels).
        3. The degree of each vertex in the graph G(V,E) is at least 2 to enable fault toleranve.
        4. The number of wavelength channels on each link represents number of links on one direction. The term of “undirected” represents two links on each edge.
    - The placements of regenerators in the network are given.
    - Details of existing lightpaths are given.
    - A new request for data communication from a specified source S to a specified destination D is to be processed.
- The problem is to add, if possible, a new translucent primary lightpath and make provisions for a corresponding backup lightpath such that:
    - A minimum number of regenerators are used on the possible path pairs (primary and backup) for the new traffic request.

    - A feasible RWA can be determined for the new primary and the new backup lightpath, over the underlying physical network.

- If ILP2 fails to find the desired path pair, we re-compute *m* edge disjoint paths between all feasible source-destination pairs and try again for a new path.
- ILP2 reports a failure only if the second attempt fails to find a solution.

3.2.1 Hypothesis

In this thesis, we propose a new heuristic algorithm “findPathPair”. We argue that findPathPair algorithm works with ILP-2 to make it more efficient and lead faster performance compared to ILP-1.

3.2.2 Assumptions

To simplify the problem, we make the following assumptions to simplify the problem:

- No consideration is made for node failures. In the real world, nodes in the WDM physical topology usually represent as optical switches/transducers in a long-haul network. The nodes are relatively easy to access, repair/replace once they fail. An edge failure, typically due to a broken optical fibre, is harder to locate in a short time. That kind of failure is needed to be considered to have a “disaster recovery” policy so that the logical topology remains intact. This is the kind of fault that occurs most frequently in long-haul networks [1].
- We consider fault tolerance for the failure of only one edge. In the real world, the probability of multiple failures on multiple fibres is very small and most work

only attempt to fix single edge faults. We have used shared backup paths with dynamic path allocation to provide fault tolerance.

- Each request for communication uses full bandwidth of a wavelength channel. One channel on a link can only be assigned to one traffic demand even if the traffic demand does not use all the bandwidth of the channel. In other words, we treat traffic grooming as a separate problem that has been solved separately.

- The primary lightpath and its backup lightpath share the same set of regenerators. In each viable segment, the segment has two components – a RWA for a primary path and RWA for a backup. Thereafter, a primary and a backup lightpath are considered as a pair in each segment. If the backup path cannot be allocated during our search for a path pair in a segment, then we consider that such a segment cannot be used.

3.3 Design Objectives

The objective of this study is to develop an algorithm for establishing, in a translucent network that is already supporting a number of ongoing communications, a new primary and a new backup path (using shared path protection) in response to a request for communication. The idea is that there is a central agent (perhaps a designated node in the network) that is maintaining a database of all communication currently in progress as well as other information, such as the physical topology of the network, the locations of the regenerators and the optical reach. When a new request for a communication arrives at any node (possibly the source node), that node will pass on the request to this central agent to determine whether the request can be handled. The algorithm we propose in this thesis will be executed at this server. This kind of scenario is reasonable when a network has stable patterns of communication and the lightpaths in existence change only slowly (perhaps a typical existing lightpath may have an expected lifetime of weeks). This justifies the use of an algorithm as described here which is expected to be executed in an offline mode but will optimize the network resources to the extent possible. Earlier experiments reported in [2] by Mr Quazi Rahman included two Integer Linear Programs (ILP-1 and ILP-2). The setup under which ILP-2 worked had two deficiencies. Before ILP-2 starts, the system generates a fixed set of paths between nodes that are within optical reach of one another and the assumption was that once a lightpath is set up, it will never be brought down. Even though ILP-1 gave the optimal value in small and medium scale networks, it was clear that a better algorithm is needed. There were two changes that we investigated with respect to Mr Rahman's work. The first was to see if the performance would improve by changing the definition of the fixed set of paths between nodes that are within the optical reach of one another, whenever a new request for communication fails. The second was to determine how the system behaves when existing lightpaths are taken down. To handle the first change, we have implemented the APFE algorithm and ran it whenever needed. To handle the second change, we have developed a simulator where we allow new lightpaths to be generated as well as existing lightpaths to be taken down.

Since an Integer Linear Program is used for the study, it is expected that the response time would be relatively slow which would make the application of such algorithms in more dynamic scenarios (where lightpaths should be set up or taken down in a matter of milliseconds) impractical. Our objective is to use the proposed method as a benchmark against which faster (but perhaps less efficient) distributed algorithms could be measured.

3.4 Introduction to the New Heuristic

For each request for communication from source S to destination D in a graph G(V,E), we need to find out a graph G'(V',E'), such that the source node and destination node are in G' and

- if there is a path pair from S to D that both paths in the path pair less than the optical reach *r*, then just one segment is needed to handle the request. The graph G' should contain nodes and edges in the path pair connecting S and D;
- if there is no "direct" route in one segment for either primary path or backup path, then G' includes all nodes and edges that will allow us to consider all possible valid paths from S to D using the pre-computed segments from
    a. S to regenerators
    b. regenerators to D
    c. any regenerator to any other regenerator

To do so, V' includes

a. source S

b. destination D

c. regenerators

d. all nodes which appear in the segments mentioned above

Similarly E' contains all edges in the segments mentioned above.

After generating G', we provide G' to ILP-2 to find the route with fewest regenerators/segments (for case 1, the G' is already the shortest path pair, ILP-2 does nothing with respect to a search for paths) and assign the wavelength to each segment.

There is an initialization step which has to be carried out once, before considering any requests for setting up lightpaths. This step (defined in algorithm Initialize given below) creates a list of path pairs where each pair denotes a primary path and a backup path from a source to a destination, where both paths have a length less than the optical reach. Details of this step are described below.

Algorithm Initilize(G)

Initialize listOfPathpairs to an empty list

FOR (all source destination pairs (s,d) in the network)

    If (shortest distance between s and d is less than the optical reach)

        (flag, P_{sd}, B_{sd}) = Call APFE (G, s, d)

    If(flag is true) save (P_{sd}, B_{sd}) in listOfPathpairs

END-FOR

Return listOfPathpairs

We save the list returned by Initialize in two lists called currentListOfPaths and originalListPaths. The originalListOfPaths is never updated but currentListOfPaths is updated as new lightpaths are deployed. Details are described below.

The algorithm uses APFE to search the path pair with shortest distance on a graph G, if there is a pair of path found for source node s to destination node d within the optical reach, and then the algorithm keeps this information in the list. Otherwise, the path pair from source node s to destination node d will not be found in the list. The list will be given to findPathPair (see description below) algorithm for generating graph G'.

The time complexity of this algorithm is $O(n^2)$ where n is the number of nodes in the network.

To generate G', we use an algorithm, called findPathPair, to find out all related nodes and edges and possible path pairs. The algorithm findPathPair is based on the network status when processing the request for communication. Therefore, if findPathPair cannot find any available path pair for request for communication, then our algorithm returns "fail to deploy" without calling ILP-2.

The Pseudo Code 3.1 shows the algorithm detail of findPathPair

Algorithm findPathPair(G, s, d)

Search currentListOfPaths to determine whether or not there is a path-pair corresponding to source s and destination d. If such a path pair exists

Generate G' with the path pair

ELSE

FOR (all nodes, i where node i represents a regenerator)

```
        Search currentListOfPaths to determine whether or not
        there is a path-pair corresponding to source s and node i.
        If such a path pair exists augment G' with the path pair.
    END-FOR
    FOR (all nodes, i where node i represents a regenerator)
        Search currentListOfPaths to determine whether or not
        there is a path-pair corresponding to node i and destination d.
        If such a path pair exists augment G' with the path pair.
    END-FOR
    FOR (all node, i where node i represents a regenerator)
        FOR (all node, j where node j represents a regenerator which is not node i)
            Search currentListOfPaths to determine whether or not
            there is a path-pair corresponding to node i and node j.
            If such a path pair exists augment G' with the path pair.
        END-FOR
    END-FOR
END-IF
Return G'
```

Pseudo Code 3.2: Algorithm of findPathPair

The target of this algorithm is to pre-calculate G' based on current network status. Then it uses ILP-2 to solve the RWA problem and find the pairs of path with fewest regenerators on the routes.

For the given translucent WDM network with regenerators already placed using some RPP algorithm, to handle a given request for communication from source node S to destination node D, the algorithm searches the list of currentListOfPaths to see if the path pair from S to D exists. If it does not exist, then it means the distance of either the primary path or the backup path in the path pair exceeds the optical reach *r*, and then we find out the shortest path pairs in the following scenarios:

- Search out the path pairs from source S to all regenerators in currentListOfPaths,
- Search out all path pairs, from a regenerator to all other regenerators in currentListOfPaths,
- Search out all path pairs from all regenerators to destination node D in currentListOfPaths.

After getting all possible path pairs to build up a new graph G', the algorithm calls ILP-2 to find out a set of path pairs from source node S to destination node D, such that the number of regenerator on the path is minimum and assign the channel number.

The time complexity of this algorithm is $O(k^2)$ where k is the number of regenerators in the network.

An example to explain how the algorithm works is given below.

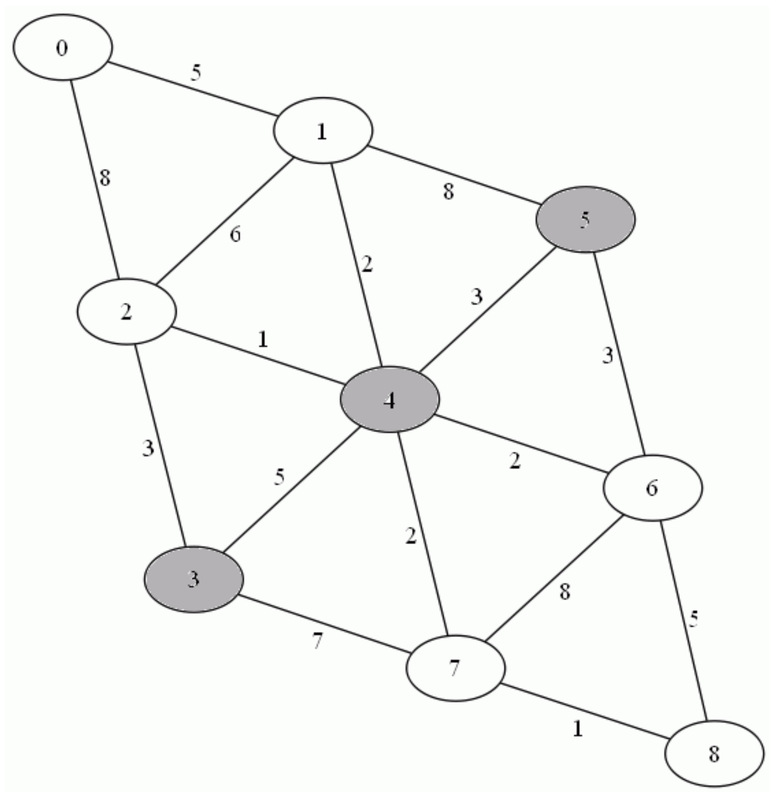


Figure 3.1 An example of a translucent network physical topology

Figure 3.1, shows an example of a translucent network, in which node 3, 4, 5 are regenerators and the optical reach is 10 units.

The results generated by the algorithm is stored in a 3-dimensional array, the size of the first dimension is the maximum permissible number of segments (Determined by allowable Bit Error Rates); the size of the second dimension is 2, - one for the primary and one for the backup path in each segment; the third dimension is the total number of edges in the graph. The entry in cell (*i, j, k*) is a boolean value, where 0 represents "not used" and 1 represents "selected in the path". This entry in cell (*i, 0, k*) ((*i, 1, k*)) indicates whether edge k in the graph appears in the i_{th} segment of the primary (backup) path. For instance, in a translucent WDM network with 16 edges, if the first index is *i* (meaning the

i_{th} segment) , and the second is j (which may be either 0 or 1, depending on whether we are describing the primary or the backup segment) we have 16 entries for the successive values of the third dimension. If these sixteen entries are 0 0 0 1 0 0 0 1 0 0 1 0 0 0 0 0, it means that edges 3, 7, 10 are selected to form the i_{th} primary (if j is 0) or backup (if j is 1) segment.

By using this format, if we have a request for communication from source node 0 to destination node 8, there is no such lightpath, that the total distance is less than the optical reach 10. Thus, the algorithm tries to find out the shortest path pairs in following routes:

- 0-3: The distance of shortest path is more than the optical reach 10, no lightpath
- 0-4: (0-1-4, 0-2-4)
- 0-5: No lightpath shorter or equal to the optical reach 10
- 3-4: (3-2-4, 3-4)
- 3-5: only one lightpath can be found that the distance is less than the optical reach 10, no path pair is found
- 4-3: (4-2-3, 4-3)
- 4-5: (4-5, 4-6-5)
- 5-3: only one lightpath can be found that the distance is less than the optical reach 10, no path pair is found
- 5-4: (5-4, 5-6-4)

- 3-8: only one lightpath can be found that the distance is less than the optical reach 10, no path pair is found
- 4-8: (4-7-8, 4-6-8)
- 5-8: (5-4-7-8, 5-6-8)

Then we will have the G’ (shown in Figure 3.2) with path pairs of route 0-4, 3-4, 4-3, 4-5, 5-4, 4-8, 5-8.

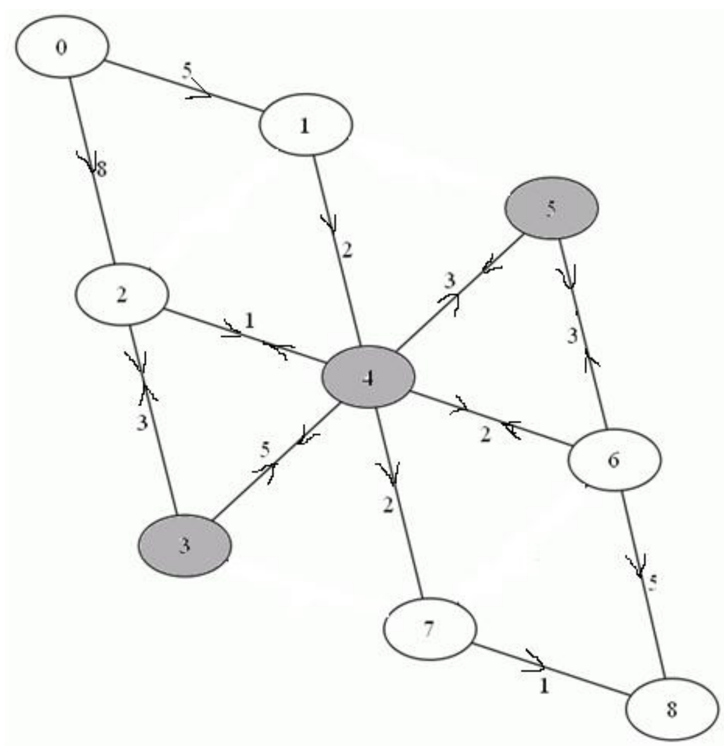


Figure 3.2 G’ from G for the request for communication Source=0, Destination=8

In this algorithm, we also need to maintain a database for all other supporting information, (such as the network status). The network status includes the traffic demands which have been deployed on the network; the channels on the links of those already used by primary paths currently deployed to handle existing demands cannot be available for other requests for communication, channels which are currently used as backup paths that can be shared with the backup path the new request for communication. Some associated information (supporting information) also needs to be maintained in the database. For instance in Example 3.1, we also need some information to be stored including the source node and the destination node of each segment, which backup paths have been reserved for current traffic demands, which nodes are regenerators.

3.5 Details of the Algorithm

According to the APFE algorithm, the algorithm finds the shortest path pair from a source to a destination. Algorithm findPathPair tries to find out if there exists a path pair from S to D within the optical reach *r*. If not, it calculates all shortest path pairs within the optical reach *r* from the source to all regenerators, from each regenerator to all other regenerators, and from all regenerators to the destination node.

Example

In Figure 3.1, if the optical reach is 10, source node is 0 and destination node is 8, there is no direct route from 0 to 8 having a distance less than 10, then the algorithm tries to route the translucent lightpath through regenerators. In this example, the network is not currently handling any request and this new request is the first request to be handled.

Source – Regenerators: 0-3, 0-4, 0-5

Regenerators – Regenerators: 3-4, 3-5, 4-5, 4-3, 5-3, 5-4

Regenerators – Destination: 3-8, 4-8, 5-8

For the path pair 0-3, there is no such path shorter than optical reach 10 (fail)

0-4: 0-1-4 and 0-2-4 (success)

0-5: 0-1-4-5, but no second route to have a pair of path (fail)

3-4: 3-2-4 and 3-4 (success), even though we have another path 3-7-4 is shorter than optical reach 10, but it is not the shortest path, longer than the two path we selected, discard it.

3-5: 3-4-5, but no second path (fail)

4-5: 4-5, 4-6-5 (success)

4-3: 4-2-3 and 4-3 (success)

5-3: 5-4-3, but no second path (fail)

5-4: 5-4, 5-6-4 (success)

3-8: 3-7-8, no second path (fail)

4-8: 4-7-8 and 4-6-8 (success)

5-8: 5-4-7-8 and 5-6-8 (success)

Then we have the path pairs (0-1-4, 0-2-4), (4-5, 4-6-5), (4-2-3, 4-3), (5-4, 5-6-4), (4-7-8, 4-6-8), (5-4-7-8, 5-6-8), According to those path pairs, we generate the following matrix when the edge numbers is indexed in sequence as 0-1, 0-2, 1-2, 1-4, 1-5, 2-0, 2-1, 2-3, 2-4, 3-2, 3-4, 3-7, 4-1, 4-2, 4-3, 4-5, 4-6, 4-7, 5-1, 5-4, 5-6, 6-4, 6-5, 6-7, 6-8, 7-3, 7-4, 7-

6, 7-8, 8-6, 8-7. We use the binary value to represent whether the edge is being used for deploying the S-D request so that a value 1 (0) means the edge is (is not) being used.

1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 1 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0

Each path calculation is based on the current network status. If a channel on a fibre has been used by other traffic demand, then the algorithm should consider this channel is not available. In this example, each primary path calculation is based on the "empty" network. The backup path calculation is also based on "empty" network, but need to be edge disjoint from primary path if exists.

After passing this matrix array and associate information to ILP-2, the final result of deployment of 0-8 is

Primary: 0-1-4, 4-7-8 on channel 0 (node 4 is the regenerator)

Backup: 0-2-4, 4-6-8 on channel 0 (node 4 is the regenerator)

One generator used for the request for communication 0-8.

3.6 Simulation

To do the experiment of the algorithm, we have developed a simulator to carry out the algorithm findPathPair in conjunction with ILP-2 for RWA problem and maintain the network status.

3.6.1 Simulator

Given the network topology G(V,E) with the needed parameters of the network, the optical reach *r*, the locations of the regenerators (we assume the RPP problem has been solved prior to the RRP problem we are resolving), and the list L of requests for communication. The simulator handles each request. If the request can be handled, the state of the network is updated and the simulator counts this request as "successful". If the request cannot be handled, the simulator counts this request as "unsuccessful". In the request for communication list L, there are two types of the events. One is a request for communication and we have used 1 to represent such a request for communication. Another type of event is a request to terminate an existing communication. We have used a 0 to represent it. A request to terminate an existing communication is meaningful only if the simulator could flag the request for communication as successful and then it means that all the traffic for this request has been communicated so that the translucent lightpath to handle it can be ended and the resources need to be released to be available for other request for communication.

In conjunction with the algorithm findPathPair, we need to have another algorithm to maintain the network status.

```
Algorithm updatePathPair(G, s, d)
Search orginalListOfPaths to determine whether or not there is a path-pair
        corresponding to source s and destination d
IF such a path pair exits
      (flag, Psd, Bsd) = call APFE(G, s, d)
      If (flag)
            Replace the paths in currentListOfPaths from s to d by Psd, Bsd
ELSE
      FOR (all node, i where node i represents a regenerator)
            Search originalListOfPaths to determine whether or not
            there is a path-pair corresponding to source s and node i.
            IF such a path pair exists
                  (flag, Psi, Bsi) = call APFE(G, s, i)
            IF (flag)
                  Replace the paths in currentListOfPaths from s to I by Psi, Bsi
      END-FOR
      FOR (all node, i where node i represents a regenerator)
            Search originalListOfPaths to determine whether or not
            there is a path-pair corresponding to node i and destination node d.
            IF such a path pair exists
```

```
                    (flag, Pid, Bid) = call APFE(G, i, d)
            IF (flag)
                    Replace the paths in currentListOfPaths from i to d by Pid, Bid
        END-FOR
        FOR (all node, i where node i represents a regenerator)
            FOR (all node, j where node j represents a regenerator)
                    Search originalListOfPaths to determine whether or not
                    there is a path-pair corresponding to node i and node j.
                    IF such a path pair exists
                        (flag, Pij, Bij) = call APFE(G, i, j)
                    IF (flag)
                        Replace the paths in currentListOfPaths from i to j by Pij, Bij
            END-FOR
        END-FOR
END-IF
```

Pseudo Code 3.3 Algorithm of UpdatePathPair

This algorithm updates the list of currentListOfPaths, so that the simulator can use findPathPair to generate a graph G' based on the updated network status, by retrieving the data from currentListOfPaths. The time complexity of this algorithm is $O(k^2)$.

The Simulator algorithm is given as follows

```
Simulator(G,L)
initialize the network status on G
for each request for communication, event, in the list L
{
    IF the type of event is a request for communication THEN
```

```
        Extract source s and destination d for the communication from the request
        G' = findPathPair(G, s, d)
        Call ILP-2 to find out the shortest path pair and
        assign the wavelengths to each segment on the route;
        IF ILP-2 returns "success" THEN
              update the network database with information about the new primary and
                    backup lightpath
        ELSE
              updatePathPair(G, s, d)
              G' = findPathPair(G, s, d)
              call ILP-2 to find out the shortest path pair and
                assign the wavelengths to each segment on the route;
              IF ILP-2 returns "success" THEN
                  update the network database with information about the new primary and
                      backup lightpath
              ELSE return "failed" for the request for communication
              END-IF
        END-IF
    ELSE        //the event is "drop" communication
        IF the request for communication of this event has been deployed THEN
            Update network database to release the resources reserved for the communication
        END-IF
    END-IF
}
```

Pseudo Code 3.4 Algorithm of Simulator

In this simulation, the simulator goes through all the items in the event list L and try to deploy lightpaths in response to the requests for communication. The Simulator algorithm receives an event from the event list. After that the algorithm determines if the event is a request for communication or a termination for a communication. If the event is a request for communication, then it uses findPathPair algorithm to generate a graph G' appropriate for this request for communication. Once G' is generated, the algorithm calls ILP-2 to find the shortest path pairs and assign the wavelengths to each segment of the path pair. If ILP-2 is not able to find the feasible path pair and returns "fail", then the algorithm performs findPathPair again after updating the network status by calling updatePathPairs and tries one more time to call ILP-2. If the request for communication has the feasible solution from ILP-2, then the algorithm updates the network status. Otherwise, the algorithm returns "fail" to the request for communication. If the event is a termination request for communication, then the algorithm updates the network status to release the associated resources.

Since the algorithm use ILP-2 as the part of the execution, and because the ILP-2 is an integer linear program, the time complexity for is exponential with respect to the number of integer variables.

From the algorithm, we can see the event list L contains requests for communication and the terminations of request for communication. The format to describe an event is as follows

Event Type	Event ID	Time	Source	Destination

Table 3.1 Data format of Event List L

Event Type – 1 means the request for communication, 0 means termination request.

Event ID – a unique sequential number of the event, the termination request has same ID with its request for communication.

Time – the time to the request for starting (stopping) the event if event type is 1 (0).

Source – source node of the request for communication

Destination – destination node of the request for communication

For example, a part of the list of requests for communication is given below.

```
1 36 0 0 1
1 24 5 5 3
1 22 7 7 5
1 10 12 2 9
1 8 13 3 1
0 22 14 7 5
1 35 17 7 2
```

Each line represents either a request for a new communication or a request to terminate an existing communication. The first item in a request is 1 (0) if it is a request for new communication (request to terminate an existing communication). The second item is a unique number which serves to identify uniquely each request for communication. The third item is the time to request for new communication (if the first item is 1) or the time to terminate an existing communication (if the first item is 0). The sixth (seventh) item is the source (destination) of the communication

The generation of the event list is described in next section.

3.6.2 Requests for Communication Generator

For simulating the algorithm and experimenting the effectiveness and efficiency, the event list generator is needed prior to the simulation. The event generator needs to know the physical topology of the translucent network, but it doesn't need to know the locations of regenerators. Also it needs to know the following parameters to define the event item in appropriate manner:

- The total time for which the simulation is to be carried out.
- Maximum duration of each event of request for communication. This is used to control the maximum time duration of each traffic request for communication.
- Erlang Distribution. This parameter controls the probability of traffic demands. In other words, it is to control the maximum number of concurrent traffic demands on the network. It also represents the load of the WDM network. The Erlang Distribution formula is

$$Erlang = \frac{\sum \lambda_i}{\tau}$$

The value of Erlang is a summary value of time during of all the traffic demands, then divided by the total time of iteration. The value of Erlang gives expression to the density of the network traffic in a fixed iteration time.

In this formula, λ_i is the duration of each event *i* generated randomly if the end time is less than the total iteration time. Otherwise, $\lambda_i = \tau - Start\_Time_i$. The τ represents the maximum iteration.

The algorithm for the event generator is given below:

```
Event_Generator (Max_Node, Max_Iteration, Max_Duration, Target_Erlang)
index=1
DO WHILE Erlang < Target_Erlang
{
        Start_time=random number which is less than the Max_Iteration
        Source =random number which is less than Max_Node
        Destination=random number which is less than Max_Node and it is not equal to
        Source
        Duration=random number which is less than (Max_Iteration-Start_time)
        save into the event list L for this event (type=1, index, Start_time, source,
destination)
        save into the event list L for the generic event (type=0, index,
        Start_time+duration, source, destination)
        Total_Duration+=Duration
        Erlang=Total_Duration/Max_Iteration
}
sort the list L by the start_time.
```

Pseudo Code 3.3 Event generator algorithm

3.7 Contributions

This algorithm improved the ILP-2 effectiveness. In another word, it reduces the failure of deployment that ILP-2 has. In ILP-2, it searches only a limited number of the first several most possible paths for the optimal result. With this algorithm implemented, it provides almost all possible paths generated heuristically to ILP-2 to search and the searching scope is still relatively small.

Compare with the ILP-1 formulation, this algorithm tremendously improves the performance. It realizes the optimization to minimize the number of regenerators in a translucent network to be computable.

The experimental results and comparison metric are presented in the next chapter.

Chapter 4

EXPERIEMENTAL RESULTS AND ANALYSIS

In this chapter, we present and discuss the results we obtained by performing the findPathPair simulation, using the heuristic algorithm we proposed on 4 different network topologies with 5 different traffic volumes.

4.1 Case Description

In Table 4.1, we present the number of requests for communication we randomly generated as the test cases.

Number of Nodes	Erlang value =10	=20	=30	=40	=50
10	42	80	138	212	242
15	50	110	137	166	219
20	43	95	142	188	285
30	44	90	141	183	217

Table 4.1 Number of request for communication in different test cases

Each row in the table represents a physical topology of the translucent WDM network. We have used the following physical topologies.

CASE 1: Node=10, Channel=8, Optical Reach=1000 km, Regenerators = 1,4,5,8

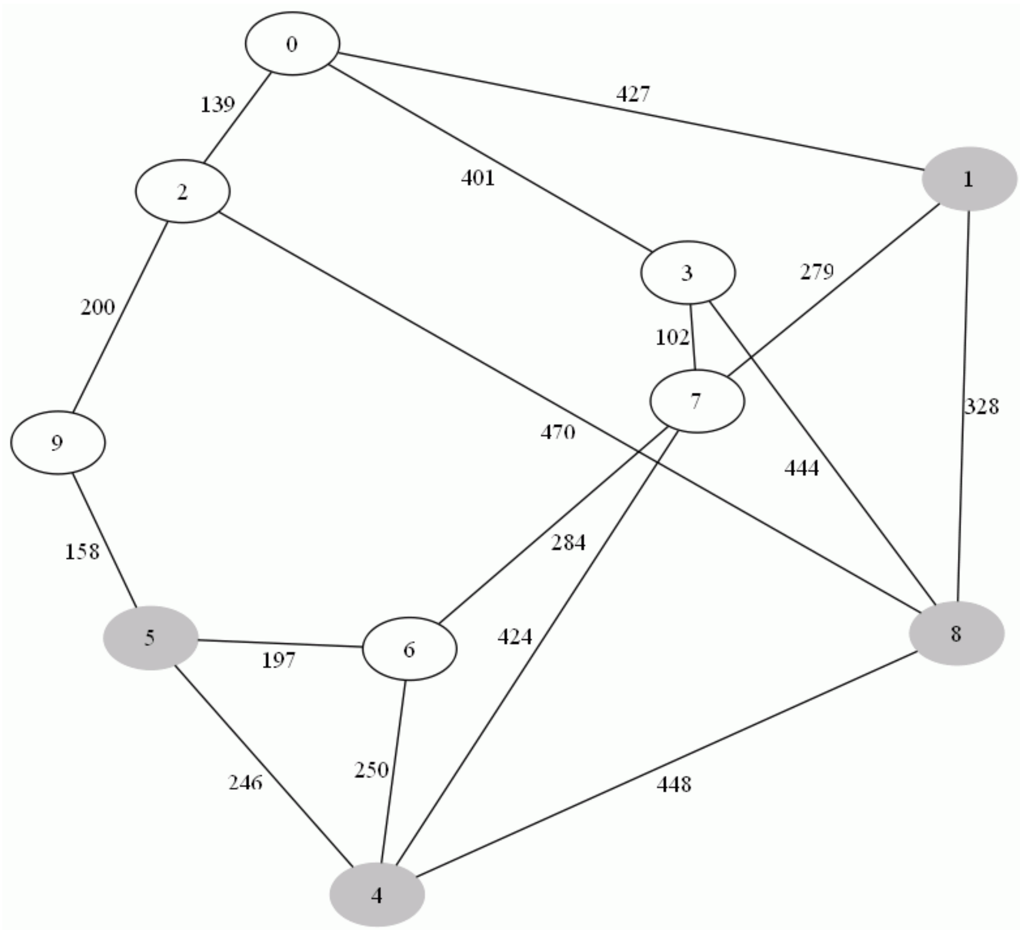


Figure 4.1 Graph of the WDM network with node=10

0	427	139	401	0	0	0	0	0	0
427	0	0	0	0	0	0	279	328	0
139	0	0	0	0	0	0	0	470	200
401	0	0	0	0	0	0	102	444	0
0	0	0	0	0	246	260	424	448	0
0	0	0	0	246	0	197	0	0	158
0	0	0	0	250	197	0	284	0	0
0	279	0	102	424	0	284	0	0	0
0	328	470	444	448	0	0	0	0	0
0	0	200	0	0	158	0	0	0	0

Table 4.2 Matrix of physical topology for WDM network with node-10

From Figure 4.1, we can have a matrix to present the physical topology of this network. In the Table 4.2, 0 represents “no direct connection” and the integer numbers are the distances on the link between nodes in kilometres (km).

CASE 2: Node=15, Channel=8, Optical Reach=1000, Regenerators=0,2,3,5,8,11

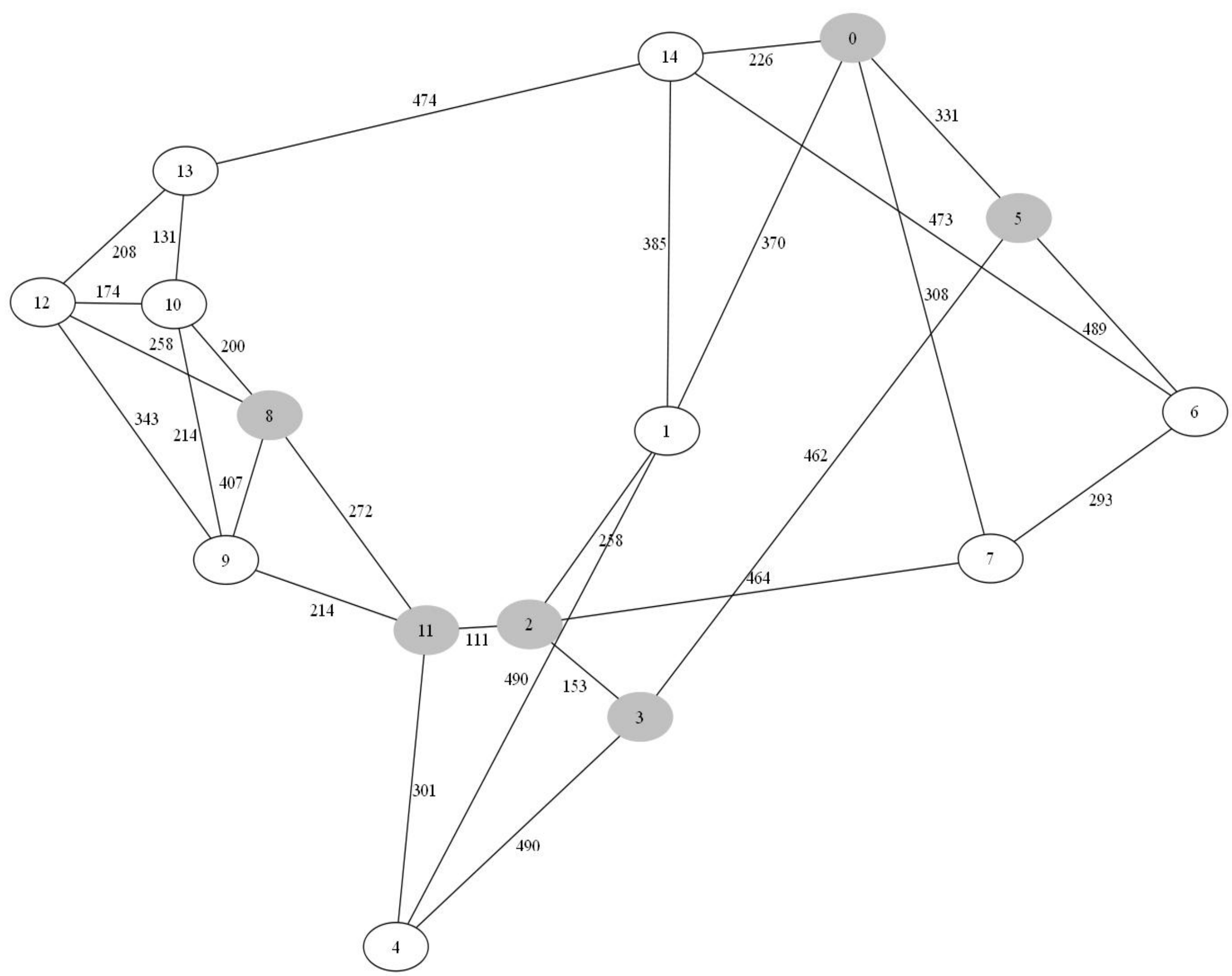


Figure 4.2 Graph of WDM network which node=15

CASE 3: Node=20, Channel=8, Optical Reach=1000, Regenerators=1,6,8,9,17,19

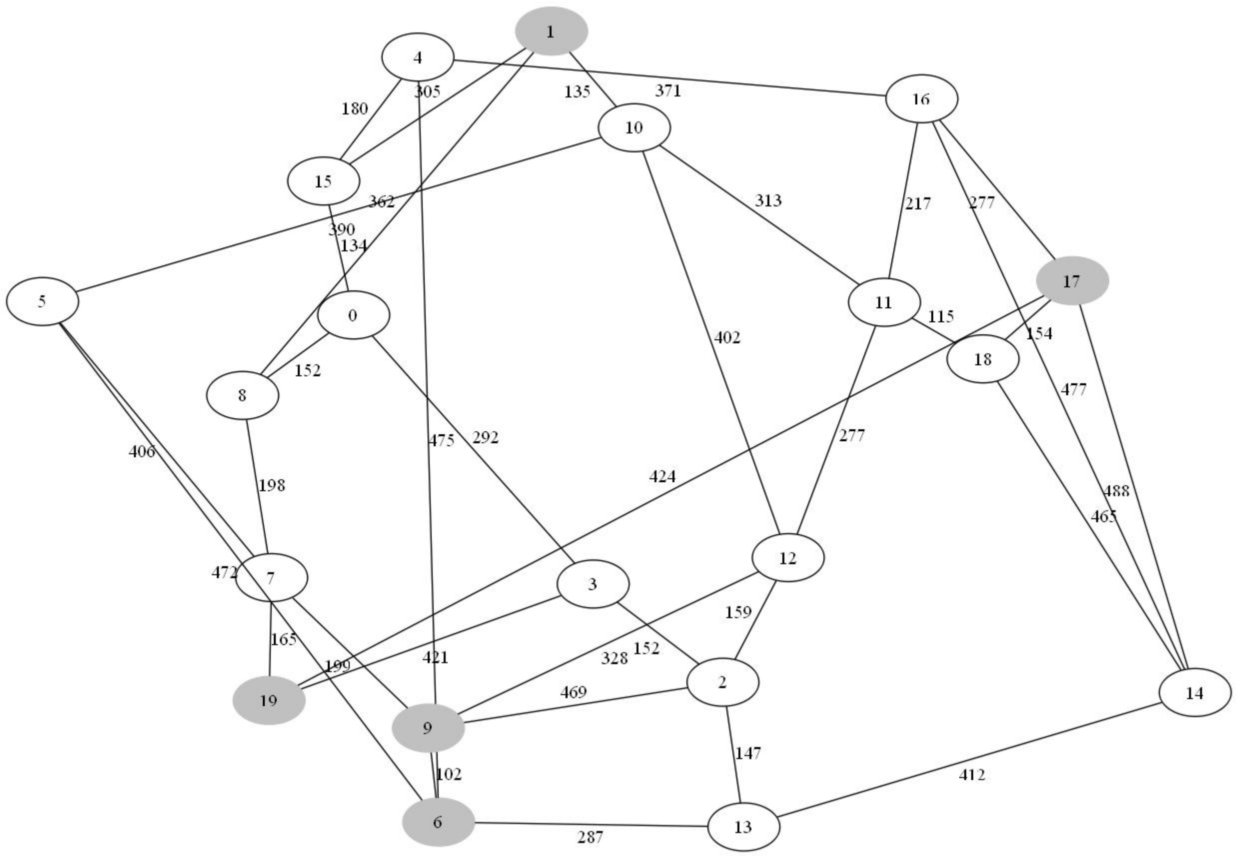


Figure 4.3 Graph of WDM network with node=20

CASE 4: Node=30, Channel=8, Optical Reach=1000, Regenerators=1,2,5,9,10,12,17,19,22,29

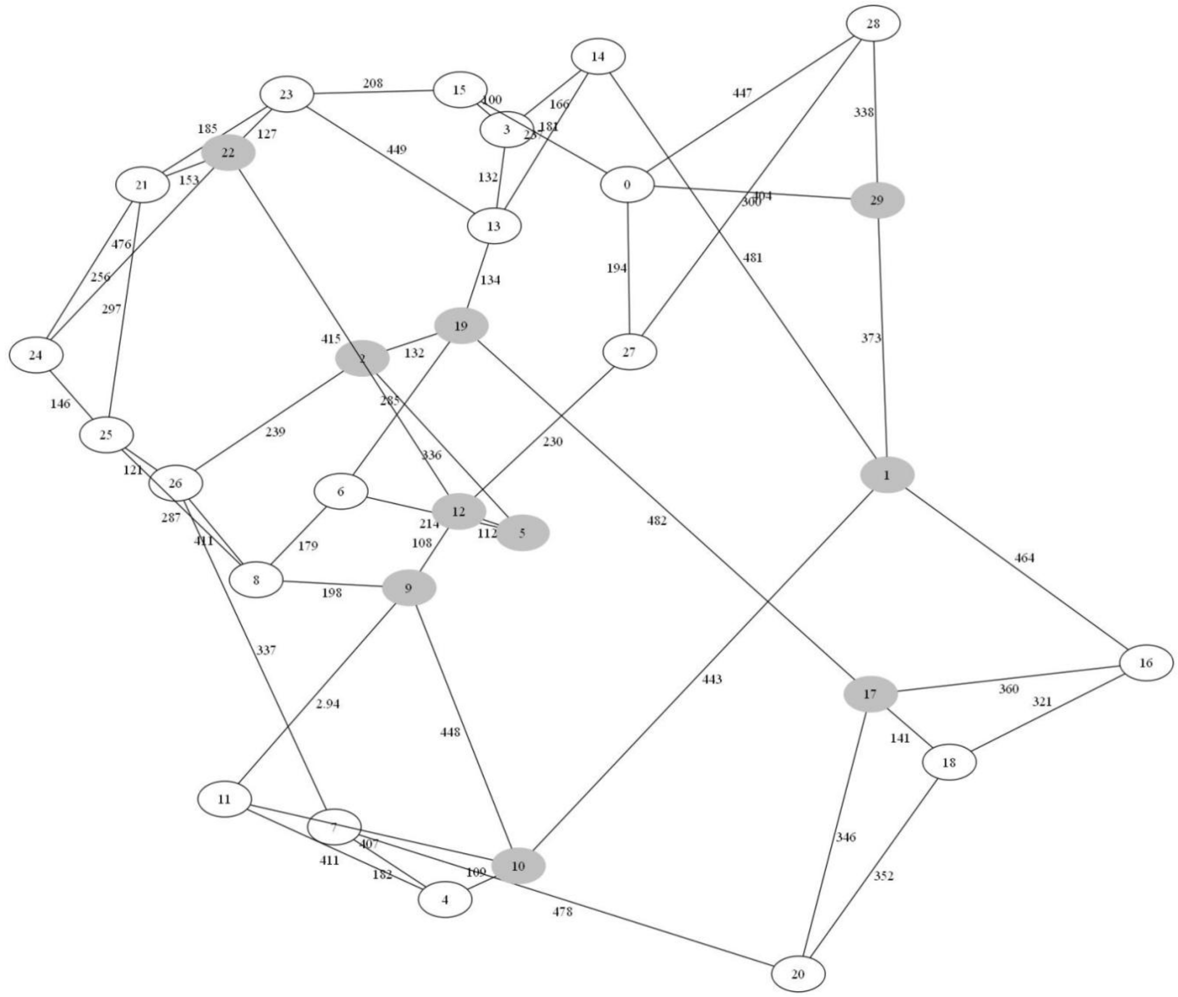


Figure 4.4 Graph of WDM network with node=30

4.2 Simulation Results

The simulation of ILP1 and the new heuristic conjunction of findPathPair algorithm and ILP2 were carried out on the same computer:

CPU: Intel 64bits 2.2GHz X 4

Sun Saloris 5.10, CPlex 11.1.0

The results are shown in the Tables 4.1, 4.2, 4.3, and 4.4. The values of Success Rate in those tables are presented by the percentage of successfully deployed requests for communication out of total requests for communication. The values of Avg 3R Rate are presented by the average number of regenerator used on each successfully deployed request for communication. The values of Efficiency in those tables are presented by the CPU execution time in seconds.

	Erlang Value	10	20	30	40	50
	Number of Requests	54	85	131	199	238
ILP1	Success Rate	100%	100%	100%	99.5%	97.9%
	Avg 3R Rate	0.222	0.235	0.260	0.298	0.369
	Efficiency	21.85	39.67	63.09	102.38	140.06
findPathPair	Success Rate	100%	100%	91.6%	82.9%	75.2%
	Avg 3R Rate	0.444	0.588	0.617	0.594	0.648
	Efficiency	1.10	2.36	4.33	7.89	10.23

Table 4.3 Comparison result for the network of Node=10

	Erlang Value	10	20	30	40	50
	Number of Requests	48	96	133	199	234
ILP1	Success Rate	100%	100%	100%	99.5%	99.15%
	Avg 3R Rate	0.583	0.552	0.752	0.803	0.888
	Efficiency	272.65	1417.34	2132.19	2874.99	3444.93

findPathPair	Success Rate	97.92%	94.79%	78.20%	69.85%	65.55%
	Avg 3R Rate	1.4468	1.3846	1.3462	1.5971	1.359
	Efficiency	3.21	8.62	13.90	24.78	33.02

Table 4.4 Comparison result for the network of Node=15

	Erlang value	10	20	30	40	50
	Number of requests	40	98	137	197	232
ILP1	Success Rate	100%	100%	100%	100%	99.14%
	Avg 3R Rate	0.350	0.316	0.438	0.416	0.9827
	Efficiency	129.76	352.90	619.34	1036.76	1091.64
findPathPair	Success Rate	100%	96.94%	89.05%	82.29%	74.57%
	Avg 3R Rate	0.950	0.905	1.180	0.9647	0.9827
	Efficiency	3.59	11.67	23.83	38.12	50.02

Table 4.5 Comparison result for the network of Node=20

	Erlang value	10	20	30	40	50
	Number of Requests	41	92	144	192	233
ILP1	Success Rate	100%	100%	100%	100%	100%
	Avg 3R Rate	1.146	0.946	1.028	0.932	1.060
	Efficiency	10483.83	13334.46	28041.35	58945.05	107202.81
findPathPair	Success Rate	63.41%	75.00%	61.81%	62.00%	59.66%

	Avg 3R Rate	1.308	1.5362	1.3258	1.2941	1.2374
	Efficiency	39.70	80.90	135.24	205.68	265.95

Table 4.6 Comparison result for the network of Node=30

4.3 Analysis

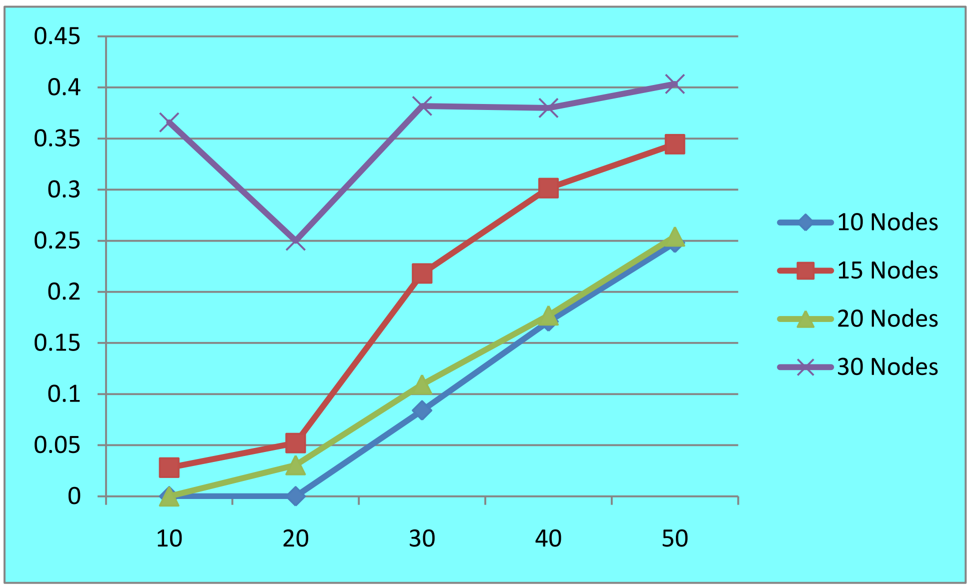


Figure 4.5 Blocking probability v/s traffic load with findPathPair algorithm

Figure 4.5 shows the effect of varying the traffic load on the call blocking probability for networks of different sizes. The traffic load was varied from 10 to 50 erlangs in steps of 10 erlangs. The call blocking probability was measured for networks having 10, 15, 20 and 30 nodes. It can be observed that when the size of the network was large and/or the network had higher traffic loads, the call blocking probability is increased. This, of course is expected. The findPathPair algorithm is a heuristic. So that, unlike ILP1, it does not give an optimal solution.

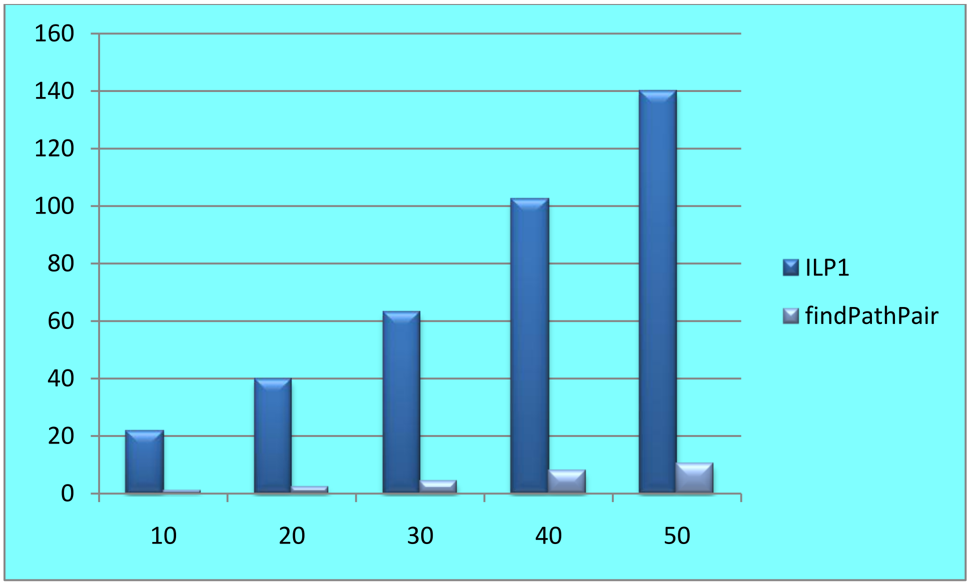


Figure 4.6 CPU time v/s traffic load on the Network of Node=10

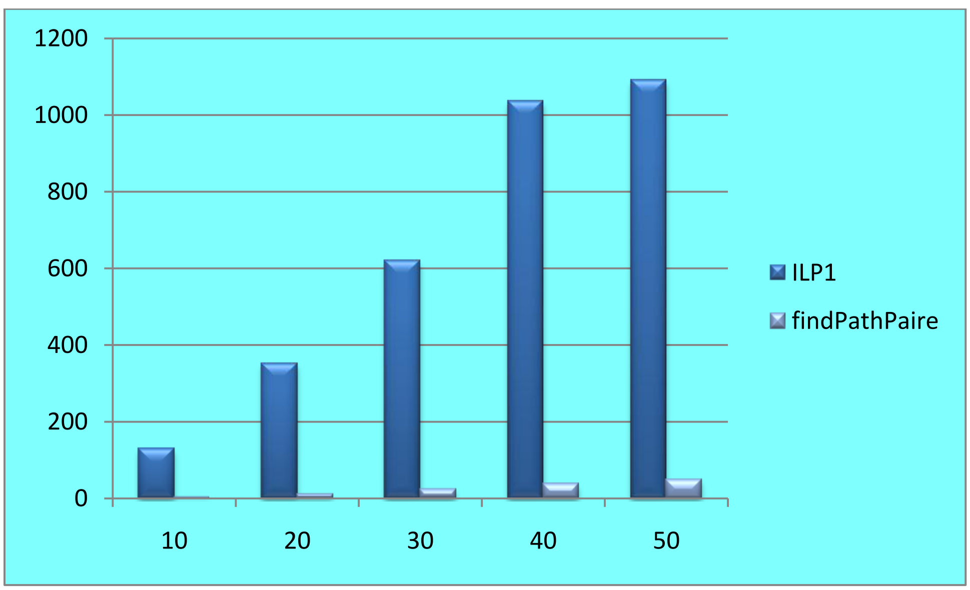


Figure 4.7 CPU time v/s traffic load on the network of node=20

Figure 4.6 and Figure 4.7 show the effect of varying the traffic load on CPU execution time (in seconds) on networks having 10 and 20 nodes. The findPathPair algorithm is much faster compared to ILP1. The CPU time is acceptable optimizing a route in response to a request for communication.

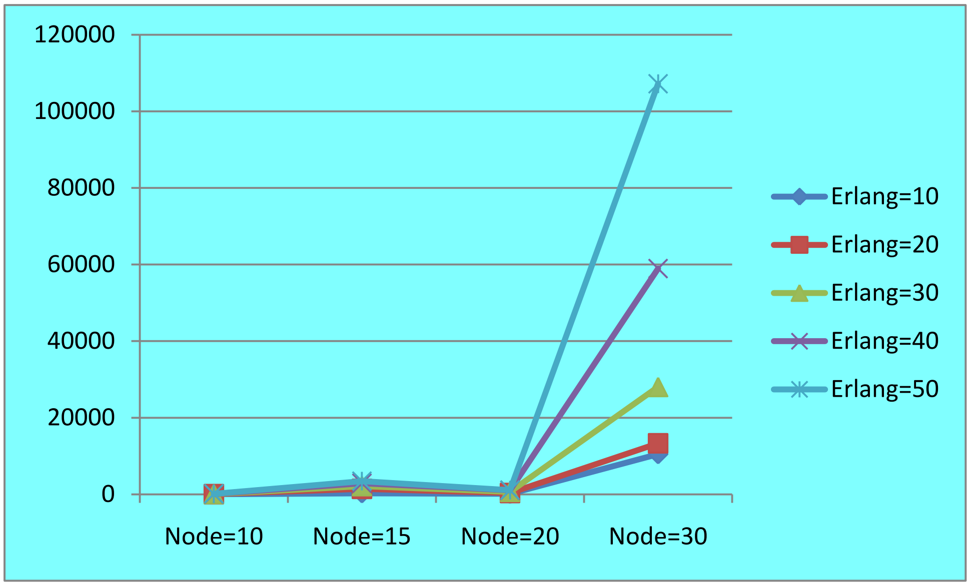


Figure 4.8 CPU time v/s/ network scales of ILP1 algorithm

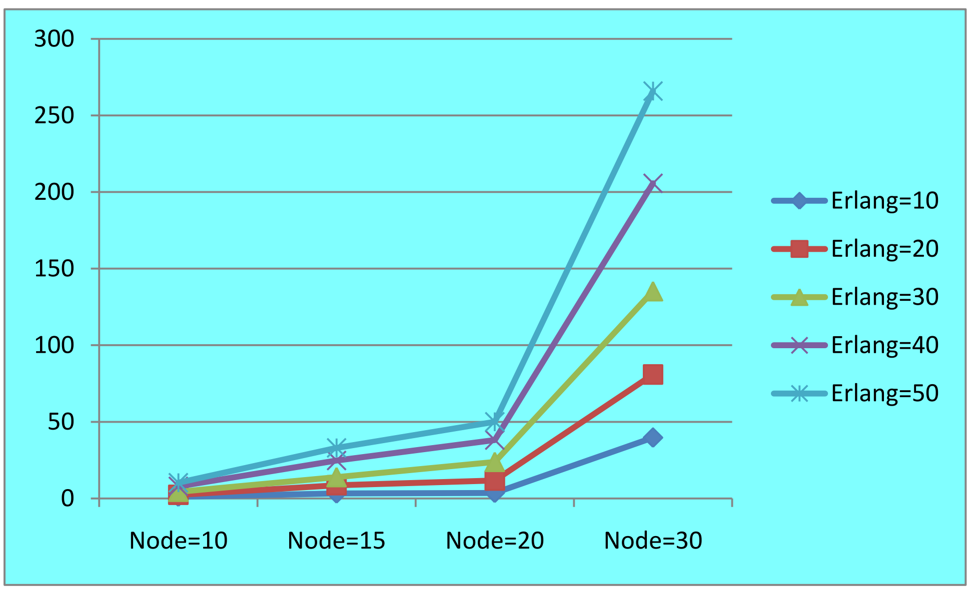


Figure 4.9 CPU time v/s network scales of findPathPair algorithm

Figure 4.8 and Figure 4.9 show the CPU execution time of varying size of network and different traffic loads using ILP1 algorithm and the findPathPair algorithm. It can be observed that ILP1 has the execution time increases rapidly when the size of the network is increased. The findPathPair heuristic algorithm performs steady of incremental of network size increasing.

From the experimental results, we conclude that findPathPair algorithm can find out the near optimal solutions for the requests for communication in the acceptable time frame, even though the call blocking probability is somewhat higher than ILP1.

Chapter 5

CONCLUSIONS AND FUTURE WORKS

Optical networks have been widely used in the modern computer networks. Translucent WDM Optical Networks with 3R regenerators placed in the network is the most recent technology in optical networks to handle the data transferring and communication over long distances. In an environment where translucent lights are used on demand, the problem we are focusing on in this thesis is to minimize the number of regenerators used (Routing with Regenerator Problem) with path protection.

In this thesis, we have introduced a heuristic algorithm with combination of shortest path pair finding and ILP formulations for RWA problem to solve Routing with Regenerator Problem in translucent WDM optical networks.

The newly introduced algorithm uses shortest path pair finding to reduce the ILP searching scope further to significantly improve the efficiency compared to the pure ILP solution and also maintains the effectiveness to be acceptable. By performing the simulation of implementing the algorithm, we pre-compute the relevant possible lightpaths for the request for communication and use the ILP formulations to solve the minimum number of regenerators used as well as wavelength assignment problems. The paper [2] states that the ILP is able to handle small size of translucent network. After experimenting on ARPANet (20 nodes and 32 links) and Italian National Network (28 nodes and 47 links), our heuristic algorithm can handle the medium size and large size of networks (covering entire North America or Italy) within the acceptable time, and also the effectiveness of result is reasonable.

According to the results of simulating the algorithm with various network topologies and different traffic volumes, we have the conclusion that the heuristic algorithm can conduct out the solution for the requests for communication in short time with an acceptable effectiveness.

Future works

The heuristic algorithm has been tested exhaustively. There are still some possible improvements open for future research. The method described here uses a restricted search in order to speed up the response time. It is possible that a more complex algorithm may allow users to specify how much restriction the user is willing to impose on the network. If the user is willing to accept a longer wait time, it is very likely that the blocking probability may be reduced further. Depending on the simulation result of implementation of the algorithm, the deployment success rate is pretty good for the “balanced” requests for communications. That means if the requests for communication are distributed to the entire network uniformly, then the result is fairly good compared with ILP-1 formulation. However, if the requests for communication are not distributed “balanced” which means some nodes or links are used by the requests repeatedly and rest of the nodes and links are quiet vacant, then the deployment success rate is relatively low.

The future research on this problem can be made on the heuristic to expend the search scope for ILP to improve the effectiveness.

For deployment of the request for communication which does not need to perform the 3R regeneration, in other words, no regenerator is involved in the entire route or neither primary path nor backup path exceed the optical reach *r*, our algorithm still needs to call ILP-2 to solve the RWA problem. The future research can improve the performance of the algorithm to solve the RWA problem without calling ILP.

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