FAILURE INDEPENDENT PATH PROTECTION AGAINST SINGLE-SRLG FAILURES IN ELASTIC OPTICAL NETWORKS

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By
Hasan Gökhan Uysal
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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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FEBRUARY 2018

In Elastic Optical Networks, flexi-grid spectrum allocation is used where the the spectrum is assigned to optical connections according to their bandwidth requirements so that the capacity is used more efficiently. Ensuring network survivability is one of the main problem in elastic optical networks. In this thesis, we study network survivability against failure of a single link or a single Shared Risk Link Group (SRLG), which is a group of links sharing a common risk of failure. We formulate the network survivability problem where the objective is to minimize the required capacity resources and maximize their efficient usage such that the elastic optical network can recover against all single-SRLG failures. We developed two formulations towards this end using flow and path formulation approaches, respectively. In both approaches, the aim is to use two paths called the active and backup paths for all connection demands. In the normal operations, the active path is used. It is switched to the backup path in case of a failure of the active path. The active and backup paths are chosen SRLG-disjoint so that the network can recover from the failure without knowing the location of the failure, which is called failure independent protection. For the spectrum allocation, an Adaptive Coding and Modulation (AMC) scheme, which assigns the appropriate AMC profile based on the path length, is used. The backup paths can be shared among active paths because concurrent failure of multiple SRLGs is neglected. In the Flow Formulation, an Integer Linear Programming (ILP) is used to calculate SRLG-disjoint active and backup paths according to a given network topology, the set of connection demands and the AMC profile. In the Path Formulation, an ILP is used to select active and backup paths from a pre-computed set of SRLG-disjoint path pairs. In both approaches, the aim is to minimize the resource usage. The formulations are tested for the 14-node

NSFNET and the 24-node USANET topologies. Although the performance of the Flow Formulation is better than the Path Formulation, the Path Formulation has smaller execution times due to its simplicity. The Path Formulation finds a solution for all possible connection demands of the 14-node NSFNET and the 24-node USANET, but the Flow Formulation was not able to find a solution for the NSFNET topology when the number of demands is large and for the USANET topology even for low number of demands. Both formulations are tested for 10 randomly selected demand sets each with 50 connection requests for 14-node NSFNET and the performance of the Flow Formulation is 5% better than the Path Formulation on the average. In some cases, the Path Formulation gives a better solution than the Flow Formulation when the runtime is limited because of the quality of the pre-computed set of path pairs. The Path Formulation is tested by limiting the number of pre-computed path pairs for all possible demands in 24-node USANET. It is found that the optimal solution first decreases rapidly as the number of path pair increases, but then it saturates when the number of path pairs per connection exceeds 30..

Keywords: Elastic Optical Networks, Shared Risk Link Groups, Path Protection, Flow Formulation, Path Formulation.

ÖZET

ESNEK OPTİK AĞLARDA TEK SRLG ARIZALARINA KARŞI ARIZADAN BAĞIMSIZ YOL KORUMA

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Esnek Optik Ağlarda, esnek-grid spektrum tahsisi, spektrumun bant genişliği gerekliliklerine göre optik bağlantılara atanmasını sağlar, bu nedenle kapasite daha verimli kullanılır. Ağın sürdürülebilirliği, esnek optik ağlardaki temel sorunlardan biridir. Bu tez çalışmasında, tek bağlantı arızasına veya arızaya karşı ortak riski taşıyan bir grup bağlantıdan oluşan tek bir Risk Paylaşan Bağlantı Grubu (SRLG) arızalarına karşı ağ sürdürülebilirliği çalışılmıştır. Ağın sürdürülebilirliği sorunu, gerekli kapasite kaynaklarını en aza indirgemek ve etkin kullanımlarını en üst düzeye çıkartacak şekilde esnek optik ağların bütün tek SRLG arızalarına karşı çalışabilmesini sağlamak amacıyla formüle edilmiştir. Akış ve yol formülasyon yaklaşımlarını kullanarak bu amaç doğrultusunda sırasıyla iki formülasyon geliştirdik. Her iki yaklaşımda da amaç, tüm bağlantı talepleri için ana ve yedek yollar olarak adlandırılan iki yol kullanmaktır. Normal işlemlerde ana yol kullanılır. Ana yol arızası yaşandığı durumlarda yedek yola geçilir. Ana ve yedek yollar, arızanın yerini bilmeden ağın etkilenmemesini sağlamak için ayrışık-SRLG olacak şekilde seçilir. Bu durum, arızadan bağımsız koruma olarak adlandırılır. Spektrum tahsisi için, yol uzunluğuna dayalı olarak uygun Uyarlamalı Modülasyon ve Kodlama (AMC) profilini tayin eden bir AMC profili kullanılır. Birden fazla SRLG arızasının aynı anda yaşanması ihmal edildiği için yedek yollar, ana yollar arasında paylaşılabilir. Akış Formülasyonunda, verilen ağ topolojisi, bağlantı talep seti ve AMC profiline göre ayrışık-SRLG ana ve yedek yolları hesaplamak için bir Tamsayılı Doğrusal Programlama (ILP) kullanılır. Yol Formülasyonunda, ILP, önceden hesaplanmış ayrışık-SRLG ana ve yedek yol çiftleri setinden seçilmek için kullanılır. Her iki yaklaşımda da amaç, kaynak kullanımını en aza indirmektir. Formülasyonlar, 14 düğümlü NSFNET ve 24 düğümlü USANET topolojilerinde test edilmiştir. Akış Formülasyonunun performansının Yol Formülasyonundan daha iyi olmasına karşın, Yol Formülasyonunun sadeliği nedeniyle daha az işletim süresi olduğu görülmüştür. Yol Formülasyonu, 14 düğümlü NSFNET ve 24 düğümlü USANET topolojilerinin olası tüm bağlantı talepleri için bir çözüm bulabilmesine karşın Akış Formülasyonu bulamamıştır. Her iki formülasyon da, 14 düğümlü NSFNET için her biri rasgele seçilmiş 50 bağlantı isteğinden oluşan 10 talep seti için test edilmiştir ve Akış Formülasyonunun performansı, Yol Formülasyonundan ortalama %5 daha iyi sonuç vermiştir. Bazı durumlarda, Yol Formülasyonu önceden hesaplanan yol çiftlerinin kalitesinden dolayı sınırlı hesaplama süresi içinde daha iyi bir çözüm bulabilmektedir. Yol Formülasyonu, 24 düğümlü USANET'de olası tüm talepler için önceden hesaplanan yol çiftlerinin sayısını sınırlayarak test edilmiştir. Yol sayısı sınırı azaldıkça en uygun çözümün hızla kötüleştiği bulunmuştur. Sınır 30'dan büyük olduğunda, en uygun çözümün doyuma ulaştığı gözlemlenmiştir.

Anahtar sözcükler: Esnek Optik Ağlar, Risk Paylaşan Bağlantı Grubu, Yol Koruması, Akış Formülasyonu, Yol Formülasyonu.

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Chapter 1

Introduction

Ultra high data rate demand is increasing day by day because of cloud computing, scientific research, video sharing etc. According to the estimation of leading network company Cisco, global IP traffic is expected to reach 194.4 exabytes per month by 2020, up from 72.5 exabytes per month in 2015 [1]. To meet the huge amount of data transmission request, optical fibers are used instead of copper due to its advantages on capacity performance. The capacity carried by a single-mode optical fiber has increased by 4 orders of magnitude in the past three decades [2].

After the development of the Wavelength Division Multiplexing (WDM) in 1992, the data transmission rate in optical communication has substantially increased. WDM increases the network capacity by assigning incoming optical signals to specific frequencies of light. Therefore, multiple independent data streams can be carried over the same optical fiber. WDM is not effective for future demands because it uses fixed-grid spectrum allocation where it uses the same frequency grid with fixed frequency spacing which results in wasted spectrum for connections requiring lower data rates [3, 4, 5].

In order to increase the spectrum efficiency, fixed-grid spectrum allocation is replaced by flexi-grid spectrum allocation where spectrum is allocated. Elastic Optical Networks proposes a solution to this problem. In Elastic Optical

Networks, the spectrum is allocated according to the data rate requirement of demands. The spectrum is divided into small frequency slots. According to the required connection data rate, a number of frequency slots are assigned to each optical connection. In WDM, the AMC profile is fixed due to the fixed-grid spectrum allocation. However, an AMC profile is used in Elastic Optical Networks. For the spectrum allocation, AMC assigns an appropriate modulation and coding scheme to the path based on the path length. As the path length increases, the number of frequency slots allocated by the spectrum increases.

In Elastic Optical Networks, one of the main problems is the survivability issue. As the data rates of demands increase, failures in networks are becoming more important since a single failure can affect a very large amount of traffic. In survivable networks, in case of a failure of a single link or a single-SRLG, which is a group of links where failure of a link in the group causes the failure of other links in the group, the traffic should not be disrupted after the failure occurs. In order to achieve this aim, an active path and a backup path can be used for each connection. For the normal operations, the connection uses the active path, and it is switched to the backup path in case of a failure.

Different techniques have been considered to ensure the survivability of elastic optical networks in the literature. In [6], an ILP model is introduced to calculate active and backup paths for connection requests subject to single-link failures. The calculation is based on selecting active and backup paths from a set of predefined path pairs by minimizing the usage of spectrum resources for a given network topology, set of connection demands and their bandwidth requirements. In [7], the calculation of active and backup paths are based on minimizing the connection blocking probability and the bandwidth blocking probability for a given network topology, set of connection demands and their bandwidth requirement. Single SRLG failure is considered.

In this study, we propose an ILP model for a problem of Routing and Spectrum Allocation with Shared Backup Path Protection (RSA/SBBP) in an elastic optical network with static traffic demands subject to single-SRLG failures. The formulation does not consider to minimize the connection blocking probability and the bandwidth blocking probability as described in [7]. The objective of the ILP is to minimize the resource usage and maximize the resource utilization efficiency. The resource usage is minimized by minimizing the total capacity usage in the network. The resource utilization efficiency is maximized by minimizing the number of edges used by active and backup paths. Since the active paths are used in normal operations, capacity usage of all active paths are considered. For the capacity usage of backup paths, only the maximum usage is considered for each edge, which corresponds to the worst SRLG failure, i.e, the SRLG failure requiring the maximum backup capacity over the link.

SBBP concept is illustrated in Figure 1.1 [8], where failure of active paths r and t causes the usage of backup paths a and path b respectively. Since the network is survivable against single-SRLG failures, the survivability is not guaranteed against concurrent failures of paths r and t. Therefore, sharing of backup paths is allowed.

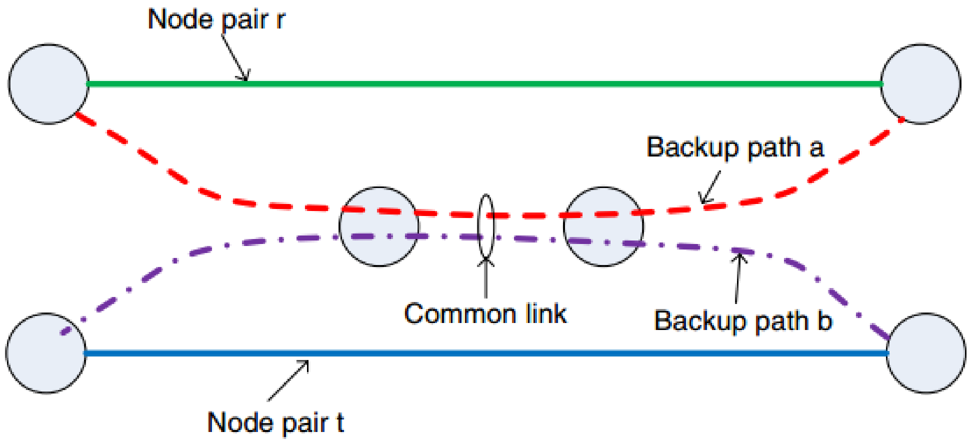


Figure 1.1: Two backup paths whose corresponding working lightpaths are mutually disjoint share a common link.

Two formulation approaches are proposed for the calculation of active and backup paths: Flow Formulation and Path Formulation. In the Flow Formulation, active and backup paths are calculated by considering the capacity constraints and shared backup path protection. In the Path Formulation, active and backup paths are selected from the set of pre-computed active and backup path pairs by considering the capacity constraints and shared backup path protection. Both optimization problems are formulated by using ILP. Pre-computed path pairs are calculated by Yen's Algorithm [9] after the modification of the network as given in [10, 11]. First, the network is duplicated and connected fro the destination node of real network to source node of duplicated network. Then, paths from the source node of the real network to destination node of the duplicated network is computed by Yen's algorithm. Then, loopless and SRLG-disjoint path pairs are selected. The ILP models are solved using the CPLEX optimizer.

Since all possible scenarios can be scanned in the Flow Formulation, it outperforms the Path Formulation. However, its disadvantage is having longer execution times because of the larger problem size. The Path Formulation achieves shorter execution times compared to the Flow Formulation since number of the problem decision variables is smaller due to the pre-computed path set. Due to its simplicity, the Path Formulation can provide solutions for larger networks where the Flow Formulation cannot provide a solution. The disadvantage of the Path Formulation is having bounded number of candidate paths resulting in higher cost since some good paths may not be contained in the set of candidate paths.

Both formulations are tested to understand the effect of the maximum runtime on the solution quality for only one randomly selected demand set with 50 connection requests for 14-node NSFNET. The Flow Formulation cannot provide a solution if the number of connection requests is higher than 50 in 14-node NSFNET. The formulations are run along 6 hours. It is found that after 1 hour, both formulation saturates. The solution of the Path Formulation is about 5% higher than the Flow Formulation.

The Path Formulation is tested by limiting the number of pre-computed path pairs for all possible demands in 24-node USANET. It is found that the optimal solution decaying exponentially. The optimal solution saturates when the limit of path pairs is greater than 30.

The remainder of the thesis is organized as follows. In Chapter 2, a literature survey on active path and backup path calculation for elastic optical networks is provided. In Chapter 3, proposed algorithms; the Path Formulation and the Flow Formulation are described. The numerical solutions for both formulations and their comparisons are given in Chapter 4. Finally, the thesis will be concluded in Chapter 5.

Chapter 2

Literature Review

In this chapter, elastic optical networks are introduced first by comparing it with the fixed-grid Wavelength Division Multiplexing (WDM) based optical networks. Then, survivability issue in optical networks and previous work done in survivable network design are presented.

2.1 Elastic Optical Networks

In the elastic optical networks, the spectrum is allocated according to the bandwidth requirements of connections. The spectrum is divided into narrow frequency slots. Optical connections are allocated different number of slots according to their bandwidth requirements. Network utilization efficiency is thus improved compared to the fixed-grid Wavelength Division Multiplexing (WDM) based optical networks where a fixed modulation and coding scheme is used throughout the network [6].

In the WDM based optical networks, the modulation and coding scheme used in the network is fixed which is determined by the worst path in the entire network. All connections consume same bandwidth even though some connections may use smaller bandwidth by employing more bandwidth efficient modulation/coding schemes if they have a higher optical signal-to-noise ration (OSNR). However, in the Elastic Optical Networks, a different modulation and coding scheme can be assigned to individual connections so that all demands have sufficient performance to reach the required distance.. Therefore, the spectrum efficiency of the elastic optical network is higher than WDM-based optical networks [12, 13, 3, 4].

In elastic optical networks, for every connection, a modulation/coding scheme is used. The modulation/coding scheme is selected according to the optical reach and the requested data rate. AMC is a resource allocation technique to select the most appropriate modulation/coding scheme. As the optical reach and data rate of a connection increases, the order of the modulation increases. Then, the spectrum allocated for the connection becomes larger as it uses a larger number of frequency slots [3, 14].

2.2 Survivability in Elastic Optical Networks

Survivability in elastic optical networks is an important issue. Link failures in the network may lead to huge data loss and severe service disruption [12]. Survivability is the capability of the network to maintain service continuity in the case of network failures [15]. In order to increase the survivability level of the optical network, protection techniques must be used.

In an optical network, a connection between the source node and a destination node is referred as a lightpath. The lightpath is called an active path if it is used to carry traffic during normal operation. The lightpath is called a backup path if it is used to carry traffic when the active path is affected by a failure. In the occurrence of a failure in an active path, the connection is switched to the backup path.

SRLG refers to a set of links with a significant probability of getting failed simultaneously [16]. Links in an SRLG may share common physical attributes, for example, a cable, duct, node or substructure. The failure in the physical attribute causes the failure of all links in the SRLG.

SRLG concept is illustrated in Figure 2.1 [17]. Although fiber links 1-2 and 1-3 seem to be independent, as Figure 2.1a shows they share a common fiber cable. Since the failure in the cable causes the failure of both fiber links 1-2 and 1-3, both links are included in an SRLG. Since each link can fail by itself, SRLGs each containing a single link are naturally included in the set of SRLGs.

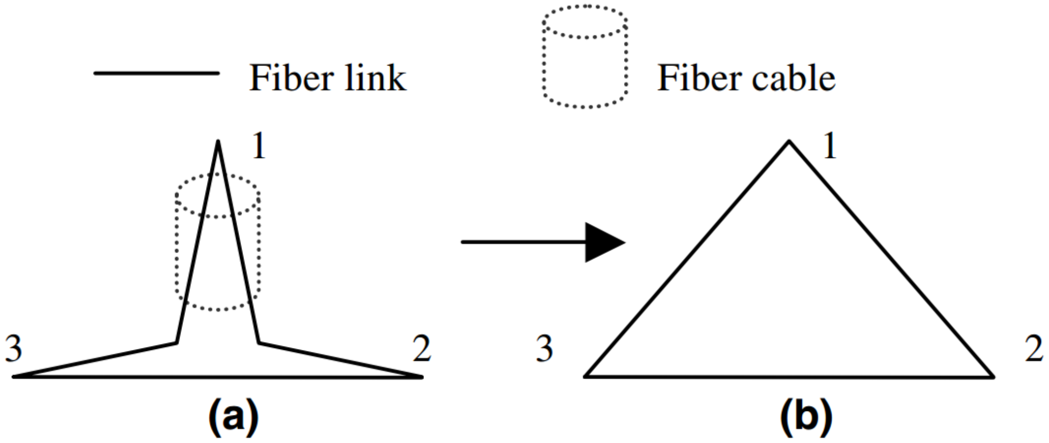


Figure 2.1: (a) Fiber cable topology. (b) Fiber link topology.

In this thesis, we consider survivability against single-SRLG failures. The case of concurrent failures of multiple SRLGs is not considered since such failures are very rare. To make the optical network resistant to the single-SRLG failures, the active path and the backup path of a connection cannot use same SRLG, because in the failure of the SRLG will cause concurrent failure of the active and the backup paths. As given in [18, 19], some heuristic algorithms such as Adaptive Frequency Assignment Algorithm and Most Subcarriers and Average Longest Path First Algorithm, which aim to find active and backup paths by minimizing the width of spectrum and minimizing the average path length respectively, can be used. Also, as given in [7], a novel algorithm which aims to minimize the bandwidth blocking probability can be used to find SRLG-disjoint active and backup paths.

In [18], an ILP model is presented to calculate active and backup paths subject to single-link failures for an offline problem of Routing and Spectrum Allocation (RSA) with Shared Backup Path Protection (SBPP) in elastic optical networks. In SBPP, backup path resources are shared since the failure of multiple active paths are considered to be rare. In [18], it is assumed that the capacity requirements of connection demands and candidate path pairs for all connection demands are given. The purpose is to select active and backup paths from a set of candidate path pairs by minimizing the width of spectrum resources required in the network. Several heuristic algorithms are proposed to find link-disjoint active and backup paths. The algorithms are formulated in two versions which are Separate Assignment (SA), where first only active paths of each demand are allocated in the network and then the backup paths are allocated, and Joint Assignment (JA) where both active and backup paths are allocated at the same time. The heuristic algorithms have different techniques to allocate active and backup paths.

The proposed algorithms are:

- **AFA**: Adaptive Frequency Assignment algorithm adaptively selects a sequence of processed demands in order to minimize the width of spectrum. First, the demands are allocated according to the number of slices required. Then, each subset is processed to find the lowest slice allocation.

- **MSALPF**: Most Subcarriers and Average Longest Path First algorithm is based on a sequential processing of demands according to decreasing number of requested slices, demands are sorted according to decreasing value of an average length of candidate paths.

In the numerical results, AFA gives the best solution which is closest to the optimum result. However, its disadvantage is having much larger execution time.

In [7], SRLG disjoint active and backup paths in elastic optical networks are calculated under dynamic traffic. The objective is to minimize the connection blocking probability and bandwidth blocking probability. ILP technique is used to minimize the objective. Given the physical topology of the network, connection request set, current availability of frequency slots in each link and modulation levels, the working paths and backup paths are calculated in order to minimize the connection blocking probability and bandwidth blocking probability.

The remaining of this thesis is organized as follows. In Chapter 3, active and backup path calculation in elastic optical networks is described. The implementation details of the Flow Formulation and the Path Formulation are given in this chapter. The numerical results for active and backup path calculations, the comparison between the Flow Formulation and the Path Formulation are described in Chapter 4. Finally, the thesis is concluded in Chapter 5.

Chapter 3

Active and Backup Path Calculation in Elastic Optical Networks

Survivability in the optical networks is an important issue. There are lots of optical connections in the network. Failure of an SRLG may cause major traffic disruptions in the network because of the large number of connection flowing through failed link(s). In order to minimize the disruptions due to link failures, protection mechanisms are used as described in Chapter 2.

In the subsections below, the SRLG disjoint active/backup path pair calculation problem will be stated first. Then, the Flow Formulation and the Path Formulation for the solution of this problem will be presented.

3.1 Problem Definition

Before describing the problem, the terminology used in this thesis will be stated first.

- **Demand Set:** Set of all optical connection requests. A demand requires a connection from the source node to the destination node.

- **Path:** A sequence of links from the source node to the destination node. If a connection uses the path primarily, it is called active path. If a connection uses the path only in the failure of the active path, it is called backup path.

The proposed solution approaches are based on finding the active and the backup paths for each connection according to the given demand set, the given set of usable AMC profile and the given network topology information consisting of nodes, edges and SRLGs. The solution must satisfy all the following requirements:

- All requested demands in the demand set shall be satisfied.

- In case of a failure of an edge or an SRLG in the active path of a demand, the backup path of the demand shall not be affected by this failure.

- Appropriate AMC profile shall be selected to set the number of frequency slot usage in the transmission according to the distance from the source node to the destination node for each active path and backup path.

According to the requirement set, the optimum active and backup paths will be found by the minimizing the sum of required capacities of each link in terms of the number of frequency slots.

In the following subsections, the subscripts and inputs of the ILP models are given.

3.1.1 Subscripts

The subscripts used in the formulations correspond to:

- i,j,k,l: Nodes

- s: Source node

- d: Destination node

- ξ: SRLG index, $1 \leq \xi \leq K$ where K is the number of SRLGs

- ρ: AMC profile index, $1 \leq \rho \leq M$ where M is the number of AMC profiles

- λ: Index of the selected candidate path

3.1.2 Inputs of the ILP Model

The inputs to the system are:

- N: Set of nodes

- E: Set of links where the indicator function e_{ij} is defined as

$$e_{ij} = \begin{cases} 1, & \text{if } (i,j) \in E \\ 0, & \text{otherwise.} \end{cases} \tag{3.1}$$

  Note that $e_{ij} = e_{ji}$

- P: Demand set, i.e., the set of node pairs (s, d) such that there is a connection request between nodes s and d. The indicator function p_{sd} is defined as

$$p_{sd} = \begin{cases} 1, & \text{if } (s,d) \in P \\ 0, & \text{otherwise.} \end{cases} \tag{3.2}$$

- $R = \{SRLG^{\xi},\, 1 \leq \xi \leq K\}$: Set of SRLGs where the indicator function S_{ij}^{ξ} is defined as

$$S_{ij}^{\xi} = \begin{cases} 1, & \text{if } e_{ij} \in SRLG^{\xi} \\ 0, & \text{otherwise.} \end{cases} \tag{3.3}$$

Note that every single link corresponds to an SRLG. Note also that $S_{ij}^{\xi} = S_{ji}^{\xi}$

- L_{ij}: Length of edge $(i, j) \in E$

Note that $L_{ij} = L_{ji}$

- d_{ρ}: Maximum optical reach allowed for AMC profile ρ

- f_{ρ}: Number of frequency slots required by AMC profile ρ

3.2 Flow Formulation

In this section, the Flow Formulation is introduced. The goal of the Flow Formulation is to calculate the active and backup paths to minimize the total number of frequency slots used at all edges in the network.

3.2.1 Decision Variables

The decision variables in the Flow Formulation:

- x_{ij}^{sd}: Active path flow

$$x_{ij}^{sd} = \begin{cases} 1, & \text{if active path of connection (s,d) passes through link } (i,j) \\ 0, & \text{otherwise.} \end{cases} \tag{3.4}$$

- y_{ij}^{sd}: Backup path flow

$$y_{ij}^{sd} = \begin{cases} 1, & \text{if backup path of connection (s,d) passes through link } (i,j) \\ 0, & \text{otherwise.} \end{cases} \tag{3.5}$$

3.2.2 Auxiliary Variables

The auxiliary variables in the Flow Formulation:

- v_{ξ}^{sd}: Denotes if an edge (or edges) from an SRLG set is used by an active path (or backup path) of a demand, the backup path (or active path) of the same demand cannot use an edge (or edges) from the same SRLG set.

$$v_{\xi}^{sd} = \begin{cases} 1, & \text{if } x_{ij}^{sd}\text{=}1 \text{ for at least one } (i,j) \in S_{ij}^{\xi} \text{ and } y_{ij}^{sd}\text{=}0 \text{ for all } (i,j) \in S_{ij}^{\xi} \\ 0, & \text{if } x_{ij}^{sd}\text{= } 0 \text{ for all } (i,j) \in S_{ij}^{\xi} \text{ and } y_{ij}^{sd} \leq 1 \text{ for all } (i,j) \in S_{ij}^{\xi} \end{cases} \tag{3.6}$$

- a_{ρ}^{sd}: AMC profile for active path of demand (s,d)

- b_{ρ}^{sd}: AMC profile for backup path of demand (s,d)

- m_{sd}: The number of frequency slots used at active path of demand (s, d)
- n_{sd}: The number of frequency slots used at backup path of demand (s, d)
- α_{ij}^{sd}: The number of frequency slots flowing through link (i, j) for active path of demand (s, d)
- $\theta_{ij}^{sd}(\xi)$: The number of frequency slots flowing through link (i, j) for backup path of demand (s, d) when the active path of the same demand uses at least one edge from $SRLG^{\xi}$

$$\theta_{ij}^{sd}(\xi) = \begin{cases} n_{sd}, & \text{if } y_{ij}^{sd}\text{=1 and } x_{kl}^{sd}\text{=1 for at least one (i,j)} \in SRLG^{\xi} \\ 0, & \text{otherwise.} \end{cases} \tag{3.7}$$

- C_{ij}: The capacity required for edge (i,j) in terms of the number of frequency slots.

3.2.3 Constants

- U: A number which is greater than the sizes of all SRLG set.
- V: A number which is greater than the maximum number of frequency slots required by all AMC profiles.

3.2.4 Constraints

The constraints in the Flow Formulation are given as follows:

Constraint 1: The Flow of Active and Backup Paths

For each demand (s, d), the flow of active paths and the flow of backup paths are described as below. The figure below shows the flow as an illustration.

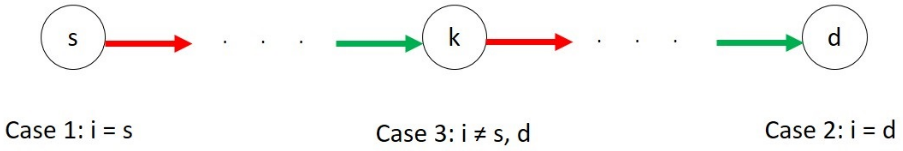


Figure 3.1: Flow of active and backup paths

Constraint 1a: Flow of active paths: For each (s, d) such that $p_{sd} = 1$

$$\sum_{j}(x_{ij}^{sd} - x_{ji}^{sd}) \begin{cases} 1, & \text{if } i = s \\ -1, & \text{if } i = d \\ 0, & \text{if } i \neq s, d \end{cases} \tag{3.8}$$

Constraint 1b; Flow of backup paths: For each (s, d) such that $p_{sd} = 1$

$$\sum_{j}(y_{ij}^{sd} - y_{ji}^{sd}) \begin{cases} 1, & \text{if } i = s \\ -1, & \text{if } i = d \\ 0, & \text{if } i \neq s, d \end{cases} \tag{3.9}$$

Constraint 2: Active and Backup Paths Should Be SRLG Disjoint

For each demand (s, d), if the active path uses at least one edge from an SRLG in R, the backup path can use no edge from the same SRLG set. This constraint enables system to be resistant to a single SRLG failure. The figure below shows the SRLG disjoint flows as an illustration.

The Figure 3.2 shows the flow of SRLG disjoint active and backup paths. Note that the source node is 3 and the destination node is 2. Since edges (3,1) and (3,2) are in the same SRLG set called $SRLG^1$, if active path uses edge (3,2), the backup path cannot use edge (3,1).

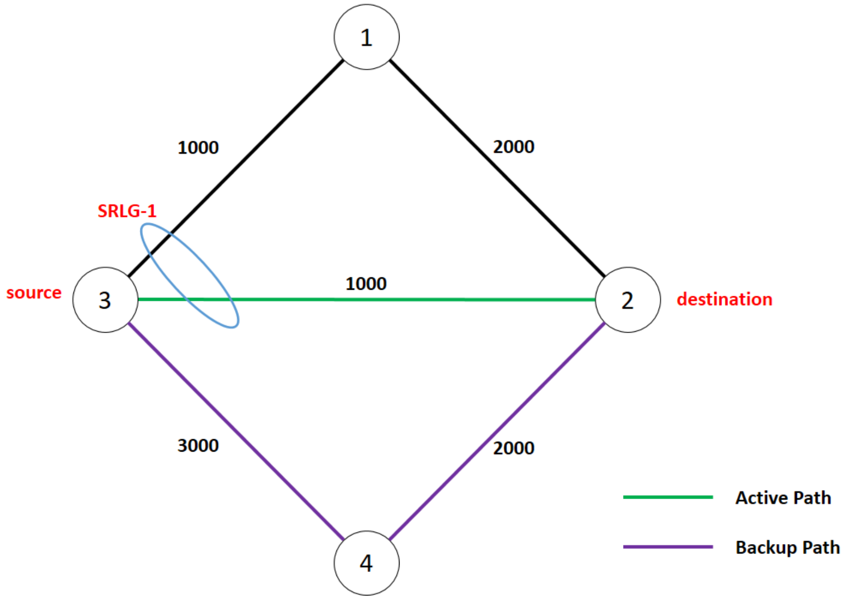


Figure 3.2: SRLG Disjoint Paths

Constraint 2a:

$$\frac{1}{U} * \sum_{ij}(x_{ij}^{sd} * S_{ij}^{\xi}) \leq v_{\xi}^{sd} \leq \sum_{ij}(x_{ij}^{sd} * S_{ij}^{\xi}) \text{ for all s,d,}\xi \text{ such that } p_{sd} = 1 \quad (3.10)$$

Constraint 2b:

$$\frac{1}{U} * \sum_{ij}(y_{ij}^{sd} * S_{ij}^{\xi}) \leq 1 - v_{\xi}^{sd} \text{ for all s,d,}\xi \text{ such that } p_{sd} = 1 \quad (3.11)$$

Note that;

- When an active path of a demand uses at least one edge from an SRLG set, the LHS of Constraint 2a becomes a nonzero number which is strictly less than 1 due to U. The RHS of Constraint 2a becomes a nonzero number which is greater than or equal to 1. Since v_{ξ}^{sd} is binary, it will be 1. Then, RHS of Constraint 2b becomes 0 which will make LHS of Constraint 2b 0.

It means that backup path of the same demand cannot use any edge from the same SRLG set.

- When an active path of a demand uses no edge from an SRLG set, the LHS and RHS of Constraint 2a becomes 0. Then, v_{ξ}^{sd} will be 0. Then, RHS of Constraint 2b becomes 1. It means that backup path of the same demand can use any number of links from this SRLG set.

Constraint 3: AMC profile selection

From the given AMC profile set, a profile should be selected for each active and backup path. Since source to destination distances may be different in active and backup paths, the AMC profiles may also be different.

Constraint 3a: Only one profile should be selected for each active path in P.

$$\sum_{\rho} a_{\rho}^{sd} = 1 \text{ for all s,d such that } p_{sd} = 1 \tag{3.12}$$

Constraint 3b: Only one profile should be selected for each backup paths in P.

$$\sum_{\rho} b_{\rho}^{sd} = 1 \text{ for all s,d such that } p_{sd} = 1 \tag{3.13}$$

Constraint 3c: The distance from the source to the destination is bounded by the AMC profile for each active path in P.

$$\sum_{ij} x_{ij}^{sd} * L_{ij} \leq \sum_{\rho} a_{\rho}^{sd} * d_{\rho} \text{ for all s,d such that } p_{sd} = 1 \tag{3.14}$$

Constraint 3d: The distance from the source to the destination is bounded by the AMC profile for each backup path in P.

$$\sum_{ij} y_{ij}^{sd} * L_{ij} \leq \sum_{\rho} b_{\rho}^{sd} * d_{\rho} \text{ for all s,d such that } p_{sd} = 1 \tag{3.15}$$

Constraint 3e: The number of frequency slots for each active path is given by:

$$m_{sd} = \sum_{\rho} a_{\rho}^{sd} * f_{\rho} \text{ for all s,d such that } p_{sd} = 1 \tag{3.16}$$

Constraint 3f; The number of frequency slots is selected by the AMC profile for each backup path in P.

$$n_{sd} = \sum_{\rho} b_{\rho}^{sd} * f_{\rho} \text{ for all s,d such that } p_{sd} = 1 \tag{3.17}$$

Constraint 3g: The number of frequency slots flowing through edges for each active path in P.

$$m_{sd} - V * (1 - x_{ij}^{sd}) \leq \alpha_{ij}^{sd} \leq V * x_{ij}^{sd} \text{ for all s,d such that } p_{sd} = 1 \tag{3.18}$$

- When $x_{ij}^{sd} = 1$, LHS of Constraint 3g becomes m_{sd} and RHS of Constraint 3g becomes N. Then, ILP will make α_{ij}^{sd} equal to m_{sd} because of minimization.

- When $x_{ij}^{sd} = 0$, LHS of Constraint 3g becomes $m_{sd} - V$ which is a negative number and RHS of Constraint 3g becomes 0. Since α_{ij} is a non-negative variable, it will be 0.

Constraint 3h: The number of frequency slots flowing through edges for each backup path in P when $SRLG^{\xi}$ is used by the active path is given as:

$$n_{sd} + V * (x_{kl}^{sd} * S_{kl}^{\xi} + y_{ij}^{sd} - 2) \leq \theta_{ij}^{sd}(\xi) \leq V * y_{ij}^{sd}$$
$$\text{for all } s, d, i, j, k, l \text{ such that } p_{sd} = e_{ij} = e_{kl} = 1 \qquad (3.19)$$

Constraint 3i:

$$\theta_{ij}^{sd}(\xi) \leq \sum_{kl}(V * x_{kl}^{sd} * S_{kl}^{\xi}) \text{ for all } s, d, i, j \text{ such that } p_{sd} = e_{ij} = 1 \qquad (3.20)$$

- When $y_{ij}^{sd} = 1$ and at least one $x_{kl}^{sd} = 1$ such that $S_{kl}^{\xi} = 1$, RHS of Constraint 3h becomes V, the LHS of Constraint 3h becomes n_{sd} and RHS of Constraint 3i will be greater than or equal to V. Then, ILP will make $\theta_{ij}^{sd}(\xi)$ equal to n_{sd} because of the objective function.

- When $y_{ij}^{sd} = 1$ and all $x_{kl}^{sd} = 0$ such that $S_{kl}^{\xi} = 1$, RHS of Constraint 3h becomes V, the LHS of Constraint 3h becomes $n_{sd} - V$ which is non negative and RHS of Constraint 3i becomes 0. Then, $\theta_{ij}^{sd}(\xi)$ will be 0.

- When $y_{ij}^{sd} = 0$, RHS of Constraint 3h becomes 0. The LHS of Constraint 3h will be negative for both value of x_{kl}^{sd}. Since RHS of Constraint 3i is non negative, $\theta_{ij}^{sd}(\xi)$ will be 0 for both value of x_{kl}^{sd}.

Constraint 4: Capacity Constraint For Each Edge
The capacity constraint is calculated with respect to the number of frequency slots passing through each edge. The capacity usage of active paths is obvious. However, for the backup paths, only the maximum protection capacity is used since we are considering protection against single SRLGs.

In a demand set P, for every edge, there is a usage of active paths. Only if there is an edge or SRLG failure, the backup path will be used. For no failure case, only active paths will be used. Therefore, all edges in the network can meet the need of all active paths.

Backup paths in the network are used only due to the failure of single SRLGs. This condition causes edges which are used by backup paths to consume more frequency slots. Since our aim is to make network resistent to single SRLG failure, the protection of the backup paths will be the maximum number of frequency slots over all possible single SRLG failures.

The capacity constraint is given by:

$$\overbrace{\sum_{sd}(\alpha_{ij}^{sd}+\alpha_{ji}^{sd})}^{\text{active path usage}} \;+\; \max_{\xi} \quad \overbrace{\sum_{sd}(\theta_{ij}^{sd}(\xi)+\theta_{ji}^{sd}(\xi))}^{\text{backup path projection for each } SRLG^{\xi}} \qquad \leq C_{ij} \text{ for all } i,j \in E \tag{3.21}$$

The capacity constraint given in Eq 3.21 is linearized as given in Eq 3.22:

$$\sum_{sd}(\alpha_{ij}^{sd}+\alpha_{ji}^{sd})+\sum_{sd}(\theta_{ij}^{sd}(\xi)+\theta_{ji}^{sd}(\xi)) \;\leq\; C_{ij} \text{ for all } i,j \in E \text{ and } 1 \leq \xi \leq K \tag{3.22}$$

3.2.5 Objective Function

Our main goal is to minimize the capacity and link usage. After minimizing the total capacity usage, we also want source to destination distances to be as minimum as minimum. Then the objective function is given in Eq 3.23:

$$\min\;[\;\overbrace{\sum_{ij}(C_{ij}*L_{ij})}^{\text{Resource Requirement}} \;+\overbrace{\sum_{ijsd}(L_{ij}*(x_{ij}^{sd}+y_{ji}^{sd}))}^{\text{Resource Utilization}}] \tag{3.23}$$

In the capacity constraint, the resource requirement part shall be the dominant part because we want the usage of the capacity to be minimum. However, it is nice to have minimum utilization of edges. In the simulations, the resource requirement part i observed approximately 100 times greater than the resource utilization efficiency part. Therefore, adding resource utilization efficiency part to the capacity constraint without scaling down it does not cause the resource requirement part to be less dominant.

3.3 Path Formulation

In this section, the Path Formulation is introduced. The basic principle of the Path Formulation is to select appropriate active and backup paths from candidate paths set to minimize the total number of frequency slots used at all edges in the network, instead of considering all possible paths as in the case of the Flow Formulation

The advantage of Path Formulation is that the ILP model does not calculate the flow of paths. It just selects the active and backup path pairs from a set of precomputed candidate paths. Therefore, the complexity is much smaller than the Flow Formulation. For larger where the Flow Formulation Approach cannot find a solution, Path Formulation Approach can be used.

The disadvantage of the Path Formulation is the quality of the solution. Since the Flow Formulation calculates all possible paths in ILP, it always founds the best solution. Since the given set of candidate paths are bounded, better paths in some situations may not be in the set of candidate paths. The comparison between both approaches will be explained in detailed in Chapter 4.

In this section, calculation of candidate paths will be explained first. Then, the selection algorithm will be stated.

3.3.1 Calculation of Candidate Paths

In this subsection, calculation of candidate paths, called Path Calculator, will be explained.

Definitions

We first state some definitions that will be used in the sequel.

Definition 1: A path is said to be “simple” (or loopless) if and only if all nodes are different.

Definition 2 Two paths are said to be “SRLG disjoint” if and only if they do not contain edges belonging to the same SRLG.

The main principle of the Path Calculator is to find all possible simple and SRLG-disjoint path pairs so that the requirements stated in Section 3.1 are satisfied.

Figure 3.3 shows the input and output of the Path Calculator.

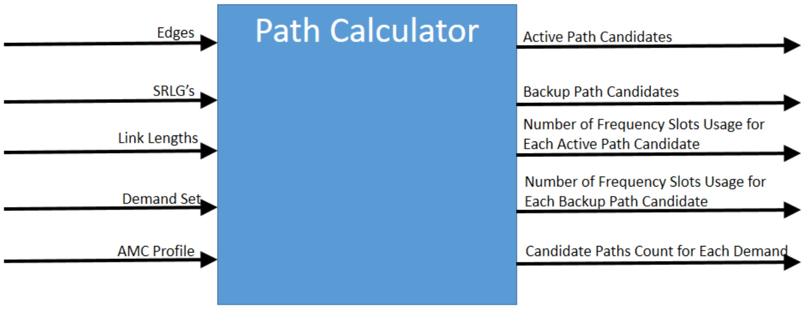


Figure 3.3: Path Calculator

The first step of the Path Calculator is to modify the given network for each (s,d) pair. The second step is to find simple, disjoint and SRLG-disjoint path pairs.

Modification of Network:

Let *(N,E)* be the given network with a set N of n nodes and a set E of edges (i, j) and $i, j \in N$. Let $\Gamma = [g_{ij}]$ be an n-by-n matrix where;

$$g_{ij} = \begin{cases} L_{ij}, & \text{if } e_{ij} = 1 \\ \infty, & \text{otherwise} \end{cases} \tag{3.24}$$

As given in [10, 11], let *(N',E')* be the modified network such that the network is duplicated and connected from the destination node of real network to source node of duplicated network. Note that *(N',E')* is different for all demands $(s, d) \in P$

- $N' = N \cup (i' : i \in N)$

- $E' = E \cup ((i', j') : i, j \in N) \cup ((d, s')$ where $L_{i'j'} = L_{ij}$ and $L_{ds'} = 0$

Then, the aim is to find a path from source node s to destination node d'. Then, the path will be like $p = q \diamond (d, s') \diamond q'$. Note that q is a path starting from node s ending at node d and q' is a path starting from node s' ending at node d'. If q and q' are simple and SRLG-disjoint paths, they can be used as active and backup paths in demand $path_{sd}$.

After the modification of network *(N,E)*, the new graph called G^{sd} is a $2 * n$-by-$2 * n$ matrix. To map the virtual edges to the graph, it is assumed that virtual nodes starts from index $n + 1$ to $2n$ while the original network nodes starts from index 1 to n.

Then;

$$G_{ij}^{sd} = \begin{cases} g_{ij}, & \text{for } (i,j) \in N \text{ or } (i-n, j-n) \in N \\ 0, & \text{for } i = d \text{ and } j = s' = s + n \\ \infty & \text{otherwise.} \end{cases} \tag{3.25}$$

The modification of the network shown in Figure 3.2 is given in Figure 3.4. Note that the edge between destination node and virtual source node has zero distance.

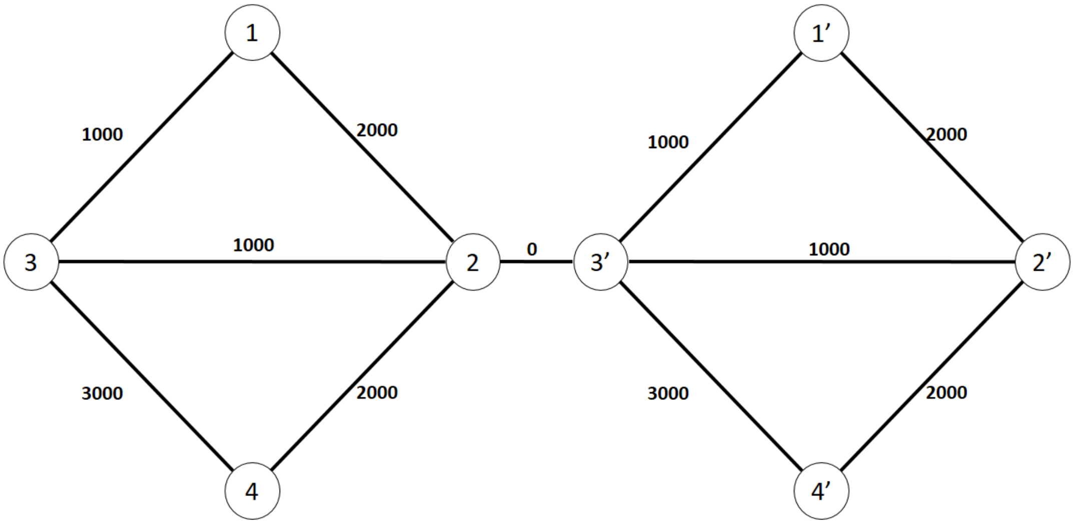


Figure 3.4: Modification of a Network

The Path Calculator Algorithm

As given in [10], the Algorithm 1 describes how to find candidate paths. As stated in Algorithm 1, after finding all possible paths from source node s to virtual destination node d', simple and SRLG-disjoint path pairs are analyzed. Then, the path from node s to node d is put to active path candidate set, the path from s' to d' is put to backup path candidate set as as denoted by X^{sd} and Y^{sd} respectively, The number of frequency slots required are denoted by CX^{sd} for active path candidates and CY^{sd} for backup path candidates. The number of candidate paths found for each demand (s, d) is stored at c^{sd}.

Algorithm 1: Path Calculator

```
input  : Network graph $G$, SRLG set
output: Simple and SRLG-disjoint path pairs for each demand $(s, d)$

for all (s,d') such that (s,d) $\in P$ do
    Construct $G^{sd}$
    $X^{sd} = \emptyset$
    $Y^{sd} = \emptyset$
    $CX^{sd} = \emptyset$
    $CY^{sd} = \emptyset$
    $c^{sd} = \emptyset$
    $count = 0$
    $p \leftarrow$ kShortestPath($G^{sd}, s, d$)
    for all paths in $p$ do
        Find $q$ and $q'$
        if simple($q$) and simple($q'$) and SRLGdisjoint($q$, $q'$)) then
            $X^{sd}(count) \leftarrow q$
            $Y^{sd}(count) \leftarrow q'$
            $CX^{sd}(count) \leftarrow$ Frequency slots usage of $q$
            $CY^{sd}(count) \leftarrow$ Frequency slots usage of $q'$
            $count \leftarrow count + 1$
    $candmax^{sd} \leftarrow count$
    $count = 0$
```

As described in the Algorithm 1, the algorithm first finds all possible paths from **kShortestPath(G^{sd}, s, d)** function [9]. This function gets modificated network G^{sd}, the source node s and the destination node d as an input and then finds all possible paths and stores them to p. The method to find the paths is based on Yen's Algorithm. Then, all paths in p are divided into q and q'. Then, disjoint and SRLG-disjoint paths are selected

For the network given in Figure 3.2 and Figure 3.4, following paths are obtained:

Table 3.1: Path Caluclator Example

Index	Generated Path	q	q’	Distance of q	Distance of q’
1	(3, 2, 3’, 1’, 2’)	(3, 2)	(3’, 1’, 2’)	1000 meter	3000 meter
2	(3, 1, 2, 3’, 2’)	(3, 1, 2)	(3’, 2’)	3000 meter	1000 meter
3	(3, 2, 3,’ 4,’ 2’)	(3, 2)	(3’, 4’, 2’)	1000 meter	5000 meter
4	(3, 4, 2, 3’, 2’)	(3, 4, 2)	(3’, 2’)	5000 meter	1000 meter
5	(3, 4, 2, 3’, 1’, 2’)	(3, 4, 2)	(3’, 1’, 2’)	5000 meter	3000 meter
6	(3, 1, 2, 3’, 4’, 2’)	(3, 1, 2)	(3’, 4’, 2’)	3000 meter	5000 meter

3.3.2 Inputs of the ILP Model

In addition to N, E, P, R and L_{ij} described in Section 3.1.2, inputs for the Path Formulation are:

- $xG_{ij}^{sd}(\lambda)$: Candidate active path indexed by λ

$$xG_{ij}^{sd}(\lambda) = \begin{cases} 1, & \text{if edge } (i,j) \text{ is used in candidate active path of } p_{sd} \text{ indexed by } \lambda \\ 0, & \text{otherwise} \end{cases} \tag{3.26}$$

- $yG_{ij}^{sd}(\lambda)$: Candidate backup path indexed by λ

$$yG_{ij}^{sd}(\lambda) = \begin{cases} 1, & \text{if edge } (i,j) \text{ is used in candidate backup path of } p_{sd} \text{ indexed by } \lambda \\ 0, & \text{otherwise} \end{cases} \tag{3.27}$$

- $nG_{sd}(\lambda)$: The number of frequency slots used at candidate active path of demand (s, d) indexed by λ

- $bG_{sd}(\lambda)$: The number of frequency slots used at candidate backup path of demand (s, d) indexed by λ.

- c_{sd}: Maximum number of candidate pairs found for the demand (s, d)

- z: The limit for usage of candidate pairs

3.3.3 Decision Variables

The decision variables in the Path Formulation is given as:

- x_{ij}^{sd}: Active path flow

$$x_{ij}^{sd} = \begin{cases} 1, & \text{if active path of demand } (s, d) \text{ passes through edge } (i, j) \\ 0, & \text{otherwise} \end{cases} \tag{3.28}$$

- y_{ij}^{sd}: Backup path flow

$$y_{ij}^{sd} = \begin{cases} 1, & \text{if backup path of demand } (s, d) \text{ passes through edge } (i, j) \\ 0, & \text{otherwise} \end{cases} \tag{3.29}$$

- r_{sd}^{λ}: Stores selected candidate pair for demand (s, d)

$$ps_{sd}^{\lambda} = \begin{cases} 1, & \text{if the demand } (s,d) \text{ uses candidate pair indexed by } \lambda \\ 0, & \text{otherwise} \end{cases} \tag{3.30}$$

- C_{ij}: The capacity required for edge (i,j) in terms of number of frequency slots.

3.3.4 Constraints

The constraints in Path Formulation Approach are described in this subsection.

Constraint 1: Selection of active and backup paths

For each demand (s,d), the flow of active paths and the flow of backup paths are selected according to these constraints

Constraint 1a: Flow of active paths:

$$x_{ij}^{sd} = \sum_{\lambda} xG_{ij}^{sd}(\lambda) * r_{sd}^{\lambda} \text{ for } (i,j) \in E \text{ and } (s,d) \in P,\ \lambda \leq min(c_{sd}, z) \tag{3.31}$$

Constraint 1b: Flow of backup paths:

$$y_{ij}^{sd} = \sum_{\lambda} yG_{ij}^{sd}(\lambda) * r_{sd}^{\lambda} \text{ for } (i,j) \in E \text{ and } (s,d) \in P,\ \lambda \leq min(c_{sd}, z) \tag{3.32}$$

Constraint 1c: Only one candidate path pair should be selected.

$$\sum_{\lambda} r_{sd}^{\lambda} = 1 \text{ for } (s,d) \in P,\ \lambda \leq min(c_{sd}, z) \tag{3.33}$$

Constraint 2: Capacity constraint for each edge

The capacity constraint for the Path Formulation is exactly the same with the capacity constraint for the Flow Formulation. Only the shape of the constraint changes due to the different decision variables.

$$\overbrace{\sum_{s,d,\lambda} nG_{sd}(\lambda) * (x_{ij}^{sd} + x_{ji}^{sd})}^{\text{active path usage}} + \max_{\xi} \overbrace{\sum_{s,d,k,l,\lambda} mG_{sd}(\lambda) * S_{kl}^{\xi} * (y_{ij}^{sd} + y_{ji}^{sd}) * x_{kl}^{sd}}^{\text{backup path projection for each } SRLG^{\xi}} \leq C_{ij}$$

$$\text{for all } (i,j) \in E \tag{3.34}$$

The constraint can be linearized as follows:

$$\sum_{sd\lambda} nG_{sd}(\lambda) * (x_{ij}^{sd} + x_{ji}^{sd}) + \sum_{sdkl\lambda} mG_{sd}(\lambda) * S_{kl}^{\xi} * (y_{ij}^{sd} + y_{ji}^{sd}) * x_{kl}^{sd} \leq C_{ij}$$

$$\text{for all } (i,j) \in E \tag{3.35}$$

3.3.5 Objective Function

To make the comparison between the Flow Formulation and the Path Formulation, the objective function of the Path Formulation is the same with the objective function of the Flow Formulation. The objective function is given by:

$$\min \left[\overbrace{\sum_{ij} (C_{ij} * L_{ij})}^{\text{Resource Requirement}} + \overbrace{\sum_{ijsd} (L_{ij} * (x_{ij}^{sd} + y_{ji}^{sd}))}^{\text{Resource Utilization}} \right] \tag{3.36}$$

In the Chapter 4, the numerical results for the Flow Formulation and the Path Formulation will be presented. Both approaches will be compared for different scenarios.

Chapter 4

Numerical Results

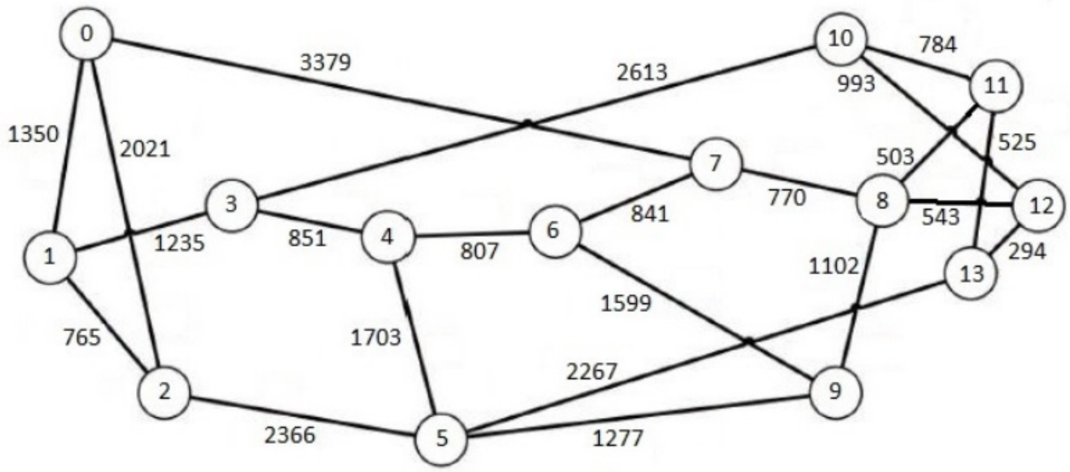
In this chapter, the implementation of the Flow Formulation and the Path Formulation and the simulation settings are presented first. Then, the performances of the Path Formulation and the Flow Formulation are evaluated. The purpose of the comparison in both approaches is based on the capability of obtaining a solution with smaller objective function, execution time and understanding the effect of SRLGs. Also, for the Path Formulation, the solution is compared as the bound on the maximum number of candidate paths changes.

4.1 Implementation and Settings

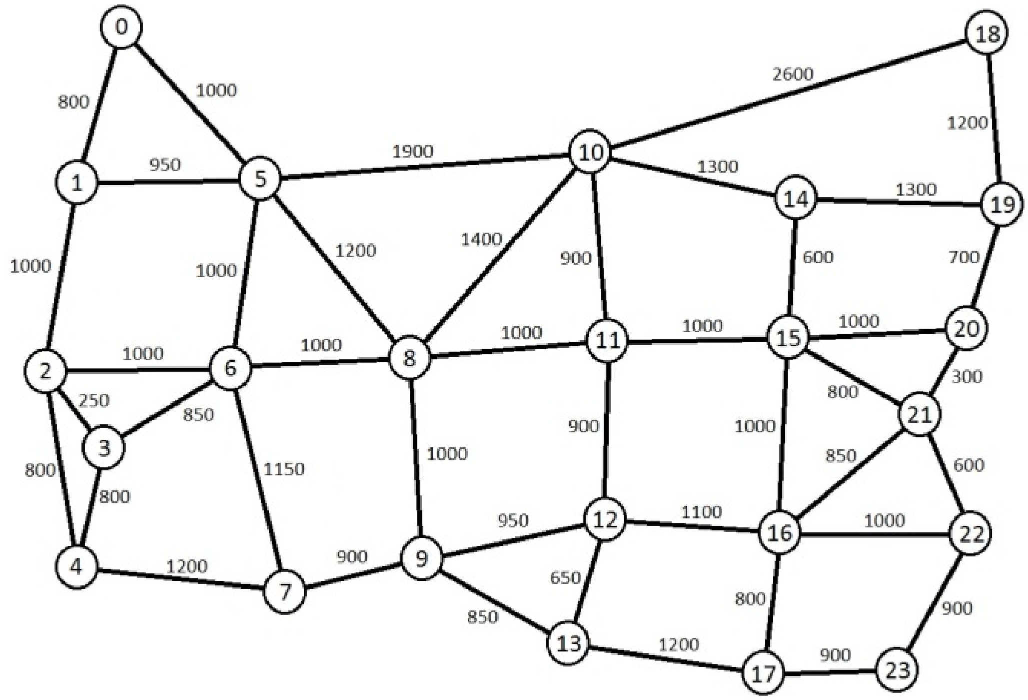
The Flow Formulation and the Path Formulation are implemented in GAMS and the ILP model is solved using the CPLEX optimizer.

CPLEX is a high performance solver for ILP problems. It is one of the solvers which is hooked up to GAMS. GAMS is an algebraic modeling language allowing the description of the ILP model in algebraic statements that can be converted to formats understandable by the solver. CPLEX gets the constraints from the GAMS and solves the problem according to the objective function.

The 14-node NSFNET and the 24-node US National Network (USANET) topologies shown in Figure 4.1 are used for the numerical studies, where edge lengths are expressed in km.



(a) 14 Node NSFNET



(b) 24 Node USANET

Figure 4.1: Network Topologies

The set of connection demands is prepared using 3 different cases described as follows:

- 10 randomly selected demand sets each with 50 connection requests for NSFNET
- A demand set containing all possible connection requests for NSFNET
- A demand set containing all possible connection requests for USANET

Optical connection demands are assumed to be full duplex and there can be at most one demand between two nodes. The bit rate for each optical connection request is set to 1 Tbps. Link capacities are set to 100 slices for both topologies. The four modulation formats showed in Table 4.1 are used [20].

Table 4.1: Modulation Format

Profile ID	**Modulation Format**	**Slot Capacity**	**Optical Reach**	**Number of Slots Needed for 1 Tbps**
1	BPSK	12.5 Gbps	9600 km	80
2	QPSK	25 Gbps	4800 km	50
3	8 - QAM	37.5 Gbps	2400 km	27
4	16 - QAM	50 Gbps	1200 km	20

The three cases given above are implemented with two different situations:

- All SRLGs contain a single link (called single-link SRLGs)
- In addition to all single-link SRLGs, additional SRLGs are added (called multi-link SRLGs)

In order to understand the behavior of the algorithms, two SRLGs for NSFNET and three SRLGs for USANET are defined. These SRLGs are shown in Table 4.2 and Table 4.3.

Table 4.2: 14-Node NSFNET multi-link SRLGs

SRLG ID	EDGES
1	(5,6), (5,13)
2	(6,7), (6,9)

Table 4.3: 24-Node USANET multi-link SRLGs

SRLG ID	EDGES
1	(2,3), (2,4)
2	(9,12), (9,13)
3	(15,21), (16,21)

4.2 Analysis

In this section, the results for the Flow Formulation Approach and the Path Formulation Approach are studied. At first the results for the Flow Formulation Approach are given. Then, the results of the Path Formulation Approach are given. At the end, the comparison between the Flow Formulation and the Path Formulation Approaches is evaluated.

4.2.1 The Analysis for The Flow Formulation

The complexity of the Flow Formulation is so high such that it cannot find an optimum solution for the 14-node NSFNET when all possible demands are considered. Therefore, the formulation is tested with the 10 sets of randomly selected 50 demands for the 14-node NSFNET. For all sets, the algorithm is forced to stop after 40 minutes. Also, to understand the effect of the maximum runtime on the solution quality, for only one set, the algorithm is run for 6 hours. The Flow Formulation does not provide a solution for the 24-node USANET.

The analysis of the Flow Formulation Approach is based on comparing the ILP solution with single-link SRLGs and multi-link SRLGs. Also, the effect of the execution time on ILP solution is evaluated.

Figure 4.2 shows the solution of all sets. As it is seen from the figure, the single-link SRLGs case is larger than the multi-link SRLGs case for all sets because existence of additional SRLGs limit the usage of some paths. This restriction causes the solution to be larger.

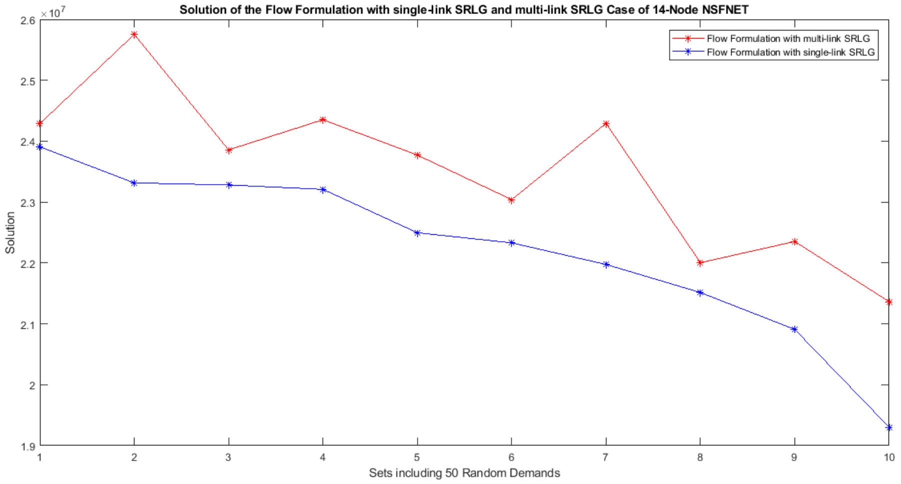


Figure 4.2: The Flow Formulation with single-link SRLG and multi-link SRLG for 14-Node NSFNET

One of the 10 sets in the single-link SRLGs case is tested such that the algorithm is forced to stop after 6 hours. Figure 4.3 shows the solution and lower bound obtained from CPLEX for this solution with respect to the execution time. According to the figure, the solution approaches lower bound as time passes. The optimality gap is calculated with respect to the solution and the lower bound obtained form CPLEX.

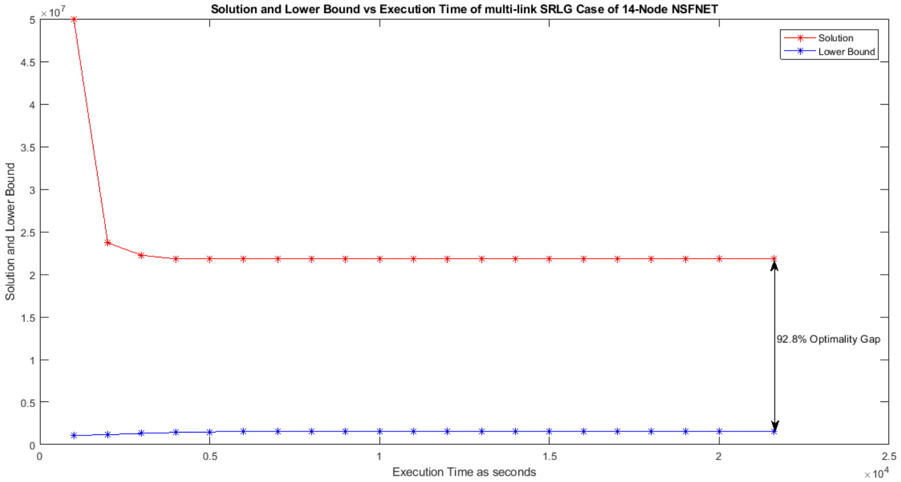


Figure 4.3: ILP Solution and Lower Bound for single-link SRLG Case of 14-node NSFNET vs Execution Time

4.2.2 The Analysis for The Path Formulation

In the Path Formulation, since the pre-computed candidate paths are given to the CPLEX, the complexity of this approach is lower than the Flow Formulation. Therefore, the approach is tested with 10 randomly selected demand sets each with 50 connection requests for 14-node NSFNET by giving all possible candidate paths to the CPLEX and all possible demands for 24-node USANET by restricting the number of candidate paths with different bounds. For all simulations, the algorithm is forced to stop after 40 minutes. Also, to understand the effect of the runtime limitation on the solution quality, for only one set, the algorithm is run along 6 hours. This approach can generate solutions for the 14-node NSFNET even all possible demands are considered.

The analysis of the Path Formulation is based on comparing the solution for the single-link SRLGs and the multi-link SRLGs, the effect of the execution time on ILP solution and the lower bound obtained from CPLEX for this solution and the effect of the bound of maximum candidate paths to the solution and the lower bound.

Figure 4.4 shows the solution for 10 sets of randomly selected 50 demands for 14-node NSFNET. Similar to the Flow Formulation Approach, the existence of the SRLG enables network not to use some path and this restriction causes the solution to be larger.

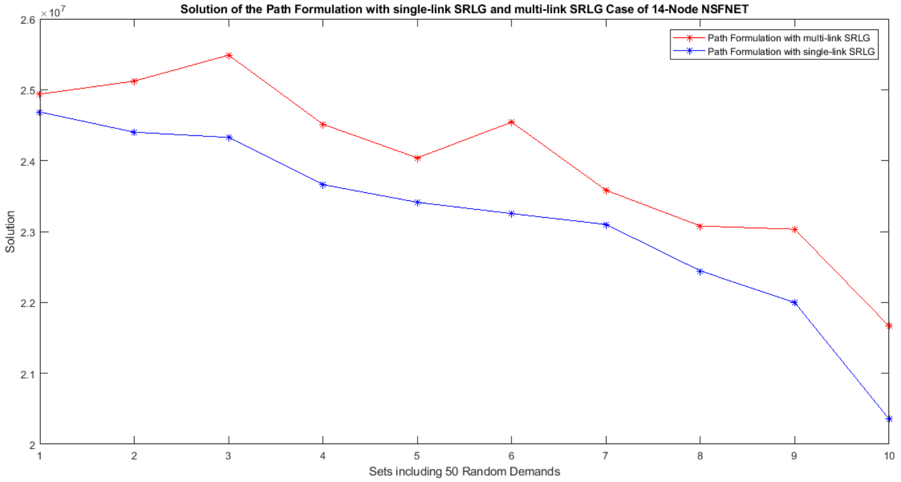


Figure 4.4: Path Formulation with multi-link SRLG and single-link SRLG for 14-Node NSFNET

Figure 4.5 shows the solution and the lower bound obtained from CPLEX for this solution with respect to the execution time by using all candidate paths with multi-link SRLGs case and the algorithm is forced to stop after 6 hours. According to the Figure 4.5, the solution slowly approaches to the lower bound as time passes. The optimality gap is calculated with respect to the solution and the lower bound obtained form CPLEX.

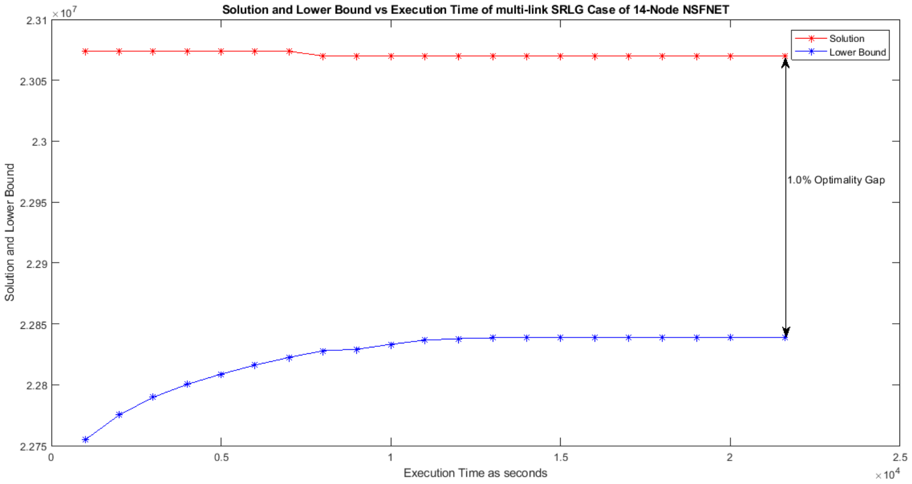


Figure 4.5: ILP Solution and Lower Bound for 14-node NSFNET vs Execution Time

Figure 4.6 and Figure 4.7 show the ILP solution with respect to the bound of maximum candidate paths for all possible demands of 24-node USANET with the multi-link SRLGs and with the single-link SRLGs cases, respectively. According to the figures below, as the bound on the maximum number of candidate paths increases, the solution decreases.

In the multi-link SRLGs case, when the bound is higher than 50, because of the CPU limitations, CPLEX cannot find a solution. In the single-link SRLG case, when the bound is higher than 50 CPLEX cannot find a solution. The difference is because of the network complexity. The complexity of the multi-link SRLG case is less than the single-link SRLG case because some paths cannot be used in the multi-link SRLG case.

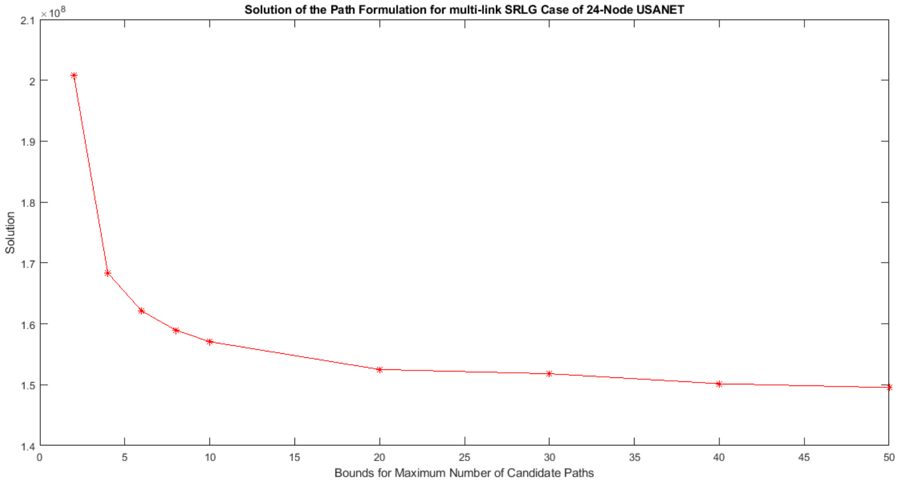


Figure 4.6: ILP Solution for multi-link SRLG Case 24-node USANET vs Bound of Maximum Candidate Paths

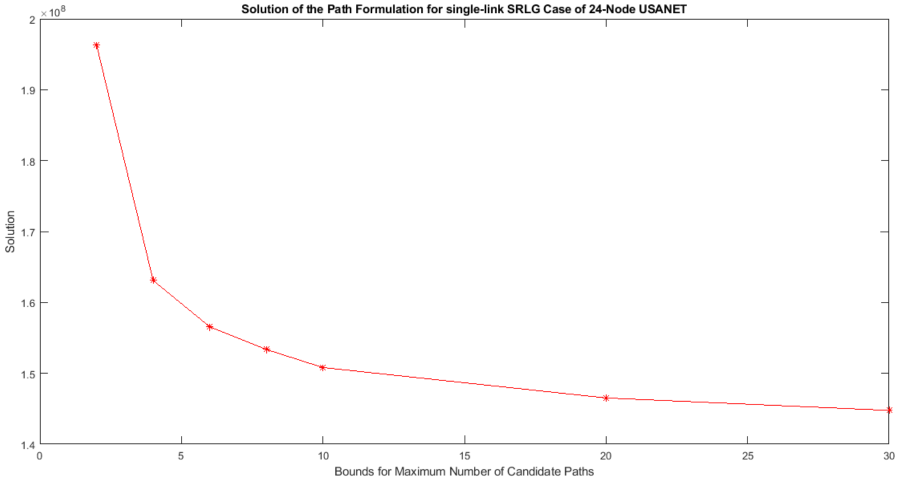


Figure 4.7: ILP Solution for single-link SRLG Case 24-node USANET vs Bound of Maximum Candidate Paths

Figure 4.8 and Figure 4.9 show the ILP solution and the lower bound of multi-link SRLG and single-link SRLG cases of 24-Node USANET obtained from CPLEX with respect to the execution time respectively. In these simulations, the bound on the maximum number of candidate paths is set to 30 for single-link

SRLG case and 50 for multi-link SRLG case. The figures illustrate that as the execution time passes, the solution approaches to the lower bound. The optimality gap is calculated with respect to the solution and the lower bound obtained form CPLEX for each case.

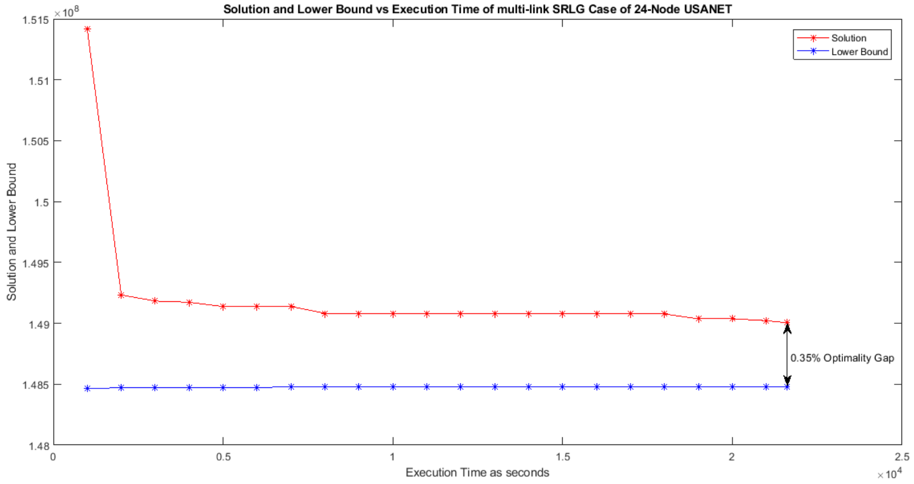


Figure 4.8: ILP Solution and Lower Bound for multi-link SRLG Case 24-node USANET vs Execution Time

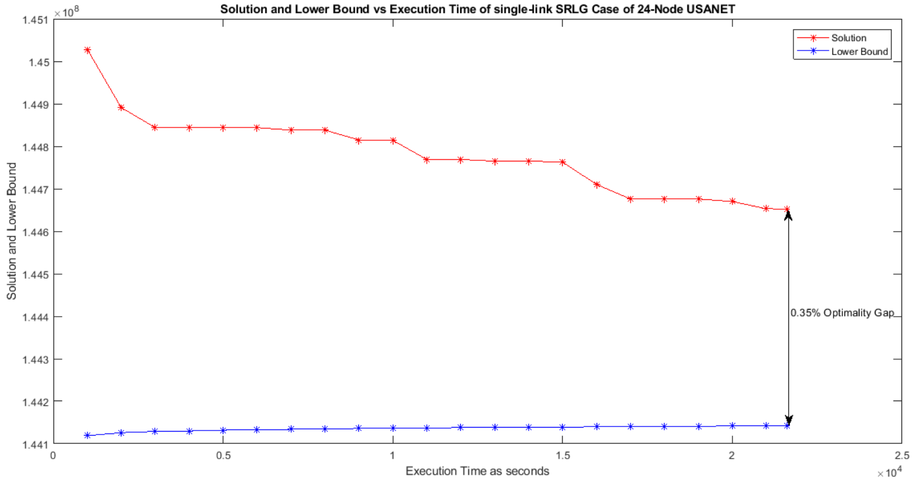


Figure 4.9: ILP Solution and Lower Bound for single-link SRLG Case 24-node USANET vs Execution Time

4.2.3 Comparison Between the Flow and the Path Formulations

Theoretically, the performance of the Flow Formulation is expected to be better because it can utilize all possible path pairs. However, because of the CPU limitations, the algorithm stops before the ILP solution finds the best solution. Therefore, in some cases, Path Formulation may even obtain better results because the candidate paths given to the CPLEX may contain best paths.

The comparison between the Path Formulation and the Flow Formulation is based on comparing the ILP solution and its lower bound obtained from CPLEX of 10 randomly selected demand sets each with 50 connection requests of 14-node NSFNET for both multi-link SRLG and single-link SRLG cases. Figure 4.10 and Figure 4.11 show the ILP solution of the Flow Formulation and the Path Formulation. According to the figures, for the single-link SRLG case, the Flow Formulation is better than the Path Formulation for all cases. This is expected because of the performance of the Flow Formulation. However, for the Set-5 and the Set-6 of the multi-link SRLG case, the Path Formulation seems to be better. This is because of the CPU limitation and the quality of the candidate paths. Because of the CPU limitations, the algorithm must be stopped after a certain time even the best solution is not reached. Also, if the set of candidate paths involves the best paths, the Path Formulation can reach to the best solution.

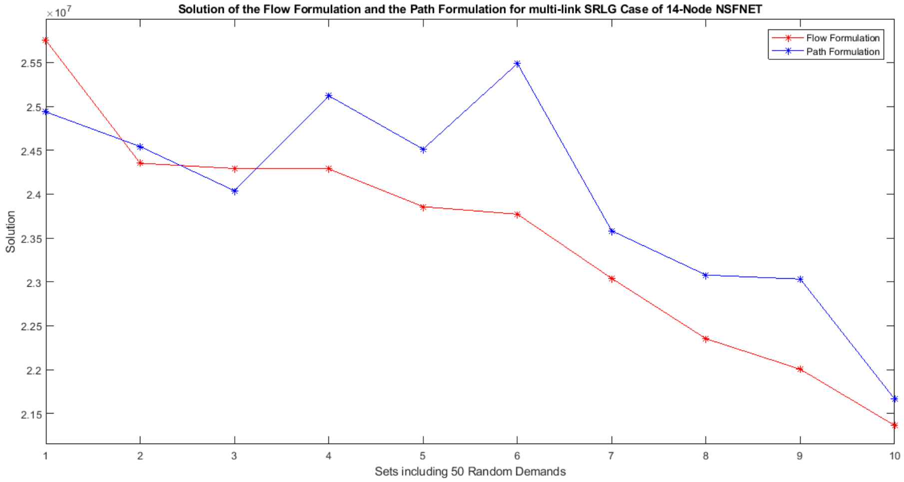


Figure 4.10: ILP Solution of the Path Formulation and the Flow Formulation of 10 randomly selected demand sets each with 50 connection requests in multi-link SRLG Case of 14-node NSFNET

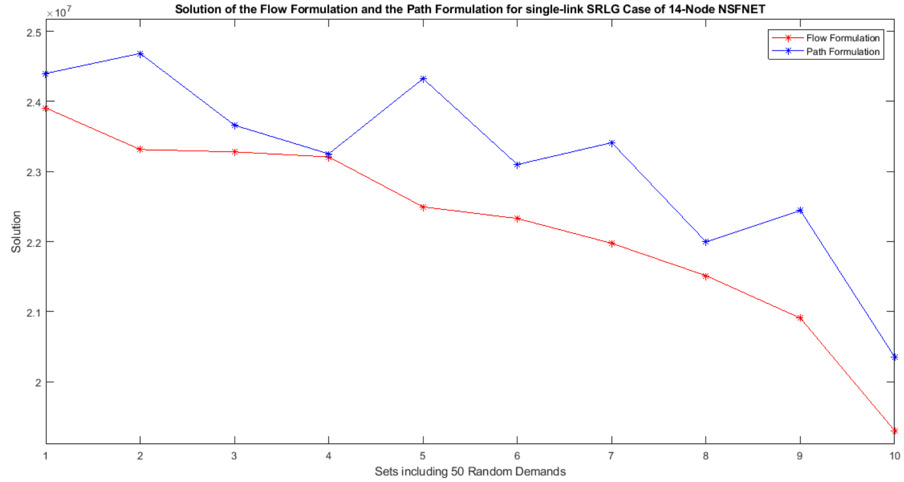


Figure 4.11: ILP Solution of the Path Formulation and the Flow Formulation of 10 randomly selected demand sets each with 50 connection requests in single-link SRLG Case of 14-node NSFNET

Chapter 5

Conclusion

Elastic optical networks offer higher spectrum usage efficiency compared to WDM based optical networks because of its flexi-grid spectrum allocation. In this thesis, SRLG-disjoint active and backup path calculation for elastic optical networks was studied. The Shared Backup Path Protection technique is used to decrease the network resource usage. For the spectrum allocation, an AMC scheme, which assigns the appropriate AMC profile based on the path length, was used. The active and backup paths are calculated such that the network can fully recover from any single-SRLG failure. Two different approaches were presented: the Flow Formulation and the Path Formulation. The objective of both formulation is to minimize the resource usage and maximize the resource utilization efficiency. The resource usage is minimized by minimizing the total capacity usage in the network. The resource utilization efficiency is maximized by minimizing the number of edges used by active and backup paths. The goal of the Flow Formulation is to calculate the SRLG-disjoint active and backup paths whereas the Path Formulation selects appropriate active and backup paths from pre-computed path pairs with respect to the objective. The path pairs were computed by using Yen's algorithm which is based on finding k-shortest paths. The formulations are tested for the 14-node NSFNET and 24-node USANET topologies. The Flow Formulation could not find a solution for the 24-node USANET topology even with low number of connection demands. It could only find a solution for the 14-node

NSFNET topology when the number of connection demands is less than or equal to 50. The Path Formulation was able to find solutions for both networks.

It is found that the performance of the Flow Formulation is 5% better than the Path Formulation on the average when both formulations are run for a runtime limit of 40 minutes. In some cases, the Path Formulation was able to obtain better results because the pre-computed path set may contain best paths. Also, for the Path Formulation, the solution was compared as the bound on the maximum number of candidate paths changes. It is found that as the bound on the maximum number of candidate paths increases, the optimum solution rapidly decreases. The optimal solution saturates when the limit of path pairs is greater than 30.

As a result, the Flow Formulation is applicable for the smaller networks since its performance is better than the Path Formulation. For the larger network, which the Flow Formulation cannot find a solution, the Path Formulation can be used as it finds solutions that are slightly worse than the solutions obtained by the Flow Formulation.

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