SLA Aware Green Routing Mechanisms for WDM GMPLS Networks

By

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I dedicate my dissertation work to my loving parents, Morteza Fazili and Simin Dokht Mirkhani for their endless support and unconditional love. Their words of encouragement and push for tenacity gave me the strength to carry on during this chapter of my life. I dedicate this work and give special thanks to my brother Mehran Fazili and my sister Mehrnaz Fazili for being there for me and their never-ending support throughout the entire doctorate program.

Table of Contents

List of Tables

List of Figures

ABSTRACT

This thesis proposes new routing and assignment mechanisms that aim at reducing the energy usage and the resulting Greenhouse Gas emission of WDM GMPLS networks. The thesis compiles information about the energy generation capacity of each state of the U.S from different resources to come up with a set of realistic energy and emission parameters while benchmarking the newly proposed routing mechanism. The compiled information on energy is realistic, as energy powering up a section of the network is neither 100% green nor 100% non-green as opposed to assumptions in the literature. This thesis introduces a novel Binary Integer Linear Programming method that provides a simple yet effective method of incorporating various Service Level Agreements, while "Greening" the optical network. The two new stateless routing mechanisms introduced in this thesis increase the throughput of the control plane of the WDM GMPLS network in serving connection requests by 6-fold, when compared to the capability of traditional routing mechanisms. In this thesis, a new resource assignment for WDM networks is also proposed that provides up to 8 percent increase in the success rate, and up to 35 percent energy usage reduction, when compared to First Fit resource assignment with the continuity constraint and the First Fit without the continuity constraint, respectively. The routing methods introduced in this work are intended for the control plane of GMPLS networks; however, their application could be extended to the control plane of Software Defined Networks as well.

LIST OF ABBREVIATIONS USED

A-EASB	Adaptive Emission Aware SLA Based
ASLA	Availability Service Level Agreement
ASLS	Availability SLA Satisfaction
BIP	Binary Integer Programming
CI	Confidence interval
CLE	Constrained Least Emission
CLE-C	CLE with the Continuity Constraint in resource assignment
CSPF	Constrained Shortest Path First
D	Destination
DSLA	Delay Service Level Agreement
DSLS	Delay SLA Satisfaction
EASB	Emission Aware SLA Based
EE	Energy Efficient
EIGRP	Enhanced Interior Gateway Routing Protocol
FF	First Fit
FL-EASB	Forward Looking EASB
GMPLS	Generalized Multiprotocol Label Switching
GSEASB	Green SLA Aware EASB
GSKSB	Green SLA Aware k Shortest Path
GSLA	Greenness Service Level Agreement
ILP	Integer Linear Programming
IN	Intermediate Node
KSB	k-SLA Based
LSA	Link State Advertisement / Area
MATLAB	Matrix Lab
MCSP	Multi Constrained Shortest Path
MPLS	Multiprotocol Label Switching
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NHK	N Hop a Kind
OSPF	Open Shortest Path First
RFC	Request For Comment
RSVP	Resource Reservation Protocol
S	Source
SDN	Software Defined Network
SLA	Service Level Agreement
SLS	SLA Satisfaction
SP	Shortest Path
SPCont	Shortest Path with Continuity Constraint in Resource Assignment
SPNHK	Shortest Path with N Hop A Kind Resource Assignment
TCO	Total Cost of Ownership
TE	Traffic Engineering
T-EASB	Table Driven EASB

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Chapter 1 INTRODUCTION

In a nutshell, green networks use the energy-related information in conjunction with other metrics to route the traffic from a source to a destination automatically, without human intervention. The concept of green networking is an analogy to all attempts in other industries to reduce the energy consumption and emission production. This thesis accomplishes the tasks below:

- Increase the throughput of the control plane of the GMPLS governed WDM network while reducing the emissions
- Analyse the effect of adopting green Service Level Agreement on the value of the performance metrics of the WDM Network
- Formulate an energy efficient Multi-SLA-Aware routing mechanism for processing real-time connection request of the WDM network
- Considering energy greenness ratio as opposed to considering 100% green or 100% non-green energy source type
- Introduce a new resource (Wavelength) assignment method for WDM network to increase the success rate of the network while reducing the energy consumption

This chapter will explain the issue that motivates this work in Section 1.1, followed by the energy and emission related information in Section 1.2. Subsection 1.3 defines the type of the networks that benefit from new methods of this thesis, and Section 1.4 details the testbed used for the analysis performed in this thesis. Section 1.5 introduces the software used in this thesis to performe the analysis, followed by Section 1.6 that details the organization of this thesis. Explanation of the motivation behind the work done in this thesis comes next.

1.1. Energy, Emission, and the Global Warming

By increasing the capacity and speed of today's networks, the energy needed to power the networks has also increased. Per articles in [1,2] the backbone network Internet, is using 84 to 143 gigawatt hour of electricity per year which is between 3.6 to 6.2 % of the global energy produced. On the other hand, monitoring the emitted Greenhouse Gasses (GHGs) to the atmosphere is becoming more important because of the global warming crisis. The Co_2 content of the air as one of the most important GHGs is increasing rapidly per a report in [3] therefore IT and the communication industry has also stepped towards greener approaches with the concept of "Green Networks" to reduce the Co_2 emission. A few of the most relevant and recent agreements among the industrial countries such as the U.S. and China to lessen the amount of emissions (GHGs) is detailed in [4-6]. These agreements set goals for GHG emission reduction by industrial countries. The set goals will push governments to mandate industries to adhere some guidelines in their operation to reduce the amount of GHGs emitted. There are two general methods to reduce the amount of GHGs: one is to use energy efficient devices and equipment, and the other (not surprisingly) is to use the green sources of energy. The second method has more importance, as lowering the energy used in operation, beyond some point, will reduce the amount and scope of the operation. Therefore, we need more green energy and better methods to be able to use green energy. There are two main methods to regulate the emission reduction that are financial incentives for the emission reduction. The first method is Caps Trading discussed in [7] and [8] and the second method is the Carbon Tax presented in [9]. The first method is the fixed Cap for the GHG emissions of an organization, meaning that an organization which needs to emit more GHG, must purchase the right to produce and emit more from another organization that will produce less GHGs. By employing this method, greener organizations can have more income by selling a part of their Cap. The second method is to set higher taxes on Carbon based sources of energy. With the later approach, greener organizations pay less tax for using energy produced using green sources of energy.

This thesis has introduced different methods for reducing the GHG emission and saving the energy which are detailed in subsequent chapters. Introductory information on the type of energy and emission comes in the next section.

1.2. Energy and Emission

The emission of a source of energy for electricity generation such as Coal, Hydro or the wind is given in two forms per reports in [10]. The first form is the lifecycle amount of emission, and the second is the direct emission of a source. The life-cycle emission value gives the amount of possible emission in a unit of [g Co_2 / kWh] for the life span of a power plant that uses this source of energy. The direct emission gives the immediate value of emission with the same unit in electricity generation using that power source. The proposed methods of this thesis use the direct emission values in this analysis as the simulated time in the analysis are shorter than a lifetime of a power plant.

Many papers such as [11-14] have considered the source of energy to be either green or non-green which is not the case in reality. Electricity generated in an area is a mixture of different sources of energy which is neither 100% green nor 100% non-green. Chapter 5 of this thesis, which is the extended results of the paper in [15], addresses this issue by computing an energy dirtiness for each section of the network.

The energy saving and energy reduction methods can be used in different types of network. A primary classification of networks can be done by the way that network control-operation is performed. Network control methods are detailed in the upcoming section.

1.3. Network Control

Controlling a network in the "Control Plane" includes but is not limited to:

- Calculating a route from a source node to a destination node
- Assigning the resources of a route for Traffic Engineering tunnels or lightpaths
- Handling the failures (node and link) and topology changes in general
- Pulling the status of the network: e.g. energy used, the level of congestion in links
- Managing and setting the security policies
- Managing the configuration of elements

Networks have two major classifications with the introduction of Software Defined Networks (SDN):

- Control is performed centrally such as SDNs
- Control is done in a distributed fashion and in collaboration with all control elements of the network such as MPLS and GMPLS networks

The proposed routing methods of this thesis can operate in both types of control (Central or Distributed) environment and can be used either in SDNs or GMPLS networks. The resource assignment mechanisms in this thesis are intended for the "Forwarding Plane" of the GMPLS network but can be used in any similar Forwarding Planes. The testbed of this thesis has two layers of Control and Forwarding governed by GMPLS, detailed in next Subsection.

1.4. Testbed for Simulation

The simulated network of this thesis in Figure 1-1 from [13] is the network of NSFnet with 14 nodes and 21 bidirectional links, also used in papers of [16,17]. Numbers on the links represent the node distances in units of km. The inline amplifiers amplify the entire spectrum (all Lambdas) and are placed every 80 km unless otherwise stated in Chapter 5 and 6. Signal leveling amplifiers also level the entire spectrum and are placed every 500 km. Each chapter will add more chapter specific information about the behavior of traffic and other parameters used in the simulation. The simulation to obtain the results of each routing and assignment method has been done using various software detailed in next section.

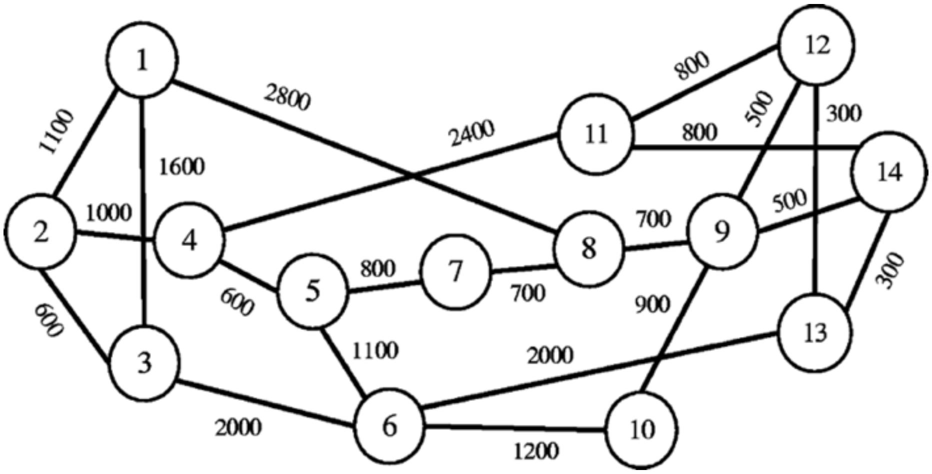

Figure 1-1. NSFnet network

1.5. Software Used for Analysis

The entire results of this thesis have been produced with MATLAB software in [18]. This thesis uses the Parallel computing toolbox to speed up the simulations by running them in parallel. In Chapter 5, the Gurobi-mex detailed in [19] has been used to interface MATLAB with the Gurobi® optimization solver in [20] to solve the Linear Programming problem for routing. Chapters 5 and 6 have use the Minitab® in [21] to calculate the Confidence Intervals (CIs) for the performance metrics. The next section details the organization of this thesis and upcoming chapters.

1.6. Organization of Thesis

This thesis has six more chapters as follows:

Chapter 2: reviews the related works in the literature and explains their link to new topics introduced in this thesis.

Chapter 3: introduces two new stateless routing and assignment mechanism for the GMPLS network that can increase the throughput of the control plane in serving connection requests by up to 6-fold, published in papers of [22,23].

Chapter 4: studies the effect of adopting Green SLA (GSLA) on the behavior of key performance metrics of the GMPLS networks. The Chapter 4 published in [24], suggest more investment on green energy infrastructure. This chapter also defines and considers Green Service Level Agreement (GSLA detailed later) for routing mechanisms by proposing a mathematical model for route greenness and proposing two algorithms for the adoption of GSLA. The results of this paper show that adoption of the GSLA by routing mechanisms decrease the resource efficiency in return for a smaller reduction in emission as compared to the other Green routing mechanisms. This Journal paper also emphasizes the importance of developing better "green-aware" mechanisms. Chapter 4 is provided as it published, due to license limitations.

Chapter 5: is the extended version of the paper published in [15] which introduces a multi-SLA aware routing mechanism that considers multiple constraints in forwarding traffic and uses a set of practical energy information. The routing method introduced by this chapter is more SLA compliant and emission efficient compared to other methods reviewed in the chapter. The method introduced in this chapter provides up to 35% % emission reduction while maintaining 100 % SLA satisfaction.

Chapter 6: introduces a new resource assignment mechanism that improves the success rate of the network when compared to the traditional resource assignment of First Fit with the continuity constraint in resource assignment. The assignment method of this chapter provides to 36% less energy when compared to the usage of First Fit without the continuity constraint.

Chapter 7: draws the conclusion and states the future work.

Chapter 2 A REVIEW OF RELATED WORK IN THE FIELD OF GREEN ROUTING AND RESOURCE ASSIGNMENT MECHANISMS

This chapter provides the reader with some insight into the technical background on the foundation work of this thesis. This chapter is segmented as follows: Section 2.1 reviews the Service Level Agreements used in this thesis. Section 2.2 reviews the energy and emission efficient routing mechanisms that form the foundation of the new methods introduced in this thesis. Introduction to Emission Topology Database is also visited in Section 2.2. Section 2.3 reviews the concept of Emission Topology Change and explains a routing method that initiates the reprovisoning of established connections due to a change in emission topology database. Section 2.4 reviews the resource allocation mechanism used in the reconstructed or new methods of this thesis. Section 2.5 reviews the power state of elements of the forwarding layer, followed by Section 2.6 that reviews a few Integer Linear Programming methods intended for routing and assignment in optical networks.

2.1. Service Level Agreements used in Green Networks

2.1.1. Availability

An Availability Service Level Agreement (ASLA) ensures that the connection request is served with a route and lightpath that does not pass through certain less reliable sections of the network. The overall availability of the route is the product of availability of all links of the route. Equations (2-1) and (2-2) show the calculation of route availability. MTBF is the Mean Time Between Failures, and MTTR is the Mean Time to Repair. In this thesis, a topology database of the link availabilities (A_{ij}) is built. It is used for decision making when calculating the availability of the route using RFC 4203[1] referenced in [25].

$$A_{ij} = \frac{MTBF_{ij}}{MTBF_{ij} + MTTR_{ij}} \tag{2-1}$$

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[1] RFC 4203 specifies the encoding of the extension to the OSPF routing protocol in support of GMPLS operation.

$$A_R = \prod_{(i,j)\in R} A_{ij} \tag{2-2}$$

The papers in [26-28] have proposed, and used, a topology database for maximum route availabilities (A_R) using the same extended link availability attributes. In this thesis, although the requested Availability of the connection requests is considered when fining a route (also in [29]) with all proposed routing methods of this thesis, the route availability topology database is not populated. The first reason is that more than one route is found in the initial route calculation of the routing methods of Chapters 3 and 4, similar to the method in [13,30]. Therefore, more than one route availability is needed. The second reason is, there may be no resources left (Lambda) to forward a new lightpath through the route whose availability is given by the route availability table, and therefore a new route and a route availability calculation may be needed.

A route R, with lower availability may be assigned to a connection by paying penalties to the requester of a connection, or by an accompanying backup route (To improve the overall Availability) to be used in the event of failure of the primary path.

2.1.2. Delay

A Delay Service Level Agreement (DSLA) specifies the total end-to-end delay for the lightpath or route R. The end-to-end delay of the route serving a connection request must be less than the value specified in DSLA. The end-to-end delay of the lightpath from source node S to destination node D comes in Equation (2-3):

$$T_R = \sum_{(i,j)\in R} T_{ij} + \sum_{j\in R\ ,j\neq S\ j\neq D} \delta_j \tag{2-3}$$

In which T_{ij} is the time delay for the light to traverse each link (i,j) of the route R, and δ_j is the amount of delay in Lambda or resource conversion. DSLA in this thesis is concerned with establishing the lightpath in core nodes and delays in access and aggregate nodes are not considered. The DSLA as a constraint for finding a route is studied in Chapter 5.

2.1.3. Greenness

A Green Service Level Agreement (GSLA) as defined in [31,32] specifies the minimum percentage of green energy to be used while serving a customer. The reason for the introduction of this SLA as mentioned in Section 1.3, is to reduce the emission and promote the usage of green energy. With considering GSLA, the amount of reduction in emission can be quantified and measured for compliance. It is possible that companies that provide service to government organizations may be asked to use a minimum percentage of green energy for their continued contract with governments. On the other hand, government organizations and the bigger segment of the private sector may refuse to do business (due to government penalties, higher taxes, etc.) with organizations that do not conform with green policies of the Provincial or Federal government. However, as with other SLAs, GSLA also faces an interesting challenge. Per framework introduced in [33], GSLA also needs a trusted third party Moderator for monitoring the compliance and logging the violations. It is also very cumbersome to monitor the GSLA violation from the technical point of view. On the other hand, the type and value of the penalties must be negotiated for a different amount of violations.

Chapter 4 defines the ratio of a total number of “Green Powered” inline amplifiers over the total number of amplifiers of a lightpath, as a basic definition for GSLA in GMPLS networks.

In Chapter 5 a new definition for greenness is considered as explained in Chapter 5.

2.2. Routing Mechanisms

2.2.1. Emission as a Route Cost and Traffic Engineering Extensions for OSPF

Authors of the paper in [34] have introduced a new opaque LSA to propagate the link energy type (e.g. coal, wind, etc.) and build an emission topology database table knowing the link energy usage. This thesis uses the same LSA to build the same emission topology database conceptually shown in Equation (2-4) for a network with n nodes.

$$M_{n\times n} = \begin{bmatrix} \infty & \cdots & m_{1n} \\ \vdots & \ddots & \vdots \\ m_{n1} & \cdots & \infty \end{bmatrix} \tag{2-4}$$

In Equation (2-4) m_{ij} is the emission of the link connecting node i to node j. The member of the main diagonal of the M_{nxn} matrix, as well as the value for non-existent links(when there is no link between node i and j), are considered infinity. The same emission topology database is used in Chapters 3 and 4. This topology database is similar to other Traffic Engineering (TE) topology databases created in the control plane and is used for finding a route, or calculating the emission of a network. Chapters 5 and 6 use a different type of LSA as detailed later in Chapter 5.

The authors in [11,35] have introduced a routing mechanism that finds the least or shortest emission first route for connecting a source node to a destination node. The method in these papers considers emission topology database in Equation (2-4) for finding the lowest emission route as also detailed in [34]. The shortest emission method is called Energy Efficient method (EE) in corresponding papers. EE is not an SLA-aware mechanism and uses more resources compared to traditional shortest path method (per corresponding papers), to serve an equal number of connection requests, as elaborated in [11,13,35]. However, it performs very well regarding emission reduction when compared to the shortest path method, again, based on corresponding papers. The EE has been reconstructed in the analysis sections of upcoming chapters for comparison against other proposed methods. The next section introduces a green routing mechanism that considers the resource utilization factor in serving a connection request, by using a hybrid cost.

2.2.2. Hybrid Cost of a Route

The concept of Hybrid green cost is introduced in the paper of [13]. The hybrid green cost which can be considered as a TE cost, pursues two goals: Minimizing the length of the route, and reducing the emission of the route, while being ASLA compliant. The routing mechanism that uses this hybrid cost as defined in the paper of [13] is called the Emission Aware and SLA Based routing mechanism or EASB. EASB first calculates the k most-available routes from a source node to a destination node using Equation (2-5). Equation

(2-5) gives the logarithmic value of the Availability of route R, as the cost of the route C_R, given the link availability of A_{ij} as explained in Section 2.1.1.

$$C_R = \sum_{(i,j)\in R} -\ln(A_{ij}) \tag{2-5}$$

EASB then calculates the Emission Factor of each route (EF_R) for each of the k routes using Equations (2-6). EASB then calculates the hybrid cost of each of the k routes using Equation (2-7). Finally, EASB serves the connection request with a route that has the minimum of the hybrid cost and complies with the ASLA of the connection request.

$$EF_R = \sum_{(i,j)\in R} link\_Co2_{i,j} \tag{2-6}$$

$$Cost_P = \alpha\times\lambda_R + (1-\alpha)\times EF_R \tag{2-7}$$

In Equation (2-7), λ_R is the length of the route in units of hops and $\alpha = 0.35$ is a balancing factor as explained in the paper of EASB in [13] that provides the lowest normalized hybrid cost for the combination of emission factor (EF_R) and λ_R as we can see in Figure 2-1 for the testbed network of this thesis.

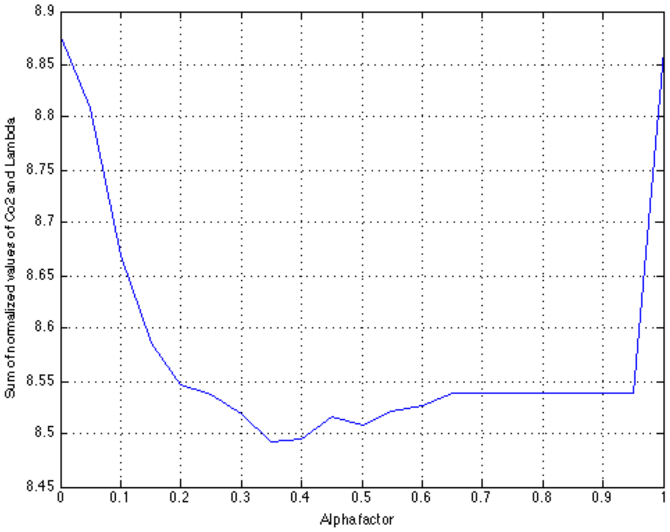

Figure 2-1. Hybrid cost vs value of α

EASB is not aware of GSLA or DSLA however it has an acceptable resource utilization when compared to EE and traditional non-green routing method, detailed in the corresponding paper for EASB. Figure 2-2, directly from the corresponding paper details the operation of EASB.

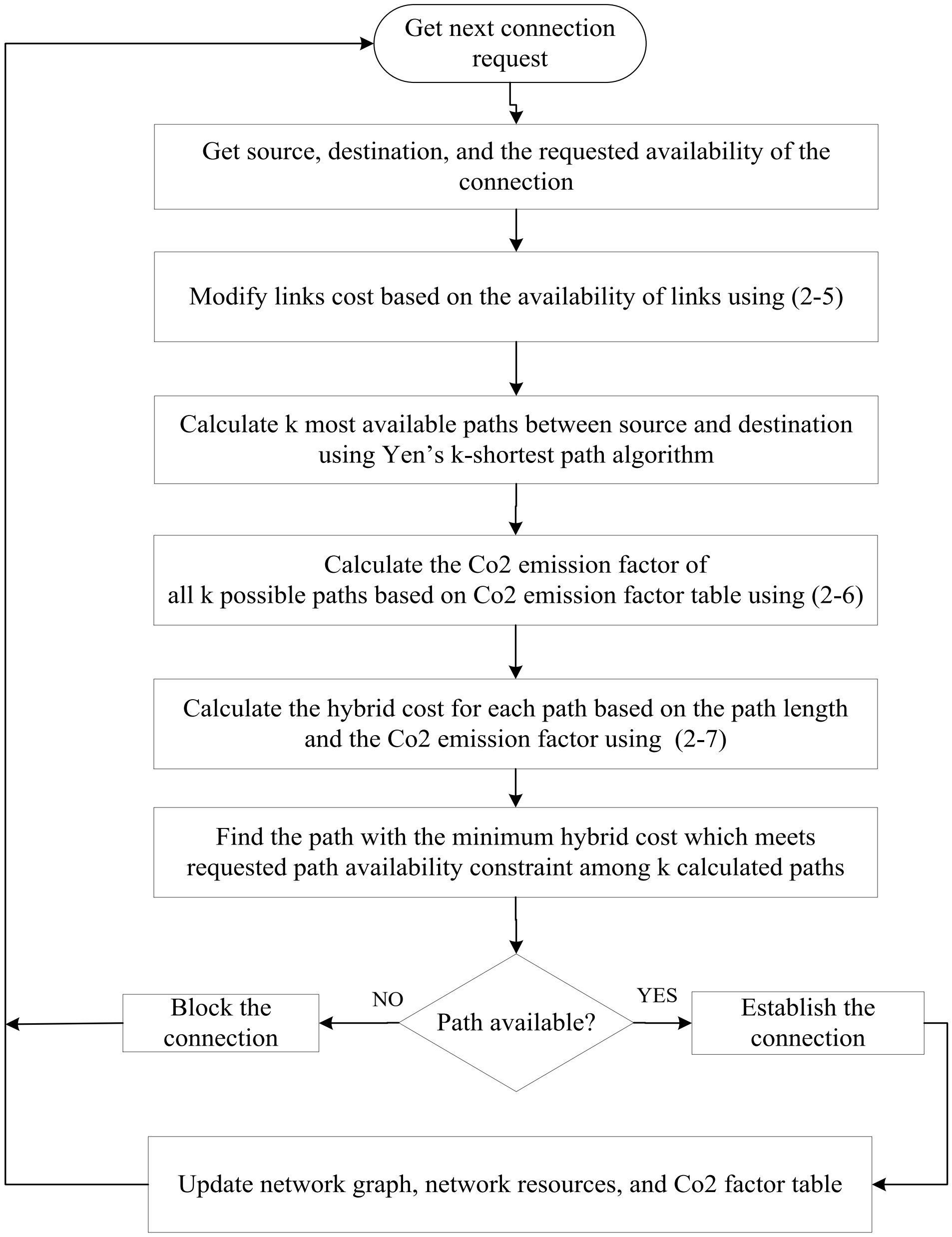

Figure 2-2. Routing with hybrid cost

EASB as an intuitive method with acceptable resource utilization as per [13,23] has also been added to the simulation and analysis sections of upcoming Chapters 3, 4 and 5. New routing mechanisms introduced in this thesis will be compared against EASB for resource utilization and other performance metrics detailed in corresponding chapters. Chapter 3 of the thesis builds a routing table for serving the connections using EASB method and shows that by using a routing table the throughput of the control plane (ability to serve connection requests) can be increased by 6-fold. EASB uses the same emission topology database of EE. Chapter 4 adds the GSLA awareness to EASB and analyse the effect of adopting this SLA on the behaviour of key performance metrics. Next section is reviewing the concept of emission topology change and modified EASB to reprovision the established connections.

2.3. Emission Topology Change and Adaptive Re provisioning

The papers in [30,36] have explained the situation in which the source of energy powering up each section of the network is changed. The emission of energy powering up each section of the network can change as green energies such as solar and the wind are available on limited bases and can change in hours. When the type of energy (or greenness of the energy) powering up each section of the network is changed, the emission topology database of the Equation (2-4) has to be updated with new link emission before serving the new connection requests. After updating or repopulating the emission topology database, the new connection requests can be served with new emission information. Similar to other types of topology change (e.g. link failure), a reprovisioning mechanism is triggered in the papers of [30,36] to re-optimize the currently established lightpaths to reduce the emission. The reoptimization is done because the established lightpaths might not be in an optimized emission state as the emission of a route can change when an emission topology change happens. The detail of the reprovisioning operation is shown in the flowchart of Figure 2-3.

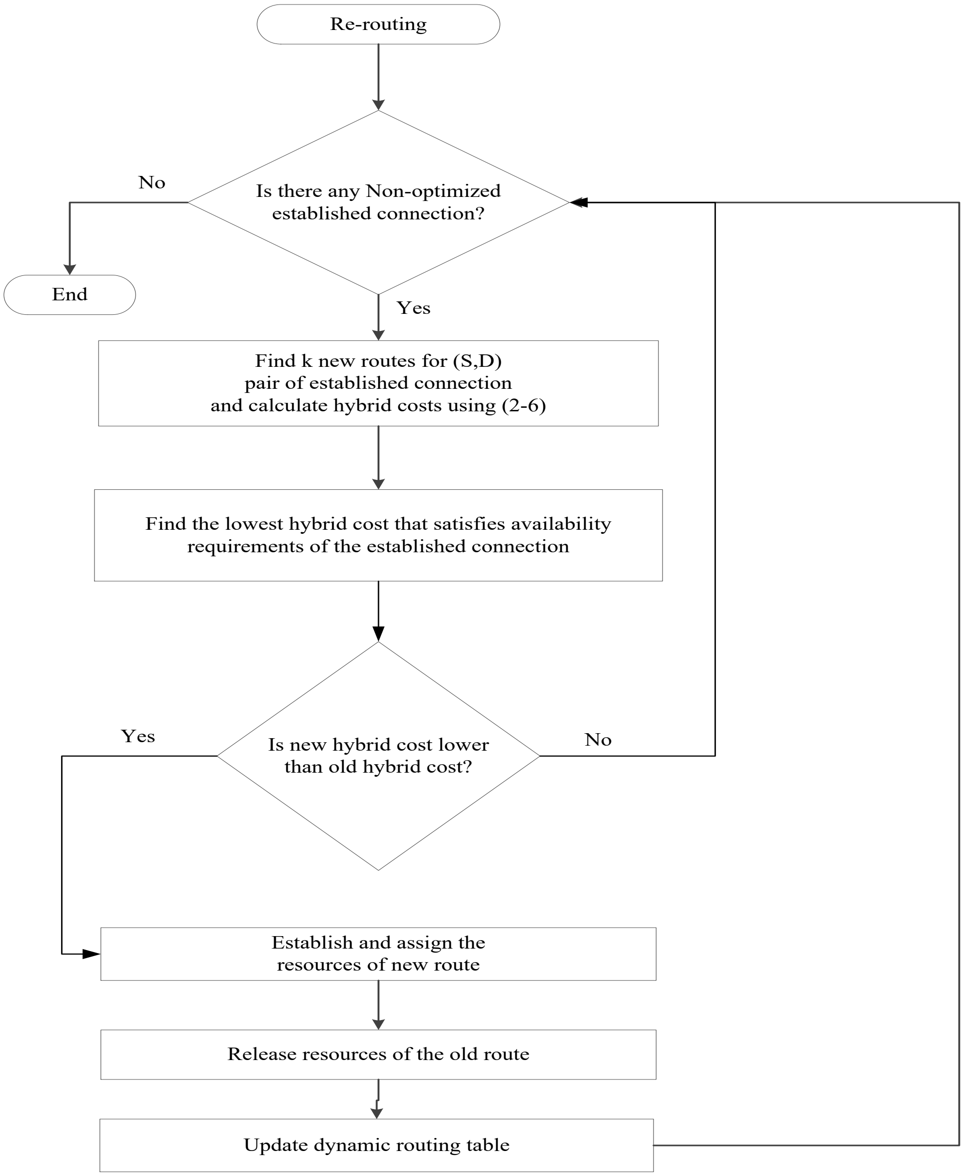

Figure 2-3. Flowchart of the Adaptive EASB

The adaptive method in papers of [30,36] does not consider the DSLA and also uses the concept of 100% green or 100% non-green energy resource for powering up each section of the network. The paper in [36] has suggested a threshold value for a change in hybrid cost to flag the emission topology, which ultimately can change the number of reprovisionings. When rerouting an established connection, a new route must be calculated and assigned before terminating and redirecting the established connection in "Make-Before-Break" fashion explained in [37,38]. By introducing the threshold value in [36] the established route is not altered, and the assignment phase of Make-Before-Brake is avoided, when there is not a significant (more than the threshold) change in the hybrid cost of the route. Effect of re provisioning with A-EASB on Green SLA compliance has been studied in Chapter 4. The next section reviews the Lambda assignment methods used in this thesis.

2.4. Resource Assignment Methods

This section lists a few important resource assignment methods from the report in [39] and the paper in [40]. First Fit (FF) and FF with the continuity constraint in assignment as detailed below are used in upcoming chapters of this thesis. More detail on the setup and pairing with routing method is given in each subsequent chapter.

2.4.1. Random

This method assigns a random Lambda number to each hop of a lightpath passing through the optical links. This method is a very easy and intuitive way of assigning the Lambda (Resource) however since it does not consider the Continuity Constraint (explained later) it may need more "Lambda Conversion" which adds to the energy consumption, and increases the end-to-end delay of the lightpath.

2.4.2. First Fit

The First Fit (FF) method assigns the first available Lambda number to the lightpath passing through each optical link. For simplicity and to be consistent with other related work FF method has been used in the proposed routing methods of this thesis. Chapters 5 and 6 use FF with continuity constraint. Furthermore, Chapter 6 benchmarks the performance of a new assignment mechanism against FF and FF with the continuity constraint which is discussed next.

2.4.3. Continuity Constraint

The continuity constraint, continuous, or CNT as explained in [39] is a situation in which the same Lambda number is assigned to a lightpath for all links of the route. Considering the continuity constraint adds to the complexity of assigning a Lambda for a lightpath, however it has the advantage of saving energy (since no Lambda conversion is performed), and decreasing the end-to-end delay of the lightpath. The percentage of energy saving and decrease in the delay has been studied and simulated in Chapter 5 of this thesis with the newly proposed routing mechanism of Chapter 5.

To be able to save energy, the energy state of the optical elements must be known to the assignment method. Depending on the number and type of power states of optical elements, different routing and assignment methods can be chosen to serve a connection request. The next section details the power state of the elements used in the simulation and analysis section of each chapter.

2.5. Optical Forwarding Element and Their Operational States

In this thesis, the forwarding elements of the network that have no role in directing any lightpath may be placed in the OFF state and unlike the paper in [41-44] no sleeping mode or state is considered. Sleeping mode reduces the life time of equipment and is economically infeasible as discussed in [45]. In this thesis, the elements of the control plane or the electrical control and decision-making plane are considered ON at all times as they perform the routing and re-provisioning task for the lightpaths. When performing Make-before-Break re-provisioning for lightpaths or Traffic Engineering tunnels of MPLS, the control plane may wait for the period of the “wake up duration” or boot duration of a router (when the control plane is turned ON) and then switch over to the newly provisioned route. However, in the event of failure, the already calculated backup path must be used right away in similar fashion to the Fast Reroute mechanism in [46] to mitigate the effect of failures, such as SLA violation and data loss. Therefore, wake up time may cause an ASLA and DSLA violation and penalties to the Service Providers. Figure 2-4 from [40] shows the separated electronic control plane of a node. In this thesis power reduction and optimization is performed for the optical or forwarding plane only, since the increase in power consumption of the control plane is increased by 3% only, per work in [45,47] and may be considered constant. The specification and power rating of each forwarding element is gathered in the upcoming section.

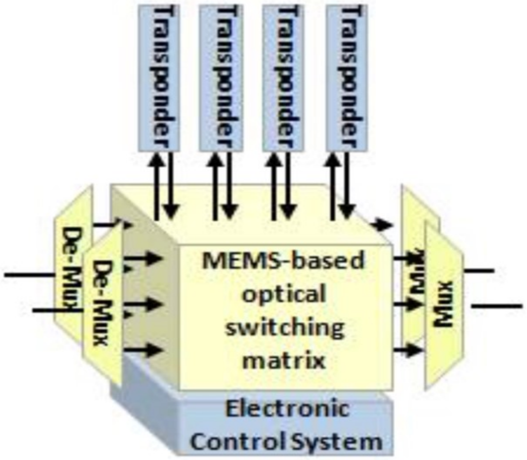

Figure 2-4. Separated Control and forwarding layer of each node

2.6. Power Consumption Specification of Optical Elements

Chapters 3 and 4 of this thesis are using the power and energy values for each element of the Optical forwarding plane detailed in [40] and 15 W needed for inline amplifiers. Each inline amplifier is placed every 80 km, based on information in this paper. Chapters 5 and 6 use the power values specification of optical elements by ADVA in [48]. The power values used are as follows in Table 2-1:

Table 2-1. Energy parameters at each node and link

Operation	Proportional Amount of Power	Note
Inline Amplifier	50W for all 96 Lambdas	Denoted by ε^1
Signal Leveling Amplifier	100W	Denoted by ε^2
Switching each Lambda with Lambda conversion using two transponders (OEO operation)	170W	Denoted by ε^3
Adding or dropping each Lambda at the source and the destination node	85W	Denoted by ε^4

To be able to consider more than one constraint, various TE metrics, and power state of forwarding elements in routing and assignment, an Integer Linear Programing (ILP) method can be formulated to serve a connection request. The next section reviews some existing ILP methods developed to save energy and emission in optical networks.

2.7. Integer and Mixed Integer Programming Formulation of Optical and Optical/Electrical Networks

The entire section here details the papers with Integer Linear Programing (ILP) or Mixed Integer Programming (MIP) for optimizing power and emission in optical networks. These methods are the “Power Models” that are formulated depending on the type of the network and type of the optical equipment used in the network. The work in [14,42,49] have proposed the three State of ON, OFF and SLEEP for network elements and tried to maximise the amount to “sleeping” elements when possible. Paper in [49] attempts to optimize the optical network so that all 1:1 protection paths are placed in sleep mode, and it is called “*Minimum Power with Devices in Sleep Mode Strategy.”* The work in [14] tries to maximize the elements that are supporting 1:1 backup protection role to maximize the number of sleeping devices. As mentioned before, no sleeping mode or state is considered in this thesis. The paper in [49] also attempts to minimize the power with or without sleep mode, however, does not consider the type of energy or percentage of the greenness of energy powering ON the networking elements. The work in [50] also explains the complexity of the Mixed Integer Linear Programming (MILP) approach in detail. The proposed approach in Chapter 5 tries to minimize the complexity of the ILP and keep it in order of O^2. The new routing mechanism introduced in Chapter 5 of this thesis uses a simple yet effective ILP formulation for fast resolution time (less than a second).

Reference [51] has formulated a very detailed model for reducing the energy in optical elements of the network which consists considering the node energies as well as link energies. Although the model is very comprehensive, it fails to return a result after a full day of intensive computation as stated in the paper. The result of computation in this case means having a route that complies with all constraints, or determination of the situation in which the model is infeasible, and quitting the computation. One attempt in this thesis and Chapter 5 to simplify the ILP method is to eliminate the constraint number 6 of the “E-TESP” model in this paper which is a constraint about availability of the resource in the optical links of the route to be used for serving the connection request. In this thesis, a dynamic network is used for calculating the route in all chapters of the thesis. The dynamic network means that when the last resource of a link is assigned, the link is taken out from the network topology and is not used for routing the later connection requests.

The work in [45] has proposed a very detailed model for energy when combining optical and non-optical networking elements for assigning the resources and has come up with three comprehensive formulations for energy consumption and emission. The paper in [45] work has proposed a formulation for maximizing the energy difference between non-green and green energy to maximize the use of green energy. In another approach, it also has proposed a formulation to minimized the total energy used in the network, minimizing the cost of Routing and Wavelength Assignment (RWA) formulation and minimizing total GHG emitted. The paper in [45] also suggests some key information about the amount of energy used for transporting a single Lambda for transparently passing, converting to other Lambda number, and when performing optical to electrical conversion (OEO). The formulation of ILP method of Chapter 5 is inspired by the detailed information about Lambda conversion mechanism proposed in the paper of [45], with dropping a Lambda at the intermediate node and adding it back to perform the Lambda conversion. Based on the paper of [45] this thesis also assumes that the lightpath is not splitable : *"the traffic is unsplittable in the optical domain: i.e. a traffic demand is routed over a single lightpath; (in theory, in the electronic domain a demand may be splitted into n flows, but in the optical domain these will appear as an unsplittable optical flows)"*.

The work in [52] has performed a detailed analysis on the power consumption of IP over WDM network and has formulated an objective function to minimize the number of required Lambdas or resources between any given nodes when the traffic pattern is known. This work also provides some power values for elements that were used in the initial simulations of the proposed work until the detailed specification of modern equipment were gathered. The paper in [52] also compares the various architectures for the optical network including the forwarding method used in Chapter 6.

The paper in [53] proposes energy aware resource allocation for a scheduled demand. Although this paper introduces a simple and effective model for reducing the energy, it does not consider the various SLAs such as Availability and Delay in finding a route before assigning the resources. Without considering the availability SLA, it is not possible to prioritise the requests that have higher importance and priority with the higher Availability needed. When the ASLA of the request is recognized, the lightpath of the connection can be routed though links that have higher Availability and resource of links with a higher Availability can be used with higher priority connection requests.

Reference [54] defines the QoS as the maximum capacity of the link and no other SLAs or other QoS parameters are considered as a constraint in finding a route. Later in the paper an ILP method only uses the flow conservation constraint in finding a route. The proposed method of Chapter 5 considers ASLA, DSLA Flow conservation constraints, and subtour elimination constraints as constraints to be met when finding a route.

None of the papers in this section considers the energy greenness and formulating a model for reducing the emission as opposed to the energy of the network. The method of Chapter 5 ensures that links with higher greenness are used first before using the less green links of the network.

Chapter 3 DYNAMIC STATELESS SLA AWARE ROUTING MECHANISM

This chapter details the proposed routing methods of Table Driven EASB (T-EASB) and Forward Looking EASB (FL-EASB), published in [22,23]. These papers elaborate two Table Driven routing and wavelength assignment mechanisms which are intended to increase the throughput of the control plane of the GMPLS networks. T-EASB and FL-EASB methods are based on Table Driven Design of Chapter 2 of the book in [55] and the Hybrid Emission Aware and SLA Based (EASB) routing mechanism detailed in Section 2.2.2. The application of the table in this chapter is to transform the given information: source node and a destination node, to a set of routes between the source node and the destination node. These routing methods intend to reduce the time needed for finding a route for connection request before being assigned.

3.1. Introduction

Both Table Driven Emission Aware and SLA Based (T-EASB), and Forward Looking Emission Aware and SLA Based (FL-EASB) perform a “Route Lookup” from a routing table which is populated beforehand as opposed to calculating a route for each connection request. Since a route is looked up for a connection and checked for availability of the resources to establish the lightpath, these routing methods are stateless routing mechanisms. Stateless in the sense that the routing mechanism does not need to be aware of the availability of the resources for the route when serving the connection request. The assignment method (which is the First Fit without the continuity constraint as explained in [39] and 2.4.2) tries to assign the resources of the given route. If the assignment is successful, the connection is established. If the assignment is not successful, the route that was looked up is marked as unavailable, and next best route to destination is considered for assignment. This process continues up to k-times (as k routes are stored for each source-destination pair) to find and assign a route for the connection request. Although this operation may seem lengthy, the results of analysis in the paper of T-EASB shows that in the worst-case scenario (assigning the resources for the last route in the table) the throughput of the control plane is increased by 6-fold when compared to the EASB. FL-

EASB in [22] was introduced to deal with a situation with T-EASB in which some requests may be blocked as the routing table is being populated and is not ready. FL-EASB populates the routing table, beforehand, forecasting the energy and emission status of the links for the upcoming 3 to 6 hours. In this thesis 3 to 6 hour is the time for emission topology change and updating the energy state of each element in the simulation part of the analysis. FL-EASB can consider the upcoming scheduled maintenance windows for each link (if needed) to avoid using a link in populating the routing table which is used 3 to 6 hours later.

3.2. Stateless Routing and Assignment Operation

Each cell of the routing table R denoted by r_{sd} is populated first with a stack of k-most-available routes between each source-destination (sd) pair of nodes. Since lightpaths in GMPLS networks are established in a bidirectional fashion based on RFC in [56], the return path is also needed for a connection request which the same “reversed” route in this thesis. Therefore, there is no need to calculate the return route for destination-source pairs. This means that only half of the routing table must be populated and the return paths are the transpose of “reversed routes” in all stacks as can be seen in Figure 3-1. In other words, (n)*(n-1)/2 k-most-available route operations must be performed. While populating each r_{sd}, the hybrid cost introduced in Section 2.2.2 using Equation (2-7), is also calculated and saved in a separate table of Hcost. Each route in the stack of r_{sd} is marked as “accessible” denoted by r_{sd_access}, which means that route is available to be assigned and used. After this step, the control plane is ready to serve the connection requests.

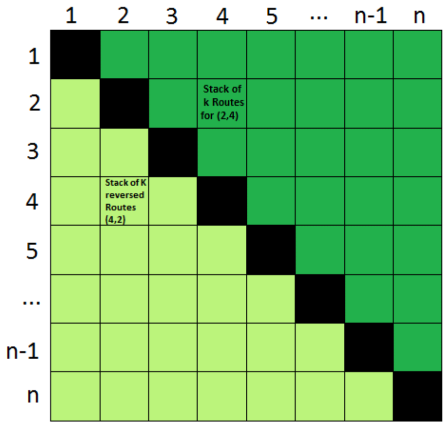

Figure 3-1. n by n routing table R

The R table is repopulated when emission topology change happens as mentioned in Section 2.3, since the emission value and the $Hcost_{sd}$ for affected routes by emission topology change are different. T-EASB is highly efficient if the total number of connection requests per each topology change interval (e.g. 3 hours) is more than a total number of calculated routes of the R table. When a connection request is received, the routes from r_{sd} cell of the R table, and the list of H_{cost} are fetched. After this step, the control plane chooses the route with minimum $Hcost_{sd}$ that meets the ASLA of the connection request. If there is such a route (it is accessible), the control plane tries to assign the resource (Lambdas) of the chosen route using the FF method. If the assignment is successful, the request is served and the dynamic resource table that keeps track of available to assign Lambdas of each link is updated. If the assignment is not successful (because no Lambdas are available to assign in a link of the route), the route is marked as "inaccessible" in the stack, and the next route with the lowest hybrid cost that meets the ASLA is chosen, and the process of resource assignment is repeated. If no route is "accessible", the connection request is blocked. When a lightpath is terminated, the Lambdas of the route are released, and the route is flagged as accessible in the stack. Table 3-1 shows the pseudocode of process of populating the R table.

Table 3-1: Creation and Population of table R

```
FOR (s=1: n)
  FOR ( d=s+1: n )
    $r_{sd}$ = k_shortestpath(s,d);
     FOR (i=1:k)
        $Hcost_{sdi}$ = Calculate the hybrid cost for $r_{sdi}$ using (2-7); $r_{sdi\_access}$=True;
        $r_{dsi}$ = Reversed ($r_{sdi}$); $Hcost_{dsi} = Hcost_{sdi}$ ; $r_{dsi\_access}$=true;
     END
  END
END
```

Figure 3-2 shows how a connection request is handled. FL-EASB is the same as T-EASB except for the fact that it populates the R table 3 to 6 hours ahead of the time using the predicted information about the sources of energy for each link.

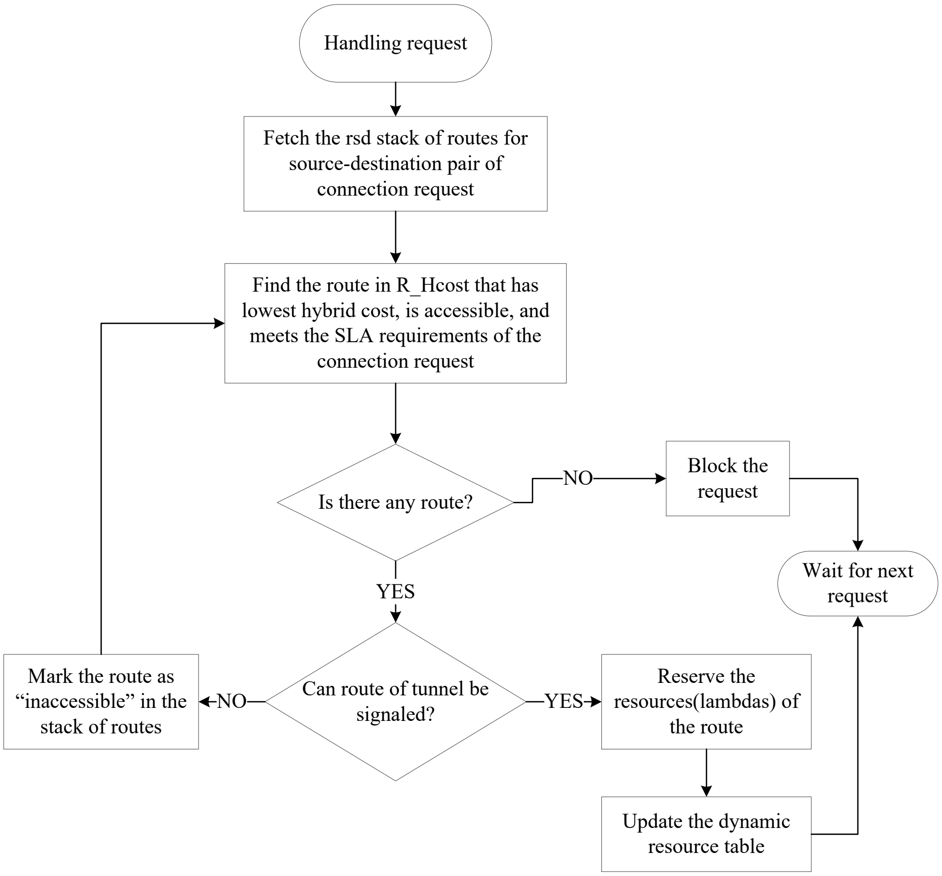

Figure 3-2. Handling a connection request

With 100% accuracy in predicting energy source of each link T-EASB and FL-EASB become the same. The prediction for the source or type of energy producing the electricity is done by power generation companies as they need to manage the demand for the upcoming hours. Power generation companies monitor the reports from weather forecasting agencies about the availability of sun and the wind to predict the production of green energy for the upcoming hours. When not enough green energy is "forecasted" to be available, power generation companies increase the usage of non-green energies to cope with the demand for electricity. On the other hand, when green energies are available the power companies can reduce the usage of non-green energies to reduce the emissions. A wrong prediction in this chapter means observing another unexpected outcome about the source of energy and ultimately different outcome for the greenness of energy of a link.

For example, having a cloudy day despite the forecasts for having a sunny day and being forced to compensate the missing portion of the energy needed in a section of the network that otherwise could be generated by solar panels and other solar technologies on a sunny day.

3.3. Analysis

3.3.1. The Simulation Network

The simulation network topology is the NSFnet network presented in Figure 1-1 and repeated here as Figure 3-3. Each inline amplifier is placed at every 80 km of optical links. Any type of energy sources can power nodes and links in the network, and the information about the type of energy of each link is disseminated through the network using the extended Link State Advertisements for energy as proposed in [34,35]. To deal with dynamic routing requests, it is assumed the routing and signaling information is propagated using the Resource Reservation Protocol or RSVP in [57] The duration of the connections follows an exponential distribution with a mean of 6 hours. The Co_2 emission for each source of energy powering nodes and optical links of the network has been adopted from the greenhouse gas emissions values provided in work [10]. Availability SLA (ASLA) requested by connection requests ranges between 0.999 to 0.99999. The availability of the links is assigned a random number between 0.9999 to 1 and does not change for the period of simulated time, 30 days.

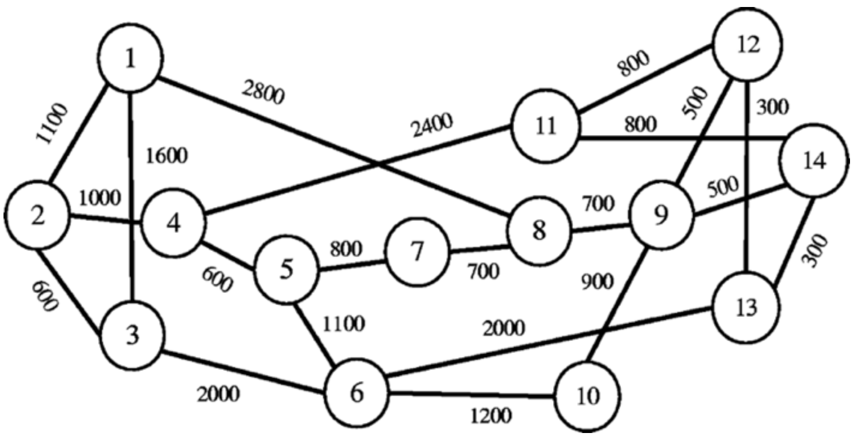

Figure 3-3. NSFnet network

3.3.2. Performance Metrics Used in This Work

EASB, T-EASB, FL-EASB, EE and a modified non-green routing method called k SLA Based (KSB) in [58] are benchmarked in this chapter. KSB first computes the k-most-available routes from a source node to a destination node and then serves the connection request with the shortest (units of hop) computed route that meets the ASLA of the connection request. The accuracy of the predictions for the energy source is kept at 95% when using FL-EASB routing mechanism.

ASLS

ASLS is the Satisfaction rate of the ASLA. This is a ratio of the number of connections that were served with a route that met their ASLA to the total number of the servered connections. FL-EASB, T-EASB, KSB and EASB that consider ASLA in finding a route for a connection request, result in 100% ASLA satisfaction.

Success Rate

The success rate is the ratio of the number of served connection requests over a total number of connection requests.

Lambda per Connection

This is the average length of the lightpath of the served connections in units of hops. A lower number is preferred for this metric. The lower the number, the more resource efficient is the routing mechanism.

Emission per Lambda

This metric is the amount of emission emitted to the atmosphere to establish a unit resource Lambda. A lower number is preferred for this metric. This metric shows the emission reduction capability of a routing mechanism. The value of the emission per Lambda will be lower for the routing mechanisms that have a higher success rate as the total emission is divided by more number of resources in operation, resulting a lower average emission. Because of this reason emission reduction must be evaluated and analysed among routing methods that have about the same success rate.

3.4. Results

3.4.1. Performance Benchmark

As we can see in Figure 3-4, overlapping EASB and T-EASB reduce the emission of the network by 21% compared to the non-green method of KSB. FL-EASB performs marginally the same with prediction up to an average of 95% accurate. The difference in emission reduction is only 2 g Co_2 per Lambda. The pure green method of EE, not surprisingly, provides the lowest emission per unit resource Lambda. The result of analysis for average connection length in Figure 3-5 shows that EASB, T-EASB, and FL-EASB have almost identical resource efficiency and consume only about 10% more resources compared to the non-green method of KSB. The reason is, the EASB family of routes find a route with minimum hybrid cost that satisfies the ASLA of the connection request. The route with the lowest hybrid cost that satisfies the ASLA may be longer trying to bypass the non-green sections of the network, therefore, is not the shortest route that complies with the ASLA of the connection request. As we can see in Figure 3-5, EE increase the average route length by about 57% when compared to KSB. This is because EE tries to find the greenest route and bypass the most of non-green sections of the network and uses longer routes. For the percentage of ASLS shown in Figure 3-6 we can see that all routing mechanism that consider ASLA constraint in finding a route for the connection request, give 100% satisfaction for the connections they serve. Without considering the ASLA for finding a route, ASLS can drop by more than 20% with EE. This may or may not be acceptable since the resources for the lightpaths have been assigned, and the lightpath has been established, since as we will see in Figure 3-7, EE has 100% success rate, and no connection request has been blocked. In Figure 3-7 we can see that EASB, T-EASB and FL-EASB perform the same regarding the number of the connection they serve. This is very important as T-EASB and FL-EASB did the routing by lookup and not the actual "per connection requests calculation." As we can see almost 10% of connection request were blocked since there was no route to satisfy their ASLA.

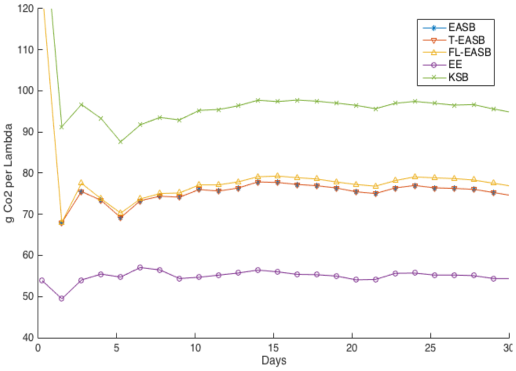

Figure 3-4. Co$_2$ emission per Lambda

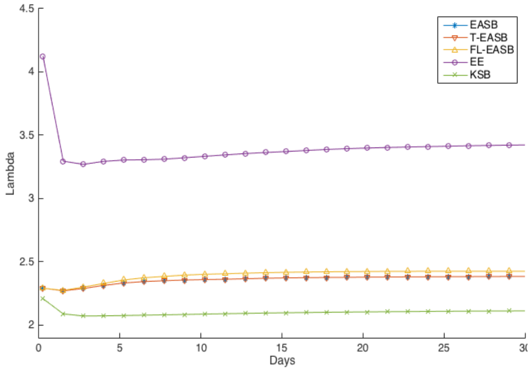

Figure 3-5. Average Lambda per Connection

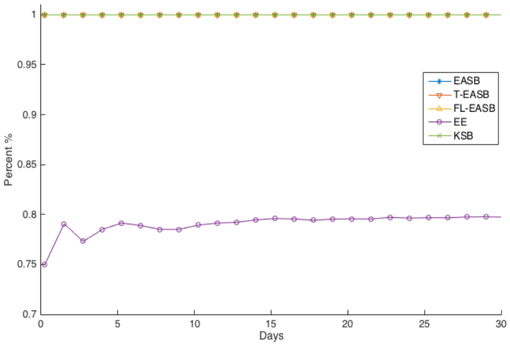

Figure 3-6. Availability SLA Satisfaction

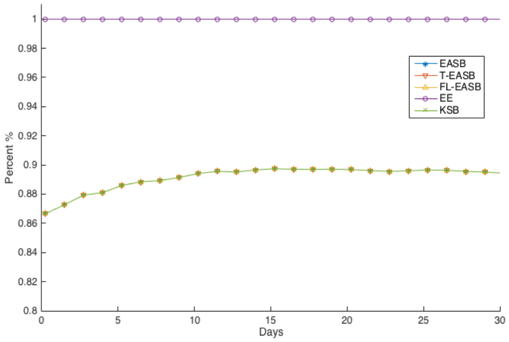

Figure 3-7. Success rate

3.4.2. Control Plane Throughput

This section of analysis shows the results of throughput enhancement for the control plane. In Figure 3-8 and Figure 3-9 a situation is enforced in which the last route is chosen to serve the request, to emulate the worst-case scenario of route lookup. This means that all k routes of corresponding r_{sd} cell have been checked and the last route has been determined as assignable. Therefore, the total time for processing these requests can be up to k-times less, when the first route of the r_{sd} is assignable. Figure 3-8 shows the time needed for route lookup or fetching the route from the R table. The time, of course, increases linearly, when serving more number of requests, however, as we will see in the next figure, the fetching time is smaller than the actual computation of route. Figure 3-9 compares the total time needed for “Obtaining” a route for the equal number of requests for EASB and T-EASB. In this figure, the total time including the time needed for populating the routing table R and serving 100 to 1000 requests is increasing slower (and is almost constant) when compared to the total time needed to serve 100 to 1000 requests using EASB and KSB. This is because the route fetching time is small. The total time for computing 100 to 1000 routes with EASB increases linearly and much faster than T-EASB. The total time needed for serving 1000 requests with EASB is at least 6 times the total time needed for populating the routing table R and fetching 1000 routes done by T-EASB or FL-EASB.

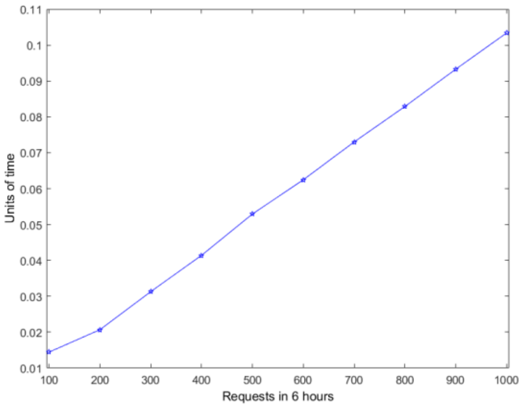

Figure 3-8. Units of time to fetch a range of 100 to 1000 connection requests in 6 hours, after populating the table R in T-EASB

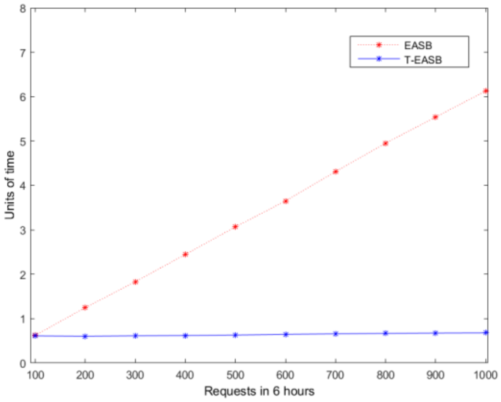

Figure 3-9. Total units of time required to process 100 to 1000 connection requests per 6 hours including time required to populate the table R in T-EASB for each scenario

3.5. Summary

Based on results of this chapter, it is possible to conclude that T-EASB and FL-EASB perform the same, compared to EASB regarding emission reduction, resource efficiency, ASLS and the success rate, while providing up to 6-fold increase in the throughput of the control plane of the GMPLS. Since FL-EASB uses the predicted source of energy for near "future," it may also include and consider other future related information such as scheduled maintenance windows for populating the routing table.

Chapter 4 GREEN SLA AUGMENTED EMISSION AWARE AND SLA-BASED ROUTING MECHANISM

This chapter consists of the journal paper published in [24]. Due to license restrictions for reusing the paper without modifications, the content of this chapter comes as published. The numbering style for figures, tables, equations and references has been updated to match the style of the thesis. The term "this paper" has changed to "this chapter" and text has been augmented with clarifying statements provided by the committee; however, figures, analysis, and other results are intact. This chapter analyses the effect of adopting Green Service Level Agreement (GSLA) on the value of the key performance metrics of the WDM networks, as briefly mentioned in Section 2.1.3. As we will see in this chapter, 20% increase in the chance of powering up links of the network by green energy leads to up to 90% success rate for serving connection requests that may ask for up to 80% greenness of energy powering up the route (GSLA up to 80%). The chapter is sectioned as follows: introduction section gives the background on the issue also explained in Chapter 1. Section 4.2 adds the chapter specific related work. The introduction to the method of adding the Green SLA awareness comes in Section 4.3 followed by analysis section 4.4 that introduces the setup for testing the GSLA aware mechanisms. At the end, the A-EASB introduced in Section 2.3 is also added to analysis for testing the effect of reprovisioning on GSLA Satisfaction. The chapter is concluded with a summary and future work. This chapter is the only chapter that considers the GSLA. Adopting GSLA increases the resource utilization without a justifiable amount of reduction in emission. As concluded in this chapter it is important to invest in greener infrastructure and green routing mechanisms.

4.1. Introduction

The effect of Greenhouse Gases (GHGs) such as Co_2 on global warming and formation of the acidic rain has been at the center of attention for two decades now. According to the study in [1] the energy needed to operate the datacenters of world's largest network, the Internet, is more than 2 % of the global energy produced. This numbers excludes the energy needed to power up all the underlying optical networks and networking equipment. This means at least 2 % of the global GHG emission is due to electricity generation needed to power ON networks, if no green source of energy is used. Various methods in different industries have been proposed to reduce the amount of energy emissions and to have greener operations. Among other industries, IT and communication industry has also proposed many ideas to reduce the amount of GHGs to develop greener methods and protocols. A few of the most important and recent agreements among the industrial countries such as the U.S. and China to reduce the amount of emissions (GHGs) is detailed in [4,6]. The agreement between the U.S. and China in [4] sets goals on GHG emission reduction in these two counties. The set goals will push governments to mandate industries to adhere to some guidelines in their operation to reduce the amount of GHGs. There are two general methods to reduce the amount of GHGs: one is to use more energy efficient devices and equipment, and the other (not surprisingly) is to use green sources of energy. The second method has more importance, as lowering the energy used in operation, beyond some point, will reduce the amount of operation. Therefore, we need more green energy and better methods to be able to use the green energy. There are two main methods to regulate the reduction of emission adopted by some countries that are financial incentives for the reduction of emission by an organization that participates in the emission reduction program. The first method is Caps Trading discussed in [7] and the second is Carbon Tax presented in [9]. The first method is the fixed cap for the GHG emissions of an organization, meaning that an organization which needs to emit more GHG must purchase the right to produce and emit more GHGs from another organization that will produce less GHGs emissions. By employing this method, greener organizations can have more income by selling a part of their cap. The second method is to set higher taxes on carbon based sources of energy. With this approach, greener organizations pay less tax on energy produced by using green sources of energy. In this chapter, organizations are customers of Internet and Infrastructure Providers (Service Providers) who want to outsource the communication infrastructure and possibly require a dedicated resource from Service Providers based on information in [38]. These organizations require a certain percentage of greenness for routes connecting different sections of the organization, to reduce the amount of emission. This means customers will set Green Service Level Agreements (GSLA) value on their requests to Service Provider to request a greener resource up to a percentage indicated in a GSLA. One challenge in using the green energy in IT industry and networking is to know which segments of a network are powered ON by green sources of energy. The other challenge is how to use information about green sources of energy powering up each section of a network, to steer the data flows from a given source to any destination using green sections of the network. By doing so, non-green sections of a network stay in hibernation or power OFF state. These challenges have been addressed by introducing green and hybrid routing mechanisms in [13] and [34,35] at the cost of having higher resource utilization compared to non-green methods (explained in more details in next sections). To provide a customer with a route that meets the requirements of the GSLA, Service Providers may choose to use the traditional non-green routing mechanisms to compute a set of routes and then select a route that meets the GSLA set by the customer, hoping to avoid the higher resource utilization (higher average length of routes). However, as illustrated in this work, the usage of non-green mechanisms may increase the resource utilization and also result in an unacceptable amount of reduction in emission. Increased resource utilization level may not be troublesome when traffic is light in the network, but it decreases the success rate of the network as we will see in next sections. This chapter is organized as follows: Section 2 details the related work in the field of green networking; Section 3 introduces the GSLA for green optical networks and discusses a model used in this work to increase the chance of having green sources of energy in a “Greener Network”. Section 3 also details the effect of re-provisioning on GSLA satisfaction. Section 4 defines the variables, simulation setup, and important metrics. Section 5 discusses the obtained results followed by Section 6 that draws the conclusion and states the future work.

4.2. Related Work

This section briefly introduces some related work which forms the foundation of this paper. These concepts have either been reconstructed or directly used in conjunction with analysis for this chapter. The Emission Aware SLA Based routing mechanism (EASB) introduced in [13] uses a hybrid metric in finding the best route for connection requests. This method reduces the amount of emission while maintaining an acceptable amount of resource utilization. Resource utilization in this work and in [35], is a measure of how lengthy (average in hops) are the routes in a Service Provider network. A lower average result in better or less resource utilization. This method has been reconstructed in the simulation part of this chapter for comparison. The papers discussed in [34,35], have proposed a new type of Opaque Link State Advertisement (LSA), originally defined in [59], to disseminate the information about the type of energy (given by smart grid) powering up each link across a link state area. The new LSAs are then used with a routing mechanism, which finds the most Energy Efficient (EE) route between a given source-destination pair of nodes, (S, D). The LSAs proposed by these papers have been used in this work to form a database of energy types for links of the simulated network. Energy topology databases based information from the smart grid, are the decision support table for routing and energy management in this chapter, and are gathered in a similar manner presented in [60]. This information is used by Service Providers to determine the greenest route among all calculated routes when no green routing mechanism is used. The reconstructed routing mechanism of (EE) has also been used in the simulation part of this work as the baseline for emission reduction and as the lower bound of the emission of optical networks. Since EE considers the energy parameters only when computing a route, it has the lowest emission among the other routing mechanisms of this chapter.

The paper presented in [13] has proposed the logarithmic form of the link Availabilities (e.g. 0.999 or 0.9999) as the link cost and has suggested a routing mechanism that finds the shortest route among a set of most available route between a source and destination pair (S,D). This routing mechanism (k SLA Based or KSB) has also been reconstructed in the simulation of this chapter with k most available routes. This method is a traditional and non-green routing mechanism, and it is used to set the upper bound of the amount of emission of optical network detailed in the analysis section.

The authors in [40] use an optical regenerator every 80 km in the optical link of the GMPLS networks, connecting two adjacent nodes, which is used in the simulation part of our analysis. The Adaptive Emission Aware and SLA Based routing mechanism (A-EASB) in [30] introduces a re-provisioning mechanism that will be used in the analysis part of this chapter to study its effect on GSLA satisfaction. This chapter uses an optical shared mesh concept further presented in [58]. Due to intensive amount of simulations for analysis in this paper, the computation power was securely outsourced, similar to work detailed in [61] for a preliminary set of test and analysis, detailed later.

In short, the reconstructed, KSB, EASB and EE will be used for the comparison in the analysis section, and the parameters for optical links and regenerators are used as the foundation of the simulation section. The next section introduces the GSLA for the optical network and details the method of the adoption of GSLA.

4.3. Green SLA for Routing Mechanism in Optical Networks

This section introduces the route greenness factor ρ for an optical lightpath and the new Green SLA (GSLA) that requires a minimum value of ρ for a route to be accepted. This section also introduces the method used in this chapter to simulate a network with more availability of green energy. The section is concluded with the explanation of a re-provisioning method used in this chapter and its effect on GSLA satisfaction.

4.3.1. Green SLA Awareness for Hybrid and Traditional Routing Mechanisms

SLAs are agreements between customers and Service Providers to communicate the requirements of customers. Based on the general definition of GSLA in [31], the GSLA for optical networks would mean that customers demand the Service Provider to provide a route that uses more than a certain percentage of green energy in total. The amount of route greenness is presented as follows:

$$M_{ij} = \left\lfloor \frac{\ell_{ij}}{\Lambda} \right\rfloor . P_{3R} . m_{ij}^{(\Theta,\Psi)} \text{ ,} \forall\, i,j \in R \tag{4-1}$$

$$\Theta = \begin{cases} 1 & if\ link\ powered\ by\ green\ energy \\ 0 & if\ link\ powered\ by\ non\text{-}green\ energy \end{cases} \qquad \Psi = \begin{cases} e^1 & if\ link\ powered\ by\ green\ energy \\ e^2 & if\ link\ powered\ by\ non\text{-}green\ energy \end{cases}$$

$$M_{SD} = \sum_{i,j\, \in R} M_{ij} \tag{4-2}$$

$$\rho = \frac{\sum {M_{ij}}_{i,j\in R,\Theta=1}}{M_{SD}} \tag{4-3}$$

In Equation (4-1), Mij is the amount of emission of each link in the route from the source node S to the destination node D, ℓ_{ij} is the physical length of the route in units of km, $\wedge$ is the maximum distance in fiber without needing regeneration which is 80 km, P_{R3} is the amount of power draw by each 3R[2] regenerator of link, which is about 15 Watts and $m_{ij}^{(\Theta,\Psi)}$ is a number-pair that consist of a flag Θ which is set to 1 in case of powering ON the link by a green source of energy and is cleared to zero with non-green source of energy. Emission value Ψ for a source of energy in the units of [g Co2 / kWh] is e^1, with value of 26 for green source of energy, and is e^2 with the value of 880 for non-green source of energy based on information in [10]. The emission of the entire route M_{SD} is defined as the sum of emission of all links of a route in Equation (4-2). Finally, the amount of greenness ρ in Equation (4-3) defined as the ratio of the sum of emission of all green-powered links of the route over the entire emission of a route, M_{SD}. The provided route by Service Provider with ρ less than GSLA, is rejected by the customer and if no other route exists the request is blocked.

As mentioned in the introduction of this chapter, Service Providers may continue using traditional and non-green routing mechanisms and then select the greenest route. The reason for this decision is based on the results illustrated in [13] and [34] stating that the green and hybrid routing mechanisms simply need more resources in terms of the available number of wavelengths to serve the equal number of connection requests. In other words, routes computed by green and hybrid routing mechanisms are longer on average, trying to bypass the non-green sections, therefore, require more number of wavelength (one wavelength per hop). To evaluate this situation and analyse the effect of GSLA on traditional non-green and hybrid green routing mechanisms, this chapter adds GSLA awareness to the reconstructed EASB discussed in Chapter 2. The result is the GSLA aware

---

[2] 3R regenerators perform Reamplification, Reshaping and Retiming of data pulse.

EASB or GSEASB that considers route Availability SLA (ASLA) and GSLA as SLAs to be met. GSLA awareness is also added to the reconstructed k most Available non-green method (KSB) elaborated in [13,62] that only considers route availability as SLA. The result is the GSKSB that also considers GSLA and ASLA as SLAs to be met when computing a route. Table 4-1 provides the algorithm of the GSEASB and Table 4-2 provides the algorithm for GSKSB. These methods are to be compared against EASB, EE and KSB by the analysis in Section 4.4. Equation (4-4) is the negative of the logarithmic value of the link availabilities in the $G(N,A)$. $G(N,A)$ is a graph with N vertices connected by bidirectional edges each with corresponding link Availabilities, A.

$$D_{ij} = -\log A_{ij} \;, \forall\, i,j \; adj\; nodes \in N \; in \; G(N,A) \tag{4-4}$$

In Table 4-1, q is a connection request from the source node SRC, to the destination node DST, with ASLA, GSLA and Duration. α is a balancing factor based on paper in [13] k shortest path on G (N,D) returns k routes in R_K. Corresponding route costs are route availabilities stored in T_{Cr}. After running each algorithm, the request q is either served with a route or is blocked.

Table 4-1. GSLA added to EASB: GSEASB

```
1)[$R_K$,$TC_r$]=kShortestPath(q( SRC,DST,$A_{SLA}$ ,$G_{SLA}$ ,Duration),G(N,D))
2) If $R_K \neq \{\}$
      For r ∈ $R_K$
          $L_r$=length( r(i))                    % i is the index of route r, in $R_K$
          $C_r$=Co2_Emission( r(i) )
          ρ(i)=greenness(r(i))                   %Based on Equation (4-1)
          H_Cost(i)=$\alpha\times L_r + (1-\alpha)\times C_r$        %α is a balancing factor=0.35 based on Equation (2-7)
       End
      Initialize (score = inf ,index = 0)
3)  For r ∈ $R_K$
          If ( score > H_Cost(i) ) && ( q($A_{SLA}$) ≤ TC(i) ) && ( q($G_{SLA}$) ≤ ρ(i))
             Score = H_Cost(i)
             Index = i
           End
       End
4) If Index≠0
          Assign_Resources ( R(index) )
          Update ( G( N , D ) )
        Else
          BLOCK(q)
      End
End
```

Table 4-2. GSLA added to KSB: GSKSB

```
1) $[R_K,TC_r]$=kMostAvailablePath (q(SRC , DST, $A_{SLA}$ , $G_{SLA}$ , Duration),G(N,D))
2) If $R_K \neq \{\}$
     For $r \in R_K$
         $\rho(i)$=greenness(r);          %Based on Equation (4-1)
     End
     Initialize (score = inf ,index = 0)
3)   For $r \in R_K$
         If ( $q(A_{SLA}) \leq TC_r(i)$ ) && ( $q(G_{SLA}) \leq \rho(i)$)
             Score = $GN_r$
             Index = $r_i$
         End
     End
4)   If Index$\neq$0
         Assign_Resources ( R(index) )
         Update ( G( N , D ) )
     Else
         BLOCK(q)
     End
End
```

4.3.2. Effect of Adopting Green SLA in "Greener Networks" on the Value of Key Performance Metrics of WDM Networks

This section of the analysis studies the effect of adopting GSLA on a network that on average has more available green energy. This means that the links of a network will be powered ON by green energy for longer duration. The analysis in Section 4.3.1 of this chapter is based on the network that has a random and equal chance of selecting the energy sources for links in the simulation part of the analysis. We define a new system with two states for each link of the network. Two states are 1, a link is using the green source of energy, and 2, link is using the non-green source of energy. By defining a one-step two-by-two Markov matrix S(i,j) for this system in Figure 4-1, we determine the chance of being in each state in the next step of time. The next step of time in our analysis is the 6 hours emission topology change interval in which another source of energy is randomly assigned to all links of a network. In this matrix, P_{11} is probability of staying in state 1 (using green energy again) and P_{12}, is probability of going from state 1 to 2 (using non-green energy when currently using green energy). P_{21} is probability of going from state 2 to 1 (using green energy next when currently using non-green energy), and P_{22} is remaining in state 2 or using non-green energy for the next 6 hours when currently using non-green energy. If $P_{11} > P_{12}$ then there is a higher chance of having green energy or staying in state

1, (again) for the next 6 hours. Similarly, if $P_{21} > P_{22}$ then there is a higher chance of going from non-green energy to green energy in the next step. For simplicity, we will equate P_{11} and P_{21}. Therefore, P_{12} and P_{22} will be the same as well. Each link has a corresponding matrix, and all P values are zero when there is no connectivity between nodes, as shown in Equation (4-5). For the sake of consistency, we will consider the same probability values for all the links of a network. With this setup, we can say that all the links of a network have the same chance of having green energy with P_{11} and P_{21}. The next section details the condition in which re-provisioning may affect the GSLA Satisfaction, (GSLS).

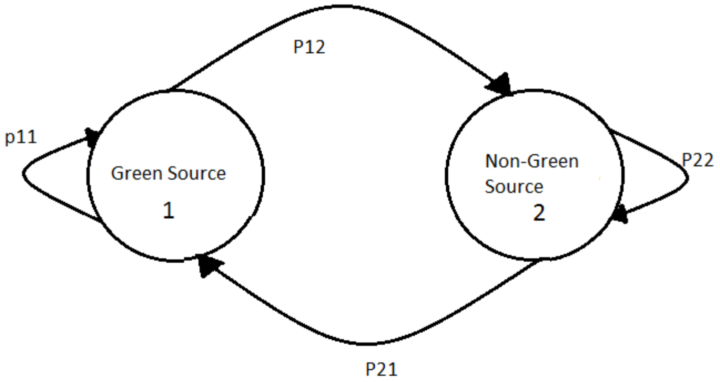

Figure 4-1. Two states of the link energy

$$s_{(i,j)} = \begin{cases} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} & \forall\, i,j \; adj \; nodes \in G(N,E)) \\ \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} & \forall\, i,j \; non- \; adj \; nodes \in G(N,E) \; or \; i = j \end{cases}$$

(4-5) Two-by-two Markov matrix for each link

4.3.3. The Effect of Re-Provisioning on Green SLA Satisfaction

In this chapter, we also analyse the effect of re-provisioning of the established lightpaths in the case of a change in the topology of a network. The type of topology change considered in this chapter is the energy and emission topology change for links of the network. The type of energy (green or non-green) is changed every topology change interval (6 hours in this chapter). Re-provisioning tries to reroute and re-provision the established lightpaths that may not be optimized and emit more emission. This is because with emission topology change, established routes may be passing through links that are not green energy powered anymore and emit more GHGs. With emission topology change a new route may be computed for the already established route that may not meet the GSLA. For this analysis the adaptive routing mechanism in [30]is considered. Adaptive EASB (A-EASB) re-provisions the established route by replacing the route with one that has lower hybrid cost. We will show that re-provisioning does not change GSLA satisfaction by a considerable amount. Table 4-3 presents the reconstructed re-provisioning algorithm of the Adaptive EASB (A-EASB) in the form of a pseudocode.

Table 4-3. Re-Provisioning with A-EASB

```
If Topology_change_Flag=1
  For e=1 to #Established_connections
    S= Established_connections (e )
    [SRC, DST, $A_{SLA}$ ,H_Cost$_S$]=get_Characteristic( S )    %S, D, Availability of route, Hybrid cost, current route
    [R,TC$_r$]=kShortestPath(S( SRC,DST,$A_{SLA}$ ),G(N,D))    %Array of routes R, and Array of associated total costs
                                                              (or route availabilities), TC
    If R≠{}
      For r∈ R
        $L_r$=length( r( i ))                        % i is the index of route r, in R
        $C_r$=Co$_2$_Emission( r(i) )                %With new emission topology info after emission
                                                         topology change
        GN$_r$=greenness( r(i) )                     %Based on Equation (4 1)
        H_Cost( i ) =$\alpha\times L_r + (1-\alpha)\times C_r$    %α is a balancing factor=0.35 based on Equation (2-7)
      End
      Initialize (score = inf ,index = 0)
      For r ∈ R
        If  ( score > H_Cost( i ))  &&  (  S($A_{SLA}$)  ≤  TC( i ) )  )
          Score = H_Cost( i ))
          Index = i
        End
      End
      IF  (   ( (H_Cost$_S$– H_Cost(i)  /  H_Cost$_S$)  ≥  0)   )
        Assign_Resources ( R(i) )
        Release ( $S_P$ )
        Update ( G( N , D ) )
      End
    End
  End
End
```

4.4. Analysis

4.4.1. Simulations Network

The network used for the analysis section of this chapter is the network of NSFNet shown in Figure 4-2 with 14 nodes and 21 bidirectional links. The numbers on the links represent the actual physical distance between nodes in km. The network consists of the two layers of data and control planes of GMPLS networks. The regenerators of the optical links amplify the entire “band” based on [11] and therefore are considered either ON or OFF with no intermediate value for the energy used. The data plane has 96 available to assign wavelengths or Lambdas in WDM fashion without the continuity constraint based on the analysis in [39]. The availability of the optical links is randomly assigned a number from 0.999 to 0.99995 and is assumed constant for the entire duration of simulations. The two types of the energy sources can randomly turn ON the links of the network, and every 6 hours of the simulated time the type of energy is randomly reassigned again for all links, which is the emission topology change interval in this chapter. The two types of energy are a green source of energy with an average of 26 gCo2/ kWh for the green source of energy and 880 gCo2/kWh for a non-green source of energy according to the document in [10]. The arrival of the connection requests is a Poisson process and follows an exponential distribution with the arrival rate of 10 connections per hour for the first scenario and 100 connections per hour for the second scenario. Duration or hold time of the connections also follows the exponential distribution with a mean value of 10 hours. The amount of load is defined as the product of connection arrival rate and connection duration in units of Erlang as illustrated in [63]. Therefore, scenario 1 is rated as 100 Erlang and Scenario 2 as 1000 Erlang. The requested route availability (ASLA) by connection requests ranges from 0.99 to 0.9995 for all sections of the analysis. The network model has been built in MATLAB programming language. All simulations take advantage of parallel computing toolbox of MATLAB which can use compute clusters.

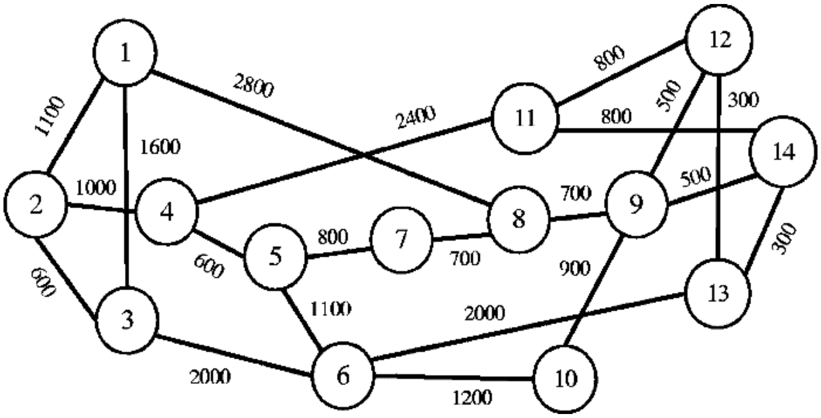

Figure 4-2. NSFNet Network

4.4.2. Variables and Performance Metrics

This section details the important variables and defines various performance metrics for each section of the analysis. The first metric is the resource efficiency, which is the average number of Lambdas (hops) per lightpath, for each route. Depending on the routing mechanism used, this value may be different. The lower value for this metric is preferable for Service Providers. Higher average for this metric means that more Lambdas must be provisioned on average to establish the equal number of connection requests. The second metric is the reduction in emission in terms of average gram Co_2 per unit resource Lambda. This metric is the emission in power generation to turn ON regenerators of a link. This parameter determines how well green sections are used. The lower the average emission, the more green-sections used in the optical networks. The third parameter is the success rate in serving connection requests, which is the ratio of the number of served connections over a total number of connection requests. Since SLAs must be met to assign a route for a connection request, some requests may be blocked because there may not be any route that satisfies the SLA(s) of the connection request. The other reason to decrease the success rate (or increase the blocking rate) is the fact that an optical network may be overwhelmed by a huge number of requests and run out of resources or available-to-assign wavelengths (Lambdas), as we will see in scenario 2. The fourth parameter is the GSLA satisfaction which is the ratio of the connection requests that were served with a route that met or exceeded their GSLA value to the total number of the server connection. Route Availability

SLA satisfaction resulted in 100 % for both scenarios in this work and was not graphed. Section of 4.2 will detail the levels of variables used for analysis.

4.4.3. Analysis on the Effect of Adopting GSLA

In this section EE, EASB, GSEASB, KSB and GSKSB are analysed and benchmarked against the four performance metrics detailed in Section 4.2. This section of analysis considers Scenario 1 and Scenario 2. EASB and KSB only consider ASLA, and GSEASB and GSKSB consider ASLA and GSLA. EE is an exception with no SLA requirement. GSLA required by connection request ranges from 10 to 20 %. In this section P_{11} =P_{21}= 50.

4.4.4. Effect of GSLA in “Greener” Network

For this part of the analysis P_{11} =70 % or 0.7 is used to increase the chance of having green energy in an optical network. As mentioned in section 3.2, $P_{11} = P_{21}$ and $P_{12} = P_{22}$. For this section, GSLA of 10 to 80 % (heavier GSLA) is proposed to see the effect of a greener network. Both Scenario 1 and Scenario 2 are considered in this section. It is expected that GSLA satisfaction and success rate will increase even with the higher maximum GSLA value. (compared to maximum 20 % GSLA of Section 4.2.1.)

4.4.5. Analysis on the Effect of Re-provisioning on GSLA

For this section, Adaptive EASB (A-EASB) is considered with all other routing mechanism in the previous sections of analysis. The amount of greenness or GSLA is also considered from 10 to 20 % as maximum possible GSLA values. For this section, the Scenario 2 is analysed only, as there is a higher chance of GSLA satisfaction violation and variation with heavy traffic. In this section only the success rate and GSLA satisfaction are analysed. This section uses the network of Section 4.2.1 with P_{11} = 50 %.

4.5. Results of Analysis

4.5.1. Effect of Adopting Green SLA

For emission reduction with light traffic intensity of scenario 1 in Figure 4a, as expected EE has the lowest average emission per unit resource lambda and forms the lower bound of Figure 4-3. KSB as the non-green method has the highest average emission and is the upper bound. The adoption of GSLA by KSB and EASB reduced the average emission per unit resource Lambda as seen in Figure 4-3. GSKSB has about 10 to 15 % lower emission as compared to KSB and GSEASB has close to 5 % less emission compared to EASB. Figure 4a indicates that selecting the greener route (not surprisingly) lowers the emission However, as we will see in later figures this comes at a cost. Figure 4-4 shows the situation for the emission reduction with the Scenario 2 when traffic is heavy. As seen in Figure 4-4, with the heavy traffic there is no significant reduction in emission and all the routing mechanisms perform almost the same. The difference between the worst and the best is scatted over only 5 %. This is because all the links of the network will be turned ON to accommodate the heavy traffic and no link even turned ON by a non-green source of energy will be turned OFF. For resource efficiency and scenario 1 in Figure 4-5, as expected, EE has the highest average resource utilization (Lambda per connection or lightpath) and KSB has the lowest average resource per connection. This means connections or lightpaths established by EE are longer (in unit of hops) on average and require more Lambda or resources. Based on Figure 4-5, the price to pay for having lower emission with GSKSB and GSEASB is the significant increase in resource utilization level. GSKSB is 0.5 hops longer on average compared to KSB which is more than 20 %. So, to decrease the emission by 10 to 15 %, GSKSB increased the resource utilization by more than 20 %. This behavior is repeated for EASB. GSEASB has more than 10 % higher resource utilization and longer connections to reduce the emission by 5 %. The hybrid method EASB averages at more reasonable value and has lower resource utilization for connections compared to GSEASB and GSKSB. The resource efficacy is even worse for GSEASB and GSKSB when traffic is heavy (in Scenario 2) as seen in Figure 4-6. Figure 4-6 shows that GSKSB and GSEASB have even higher resource utilization than EE and consume the most of the resources. This situation with GSKSB and GSEASB is highly unwanted, because as we saw in Figure 4-4 all routing mechanism performed almost the same in terms of the emission reduction. As seen in Figure 4-6 there is an increase on average resource utilization of all routing mechanisms that consider the route availability ASLA (EASB, KSB, GSEASB and GSKSB). This is due to the fact that with high traffic and utilization of all optical links of a network, some connections may need to travel longer (and less reliable) routes to be able to accommodate the availability requested by a connection. GSKSB and GSEASB will need to satisfy the GSLA with longer routes as well, that may be less green (ρ is small). EE does not consider any SLA and therefore does not behave in similar fashion. For GSLS in Figure 4-7 and Figure 4-8, GSKSB and GSEASB provided 100 % satisfaction for the requests that they "served" as they considered the GSLA in finding the route for a connection request. In Figure 4-7, the routing based on energy parameters with EE resulted in about 95 % GSLA satisfaction which is very interesting to note. The interesting fact about this observation is that, even with the EE method and routing solely based on energy and emission parameters, there is no way to provide 100 % GSLA satisfaction even for a very low maximum of 20 % GSLA value. This obesevation suggests increasing investment on green energy infrastructure for optical networks. EASB provides about 10 % more satisfaction as compared to the non-green routing mechanism KSB. In Figure 4-8 for the Scenario 2, the GSLA satisfaction becomes almost the same for all non-GSLA aware routing mechanisms again due to the high volume of traffic higher utilization of all links with higher ρ. It is interesting to note that EE and EASB have a significant drop in GSLA satisfaction. With the higher value of utilization of links, using non-green links and not considering GSLA, there is a higher chance of violating a GSLA, as seen in Figure 4-8. Figure 4-9 presents the network blocking rate or connection success rate in the Scenario 1. As seen in this figure, with low to moderate traffic and the maximum requested GSLA of 20 %, the adoption of GSLA did not decrease the success rate. Based on Figure 4-9 all routing mechanism provide almost equal success rate for connection requests even by having higher or lower resource efficiency as seen in Figure 4-5. However different results are seen for scenario 2 in Figure 4-10. As expected, adding GSLA decreased the success rate of the network not just because GSEASB and GSKSB have higher average resource utilization as seen in Figure 4-6, but also because they have to consider GSLA as well. When there is a contention for resources with heavy traffic of scenario 2, the addition of GSLA adds another constraint in finding a route for GSEASB and GSKSB, which translate into even more "failure" (or blocking connection request). In Figure 4-10 EASB and KSB perform better than GSLA aware mechanisms. EE also has a lower success rate when compared to EASB and KSB, again because of the higher resource utilization. Figure 4-11 in analysis of this section is a figure for scenario 1 when the maximum GSLA value is 80

%. As we can see in Figure 4-11, the success rate for GSEASB and GSKSB is dropped by 15 %, even for the light traffic, which is not acceptable. In this figure GSKSB and GSEASB overlap, clearly indicating that the decrease in success rate is due to the adoption of GSLA.

Based on our analysis in this section, the addition of GSLA to routing mechanisms increases the resource utilization for both scenarios, while there is no similar or better reduction in emission. In the case of light traffic, there may be no problem (although highly undesired) with an increase in resource utilization because the blocking rate of the network remains about 1 %. However, the blocking rate of the network is increased significantly with GSEASB and GSKSB in scenario 2. It is fair to assume that the usage of green and hybrid routing mechanisms (EE and EASB) may be more preferred by Service Providers because of the lower resource utilization and higher success rate when maximum greenness required (GSLA value) is about 20 %. The links of the current network in this section are turned ON by random sources of energy with equal probabilities. In the next section, we will consider the same 80 % maximum GSLA analysis for a network that on average is about 20 % greener compared to the simulated network of this section.

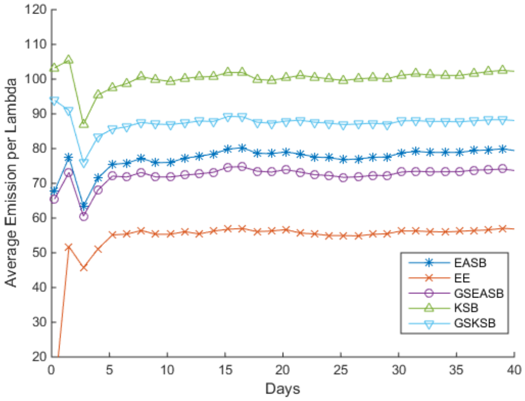

Figure 4-3. Average emission per Lambda analysis (Scene 1)

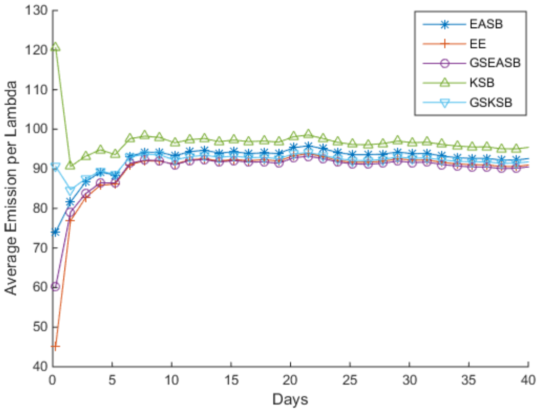

Figure 4-4. Average emission per Lambda analysis (Scene 2)

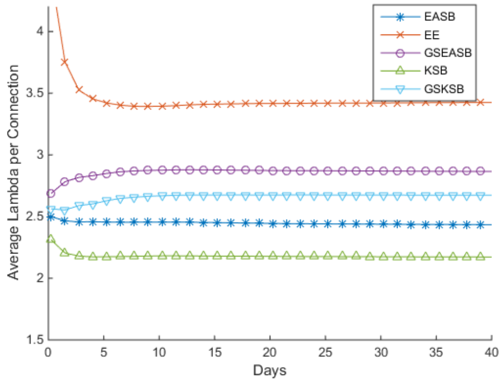

Figure 4-5. Average connection length analysis (Scene 1)

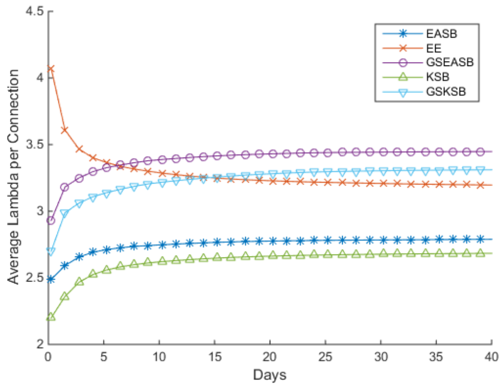

Figure 4-6. Average connection length analysis (Scene 2)

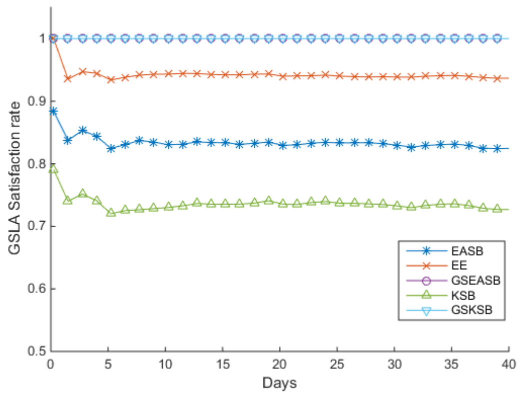

Figure 4-7. GSLA satisfaction analysis (Scene 1)

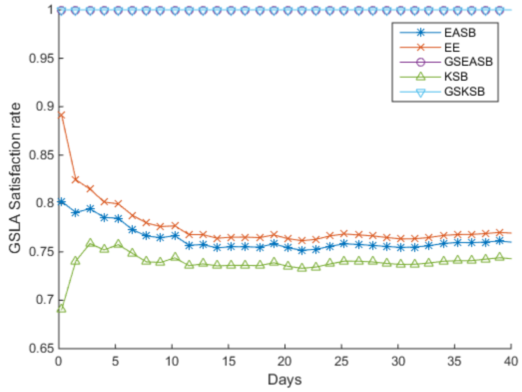

Figure 4-8. GSLA satisfaction analysis (Scene 2)

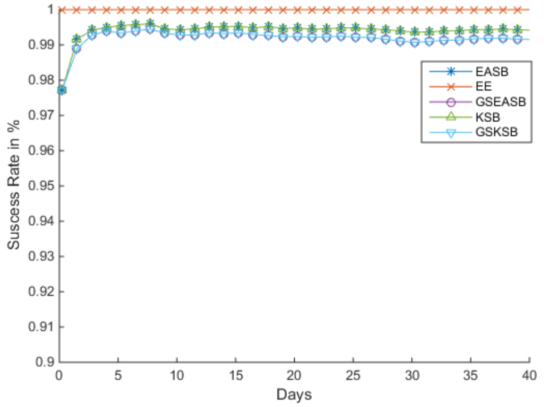

Figure 4-9. Success rate analysis (Scene 1)

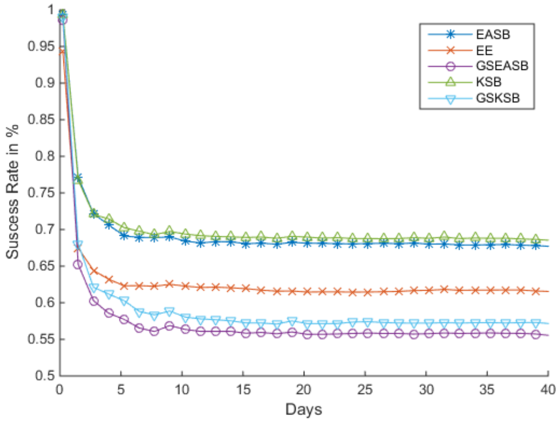

Figure 4-10. Success rate analysis (Scene 2)

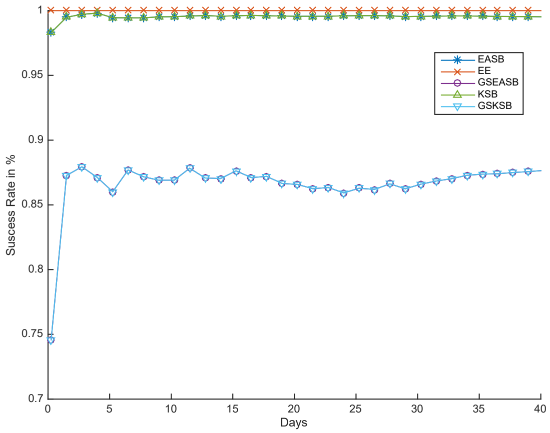

Figure 4-11. Success rate in scenario 1 with up 80% GSLA value analysis (Scene 1)

4.5.2. Effect of Adopting GSLA in Greener Networks on Optical Network Parameters

This section of analysis shows the results for performance metrics when the green source of energy has 20 % more chance (P_{11} =70) of turning ON the links of the network for both Scenarios 1 and Scenario 2. The maximum GSLA value for this section is 80 %.

As we can see from Figure 4-12 for Scenario 1, KSB and EE have the maximum and minimum emission respectively similar to Figure 4-3 However, not surprisingly the emission has been dropped by 30 units (gram Co_2 per Lambda), for almost all routing mechanisms in Figure 4-12. GSKSB has reduced the emission of KSB by about 25 %. This is a significant drop in emission by GSKSB and it is possible because GSKSB has more chance of finding a greener route on average since the network itself is greener. GSEASB also reduced the emission of EASB by about 12 %. This reduction is less than that of GSKSB because EASB itself is already a green aware and hybrid routing mechanism giving already lower emissions per unit resource. Results of the analysis for Scenario 2 in Figure 4-13 reveals that in heavy traffic conditions, the best and worst routing mechanisms are separated by12 %. This difference as mentioned in the last section, is because all sections of the network are turned ON. The surprising fact about Figure 4-13 is that GSEASB and GSKSB have lowest average emission per unit resource, however, the reason for this behavior is determined by considering Figure 4-19. When the amount of resources is limited, the success rate of GSEASB and GSKSB is close to only 57 %, therefore, they “fail” or block more connection requests and use more resources to find the greener paths for the requests they serve.

Resource efficiency of Figure 4-14 for the Scenario 1 almost repeats the results of Figure 4-5 with EE having the highest and KSB having the lowest average resource utilization. As we can see in Figure 4-14, even with greener network GSKSB and GSEASB increase the average resource usage. In this figure GSKSB with 14 % increase in average hop length compared to KSB becomes almost similar to the performance of EASB with greener network. However again EASB has lower emission as seen in Figure 4-12. GSEASB increases the resource utilization of EASB by 8 %. In Figure 4-15 and with heavy traffic of scenario2, the same overall increase in average resource utilization is observed again but as expected this increase is smaller compared to results of Figure 4-6. GSEASB has the most resource utilization, increasing the average connection length of EASB by 13 %. This is close to half of the 24 % increase in Figure 4-6 due to increase in existence of green links. GSKSB performed almost the same as EE in long run which questions the usage of GSKSB again considering the fact that GSKSB has lower success rate again as we will see in Figure 4-19.

GSLA satisfaction in Figure 4-16 for scenario 1 has an overall increase compared to Figure 4-7 especially for EE which gets close to 100 %. For EE this is about 98 % for GSLA of up to 80 % (as opposed to 95 % with 20 % GSLA value). As expected, GSKSB and GSEASB have 100 % satisfaction, because they consider the GSLA in finding the route for connection requests. EASB also has about 5 % increase from the one in Figure 4-7 and is close to 90 % for 80 % maximum GSLA, which is a considerable improvement. KSB as the non-green method has no increase in GSLA satisfaction. Increased chance of having green sources of energy in this analysis did not increase the overall GSLA satisfaction of EE, EASB and KSB as seen in Figure 4-17 for scenario 2. Except for GSKSB and GSEASB, all routing mechanisms provided the same GSLA satisfaction of close to 75 % which is close to GSLA satisfaction of KSB as a non-green method. This is no surprise because again with the limited number of resources and trying to serve as many connection requests as possible. EE and EASB tend to behave like KSB by using all the remaining, perhaps non-green links and therefore decreasing the GSLA satisfaction.

The Result of our analysis for the success rate of routing mechanisms is reflected in Figure 4-18 and Figure 4-19. Figure 4-18 repeats the results of Figure 4-9 with almost 100 % success rate for EE, EASB, and KSB for Scenario 1 in Figure 4-18. We observe about 10 % increase in the success rate of GSKSB and GSEASB compared to Figure 4-11. By increasing the probability of using the green energy by 20 % the success rate of GSEASB and GSKSB increase by 10 % to about 97 % which may be acceptable for GSLA values of up to 80 %. For Scenario 2, the overall success rate shows about 2 % increase for GSKSAB and GSEASB. Although no significant change is observed for success rate of the routing mechanisms when compared to Figure 4-10, but we have to be reminded again that Figure 4-19 shows the same results as compared to Figure 4-10, but for GSLA of up to 80 % as opposed to the 20 % maximum GSLA value of the Figure 4-10. Figure 4-19 shows that GSEASB and GSKSB increase the blocking rate of the EASB and KSB by 10 % respectively.

Based on our analysis in this section, it is possible to conclude that adoption of GSLA by traditional non-green routing mechanism and hybrid routing mechanism increases the average resource utilization and the blocking rate of a network. The amount of reduction in the average emission per unit resource does not justify the amount of increase resource utilization. A 10 % decrease in the success rate of a network when traffic is heavy translated in net 10 % loss of income for Service Providers. The next section will consider the effect of “adaptivity” in case of emission topology change in a network that has an equal chance of having a green or non-green source of energy for optical links.

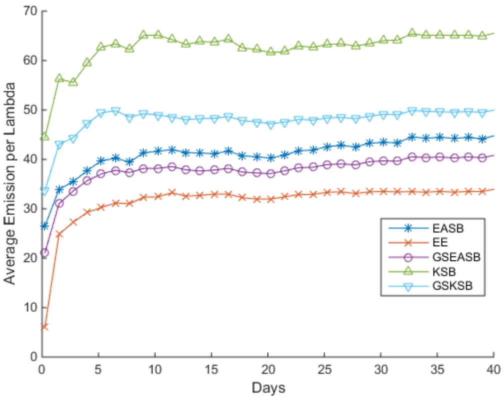

Figure 4-12. Average emission per Lambda analysis (Scene 1, max GSLA of 80%)

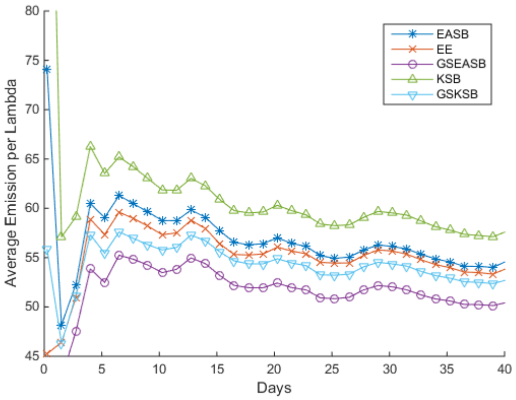

Figure 4-13. Average emission per Lambda analysis (Scene 2, max GSLA of 80%)

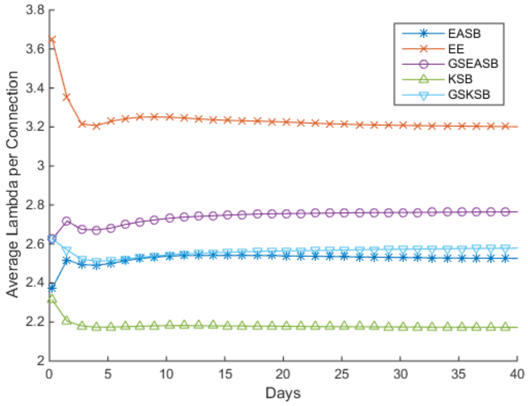

Figure 4-14. Average connection length analysis (Scene 1, max GSLA of 80%)

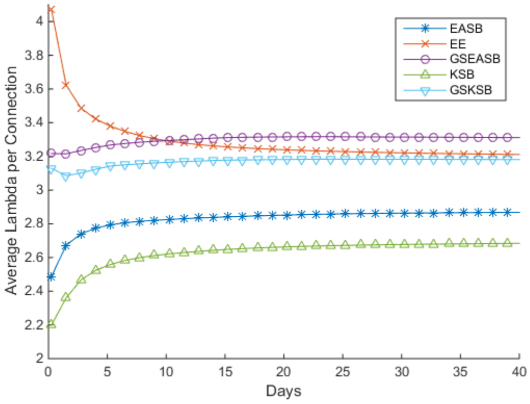

Figure 4-15. Average connection length analysis (Scene 2, max GSLA of 80%)

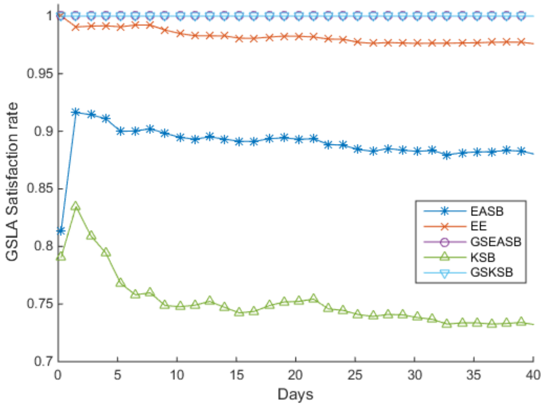

Figure 4-16. GSLA satisfaction analysis (Scene 1, max GSLA of 80%)

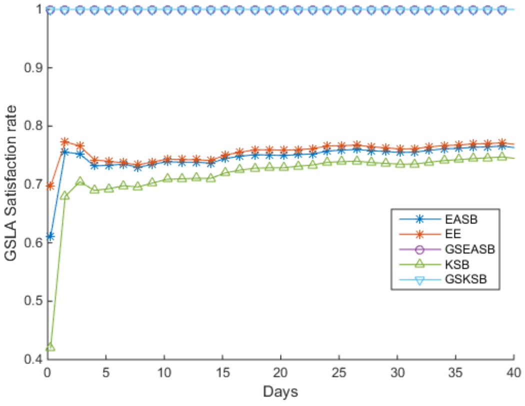

Figure 4-17. GSLA satisfaction analysis (Scene 2, max GSLA of 80%)

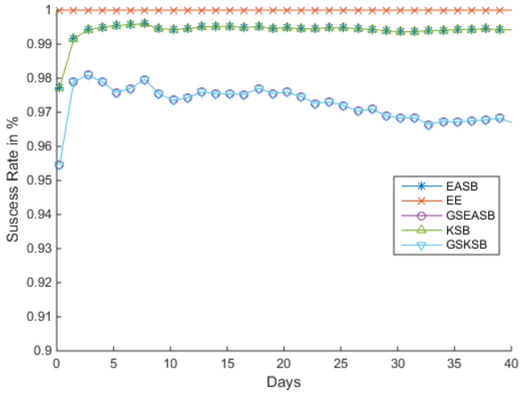

Figure 4-18. Success rate analysis (Scene 1, max GSLA of 80%)

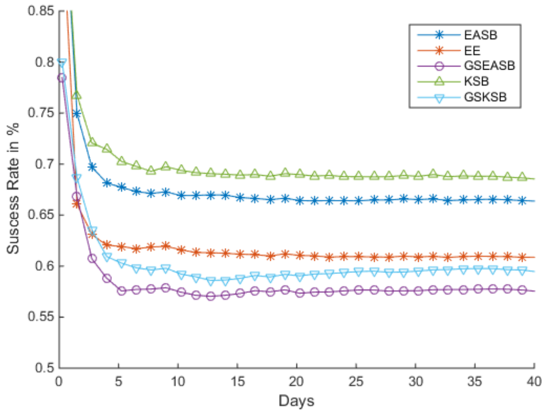

Figure 4-19. Success rate analysis (Scene 2, max GSLA of 80%)

4.5.3. Results of Analysis on The Effect of Re-provisioning on GSLA Satisfaction

In this section, we analyse the effect of re-provisioning or rerouting the established lightpaths in case of emission topology change with Scenario 2 on GSLA satisfaction rate. lower GSLAS is anticipated, because, as mentioned in Section 3.3, rerouting the routes without considering the GSLA may replace a currently established route that satisfies the GSLA of a request with a new route that does not satisfy the GSLA of the request. If a lightpath is marked for reprovisioning as a result of emission topology change, it may also be in violation of the GSLA after the emission topology change. We are interested to know the percentage drop in satisfaction. The average emission per unit resource for Adaptive-EASB (A-EASB) was slightly less as compared to EASB in Figure 4-4. The average resource utilization resulted the same outcome as Figure 4-6 with slightly less resource utilization for A-EASB when compared to EASB and they were not graphed.

As we can see in Figure 4-20, the A-EASB reduced the GSLA satisfaction rate. However the difference between the EE and A-EASB is about 5 %. This is very important, because a significant drop in GSLA satisfaction could have happened because of high intensity of the traffic in Scenario 2 when compared to other non-GSLA aware routing mechanisms. Therefore, we can conclude that emission topology change drops the GSLA satisfaction only up to 5 %. Obviously, GSEASB and GSKSB have the 100 % satisfaction here again. The drop in GSLA satisfaction is only 5 %, but by looking at Figure 4-21 we realize that A-EASB provides more than 10 % increase in success rate or lower blocking rate as compared to EE and 15 % or more success rate as compared to GSEASB.

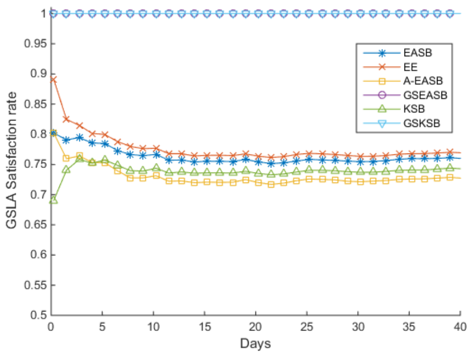

Figure 4-20. GSLA satisfaction analysis (Scene 2) with adaptive method

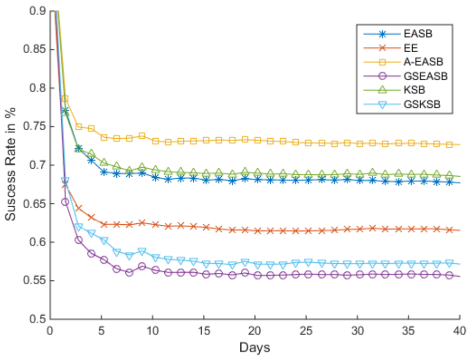

Figure 4-21. Success rate analysis (Scene 2) with adaptive method

4.6. Conclusion and Future Work

This chapter presented GSLA awareness for the hybrid and traditional routing mechanisms and the effect of the adoption of GSLA on a network through proposed mathematical models and algorithms. The discussion on the results of the analysis in this chapter had successfully showed that adopting GSLA by routing mechanisms decreased the resource efficiency with both light and heavy traffic in return for less reduction in emission as compared to green and hybrid routing mechanisms. It was also obvious that in the case of light traffic, there may be no problem with this increase in resource utilization, because the success rate of the network remains high. The success rate of network was decreased with GSEASB and GSKSB methods due to higher resource usage and utilization. It was reasonable to assume that the usage of green and hybrid routing mechanisms such as EE and EASB may be more preferred by Service Providers because of a lower resource utilization and a higher success rate. The drop in Green SLA Satisfaction is only 5 % for Adaptive-EASB compared to other non-GSLA aware routing mechanisms in return for 5 to 15 % success rate compared to GSEASB. Adaptive EASB was a reasonable choice for Service Providers to increase the success rate of networks without sacrificing the GSLA satisfaction by a considerable amount. In a nutshell. The results revealed that adopting the GSLA by routing mechanisms decreased the resource efficiency with both light and heavy traffic in return for less reduction in emission as compared to green and hybrid routing mechanisms.

The future work will study the effect of different values for GSLA violation that may change the decision of Service Providers. The amount of extra energy used by GSEASB and GSKSB will also be determined in the case of light and intensive traffic loads on optical networks. Although the green parameters used in this chapter are specific to Link State Routing mechanisms, but they very well can be disseminated as Path Attributes using Border Gateway Protocol (BGP) just like the papers in [64,65]. A part of future work will also study the effect of greening the autonomous systems and the effect of GSLA adoption on path selections.

Chapter 5 MULTI-SLA AWARE CONSTRAINED LOWEST EMISSION FIRST

5.1. Introduction

This chapter presents the extended version of the paper published in [15]. This chapter presents a Multi-SLA aware routing mechanism which considers ASLA and DSLA of the connection request. The new routing mechanism of this chapter as well as the other routing mechanisms introduced in Chapter 2 as foundation work have been reconstructed and tested with a set of realistic energy and emission information. This chapter is organized as follows: Section 5.2 gives the chapter specific related work. Section 5.3 introduces the new routing mechanism as well as introducing the realization of DSLA and the method to generate the realist energy and emission data. Section 5.4 formulates a non-green routing mechanism to be tested along with other routing methods in the analysis section. Section 5.5 reviews the testbed environment and reviews the performance metrics used in this chapter. Section 5.6 presents the results of two types of analysis performed to ensure the performance of the proposed routing method followed by Section 5.7 that concludes the chapter and states the future work. chapter specific related work comes next

5.2. Related Work

Unfortunately, when it comes to developing a new routing method for Green networks, the role of many service parameters such as Service Level Agreements (SLAs) is ignored. Green routing mechanisms in [11,12,14,34,45,51,66,67] have not considered any SLAs in the operation of the proposed Green routing methods. Not considering the SLAs makes the green mechanisms less favorable and less practical. The other major issue in the development of green routing mechanism is the inaccuracy of the testing environment for Green networks as also mentioned in Section 1.2. Benchmarking the new Green methods is not performed using accurate energy and emission information. Many papers such as [11-14,23,68] have considered the source of energy to be either 100% green or 100% non-green which is not the case in practice.

The routing method on this chapter relies on the propagation of the energy greenness parameters with a new Link State Advertisement (LSA) introduced in [69] for Link-State type Routing and Traffic Engineering (TE) mechanisms. In this chapter, a lightpath transits each node either transparently (with no extra energy) or by Lambda conversion using two transponders, similar to the setup in [15,70]. Power draw by two transponders is 170 Watts as explained in Table 2-1 from [48]. In this chapter, the inline amplifiers and signal leveling amplifiers are considered either ON or OFF and regenerate the entire spectrum (lightpaths) with no intermediate value as also explained in [11].

5.3. Multi-SLA Aware Constrained Least Emission First (CLE)

Before introducing the routing mechanism, it is beneficial to introduce the energy and emission related information used with the new method.

5.3.1. Energy and Emission Data

As mentioned earlier, the energy powering each section of the network is composed of different sources as shown in Figure 5-1, from the webpage in [71] for the province of Ontario in Canada. Each source of energy has a different value of emission as detailed in [10]. In general, coal and petroleum have the highest amount of emission e.g. 880 to 980 [g Co2 per kWh]. The amount of emission for green sources of energy such as the wind and hydro is considered zero.

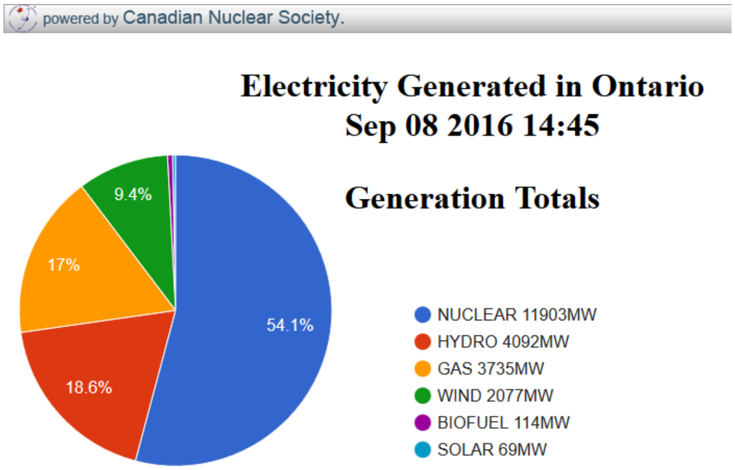

Figure 5-1. Different source of energy in province of Ontario

When performing the analysis, no single source would provide the information about the generation capacity for each section of the simulated testbed, which spans the United

States. Therefore, to obtain the generation capacity of each state of the US per source of energy, the information about the type and capacity of the US power plants that were in operation in 2011 are combined from information given in [72-74]. Table A-1 details the outcome of calculations. The numbers in this Table are average of summer and winter production capacity of each source of energy per each state. After calculating the generation capacity, the information about the average sunny days in each state from [75] were used for having random sunny hours of the daytime in simulation. Average sunny hourse are then combined with the standard specification of the solar panel from [76] to calculate the amount of available solar energy per hour, per each state (Up to the capacity of the Solar). The amount of availability of the wind power is merely randomized from 0 to 100 % of the available capacity of the wind energy, per each hour of the day, per each state.

This chapter uses the “dirtiness” instead of greenness of the energy defined in [69]:

$$\rho = \frac{\sum W_i \cdot E_i}{\sum W_i \cdot D} \qquad (5\text{-}1)$$

In Equation (5-1) W_i is the power wattage from the ith source of energy, E_i is the corresponding emission value of the energy, and D is the maximum amount of emission (for coal) at 880 [g Co2 per kWh].

Now by considering the concept of the dirtiness, emission M_{ij} of an optical link is defined in Equation (5-2) as follows:

$$M_{ij} = \left[\left\lfloor \frac{\ell_{ij}}{\Lambda} \right\rfloor \cdot \varepsilon^1 + \left\lfloor \frac{\ell_{ij}}{\Omega} \right\rfloor \cdot \varepsilon^2\right] \cdot \rho_{ij} \cdot D \qquad (5\text{-}2)$$

Were ℓ_{ij} is the length of the optical link in units of km, Λ is the distance between inline amplifiers and is 100 km, ε^1 is the power needed by each inline amplifier and is 50 Watts. Ω is the distance between each inline signal leveling amplifier, which is typically 5Λ, and ε^2 is the power needed by signal leveling amplifier and is 100 Watts as also explained in Table 2-1. ρij is the dirtiness of the energy powering the link. D is the maximum amount of emission of source as 880 [g Co2 per kWh]. This discussion leads us to the formulation of emission of a route M_{sd}, connecting source node s to destination node d in Equation (5-3):

$$M_{sd} = \sum_{\forall\, i,j \in R} M_{ij} + \left\{\varepsilon_s^4 \cdot \rho_s + \varepsilon_d^4 \cdot \rho_d + \varepsilon_{j \notin (s,d)}^3 \cdot \rho_j\right\} \cdot D \tag{5-3}$$

In which ε_s^4 is the power needed to add a Lambda in source node s, ρ_s is the dirtiness of energy turning ON the node s, ε_d^4 is the energy needed for dropping a Lambda at destination node d, multiplied by $\rho_d$which is the dirtiness of energy at destination node d. $\varepsilon_{j \notin (s,d)}^3$ is the energy needed for Lambda conversion, (if needed) in a transit node which is multiplied by corresponding dirtiness ρ_j. Energy for adding and dropping of the Lambda at source and destination nodes are the constant part of the energy needed to establish a lightpath. The strategy for minimizing the emission in this chapter is to reduce the variable energy usage in nodes by minimizing the Lambda conversions, and by using greener links for establishing the lightpaths. In this chapter as explained in Section 2.5, power reduction and optimization is performed for the optical layer only.

5.3.2. Realization of Delay SLA

Per information in [77], the maximum end-to-end delay of the North American network of NTT DATA Service Provider is 50 ms. The 50 ms is divided over four time zones, representing the distances between nodes, similar to the approach in [14]. Therefore, traversing through each zone should add a maximum of 12.5 ms to the overall end-to-end delay of the route. The information about the time zones is depicted in Figure 5-2. from World Atlas website in [78]. The zone information is overlaid with the node and link locations shown in Figure 5-3. from [79]. Based on the combined view of Figure 5-2. and Figure 5-3 the Delay SLA (DSLA) of any connection or lightpath from node 1 to node 3 (entirely in zone 1) and node 1 to node 7 (through 3 zones) could not be more than 12.5 ms and 37.5 ms, respectively. This chapter uses non-coherent transponders with no Forward Error Correction (FEC) based on information in [80] which have a delay in units of Nano seconds, therefore delay at each node is about 10 ms if Lambda conversion is performed based on information in [80]. The link delay T_{ij} is simply a division of physical length of the link by the speed of the light in a vacuum.

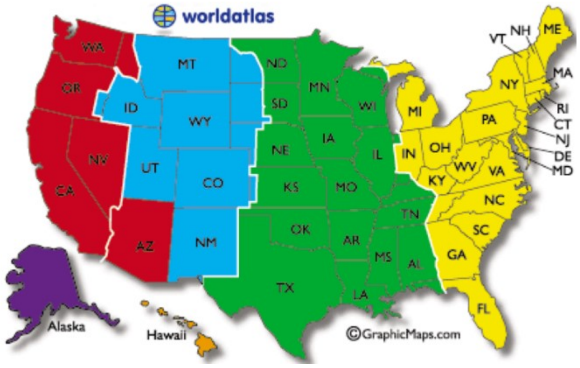

Figure 5-2. U.S. time zones;

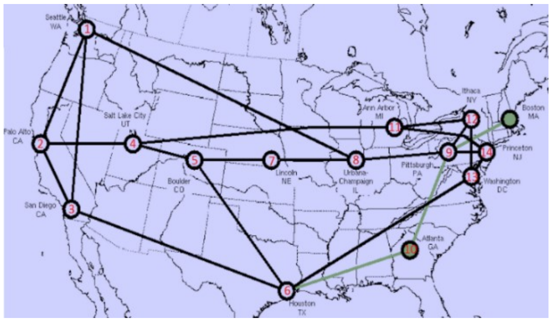

Figure 5-3. Geographic location of nodes

5.3.3. Formulation of Constrained Least Emission First (CLE)

The proposed CLE routing mechanism is intended to minimize the total emission of the route in the optical plane, while also considering the ASLA and DSLA. In other words, choosing the greenest route that also complies with both Availability and Delay SLAs. For combining multiple constraints in finding a route, this section formulates a Binary Integer Programming (BIP) method which performs the routing only and is decoupled from the assignment phase. There are two advantages for using separate routing and assignment mechanism as opposed to the combined method of singular routing and assignment Integer Linear Programing (ILP) proposed in [81]. By using separated routing and assignment methods, it is possible to evaluate the effectiveness of the routing and the assignment steps separately, using each performance metric introduced in Section 5.5.2. The first advantage is that the assignment step can be performed when it is “needed”. As we saw in Chapter 3 it is possible to populate a routing table (R table in Chapter 3) and assign the resources when there is a need for establishing the lightpath. As concluded, the method of Chapter 3 increased the throughput of the control plane by 6-fold. In a later analysis performed in Chapter 6 it is showed that the continuity constraint might decrease the success rate of the network. Therefore, the ILP method considering the continuity constraint may increase the blocking rate of the network. Because of this observation and as the second advantage, the resources of a route could be assigned by different resource assignment methods when routing and assignment phase are separated. Results of the analysis for the performance of resource assignment with the continuity constraint is provided in detail, in the next chapter.

The BIP formulation of the CLE for minimizing the emission of the route while being SLA compliant is presented in Equation (5-4) as follows:

$$min\, M_R = \sum_i \sum_j M_{ij} \cdot x_{ij} \tag{5-4}$$

Subject to:

$$-\sum_i \sum_j \left(\ln A_{ij} \cdot x_{ij}\right) \geq -\ln(ASLA) \tag{5-5}$$

$$\sum_i \sum_i T_{ij} \cdot x_{ij} \leq DSLA \tag{5-6}$$

All classical flow conservation shortest path problem constraints (5-7)

$$x_{ij} = \begin{cases} 1 & if\ links\ is\ used \\ 0 & if\ link\ is\ not\ used \end{cases} \tag{5-8}$$

$$x_{ij} + x_{ji} \leq 1 \ \ , \forall\, i,j \tag{5-9}$$

Equation (5-4) is the objective function to minimize the link emission of route R. Reduction of emission in nodes can be achieved when assigning the resources of the router with minimum Lambda conversion as elaborated in the analysis section. Equation (5-5) is the first constraint that enforces the ASLA. Equation (5-6) is the second constraint that enforces the DSLA. To save space, Equation (5-7) combines all (14 in this case) classical flow conservation constraints of the Shortest Path problem. Equation (5-8) forces the variable x_{ij} to be binary therefore if the link between node i and j is used, the x_{ij} is 1. Otherwise, it is 0. Equation (5-9) is a simple sub-tour elimination constraint that makes sure there is no loop or backtracking in the route. In this chapter, CLE is paired with two different Lambda assignment methods. The CLE 'without the continuity' constraint using the First Fit (FF) method for Lambdas assignment detailed in [39] is denoted as CLE. To minimize the number of the Lambda conversions, and observe its effect of minimizing total energy, CLE is also paired with FF with the continuity constraint (CNT) in assigning

Lambdas and is denoted by CLE-C. Figure 5-4 shows the workflow of serving a connection request.

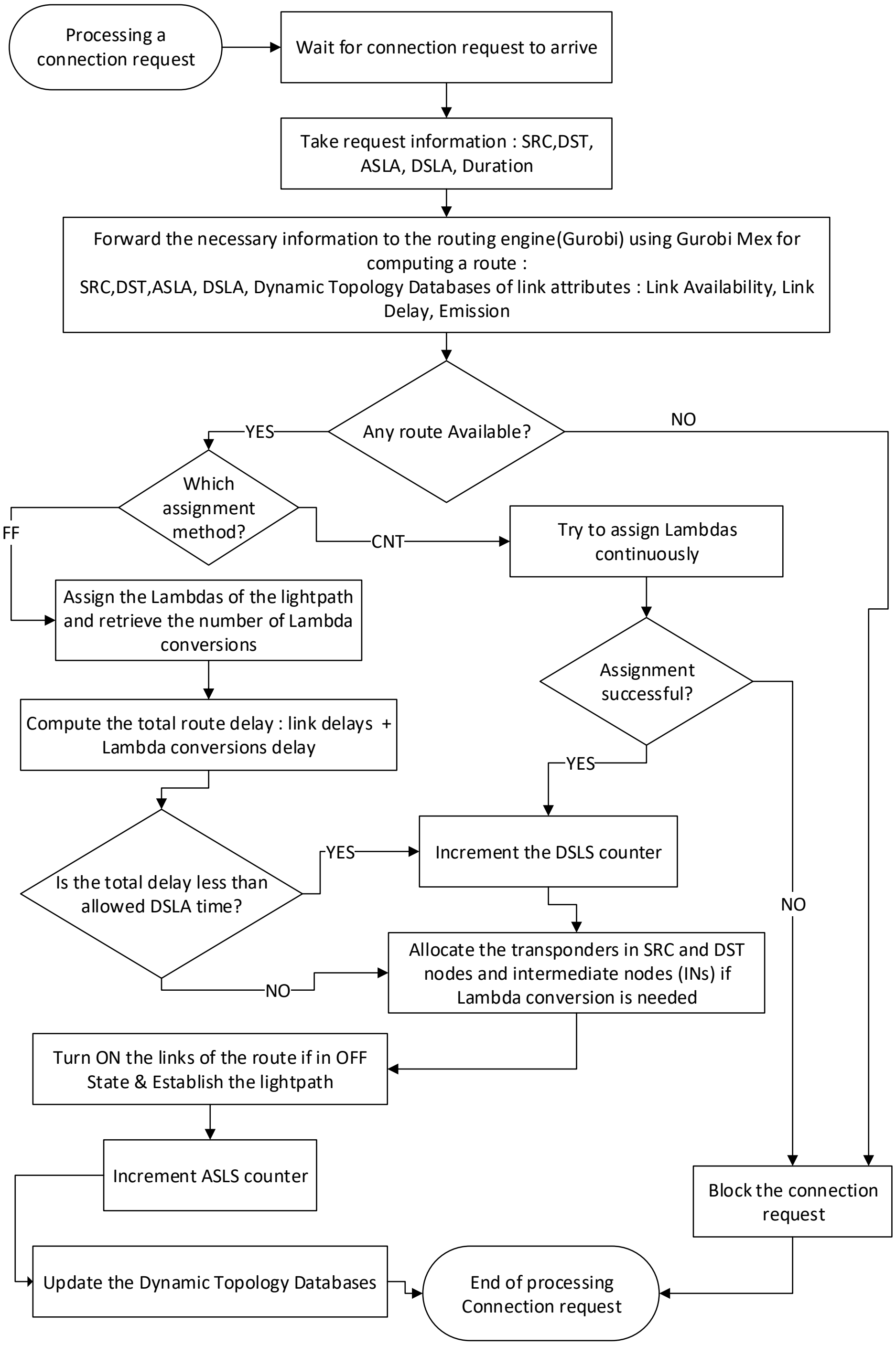

Figure 5-4. Serving a connection request

After the route is computed, the route is given to the corresponding assignment method to assign the Lambdas of the lightpath of the route. For CLE-C, the assignment is done with the continuity constraint, and when it is successful, the Delay Satisfaction (DSLS) counters are incremented as the route complies with the constraint of equation (5-6), and the lightpath is established. As the next step, the ASLS counter is incremented. If any link of the lightpath is in the OFF state, it is turned ON. Updating the dynamic topology (accounting for the Lambdas that were assigned and marking them as occupied) concludes the serving of the connection request with CLE-C. For CLE, the assignment method gives the Lambdas of the route and the number of the Lambda conversions needed to establish the lightpath. There is no chance of failure in the assignment with FF without the continuity constraint as opposed to assignment with continuity constraint. This is because, if no resources were available on the links, the route itself could not have been calculated using the dynamic topology. After assigning the Lambdas for the lightpath, the total route delay is calculated using Equation (2-3). If the total delay is less than the DSLA of the request, the DSLA counter is incremented. To complete serving the request, "Lambda conversion transponders" are assigned, and the lightpath is established. Notice that if the total delay is higher than the DSLA value of the connection request, the route is still established but, the Delay SLA satisfaction counter in not incremented. In this chapter no connection request is blocked due to DSLA violation since other routing methods in the analysis section of this chapter do not consider the DSLA at all. Not blocking the connection request due to DSLA helps keeping the success rate of the CLE and CLE-C comparable to other regenerated routing methods from Section 2.2.1 and 2.2.2. We will see that considering DSLA in finding a route, increases the DSLA Satisfaction (DSLS) by about 15%. As the last step of serving a connection request, the ASLA counter is incremented since the route complies with the constraint of Equation (5-5). This ends the serving connection request with CLE. Figure 5-5 shows the workflow of releasing a connection. When disconnecting a lightpath, Lambdas of the route are released, and the transponders for adding and dropping the Lambda as well as the transponders for Lambda conversion(s) are deallocated. If a link is now accessible because it received back a resource from the lightpath, it is added back to the dynamic topology. If a link gets back all of its resources or Lambdas, it is turned OFF.

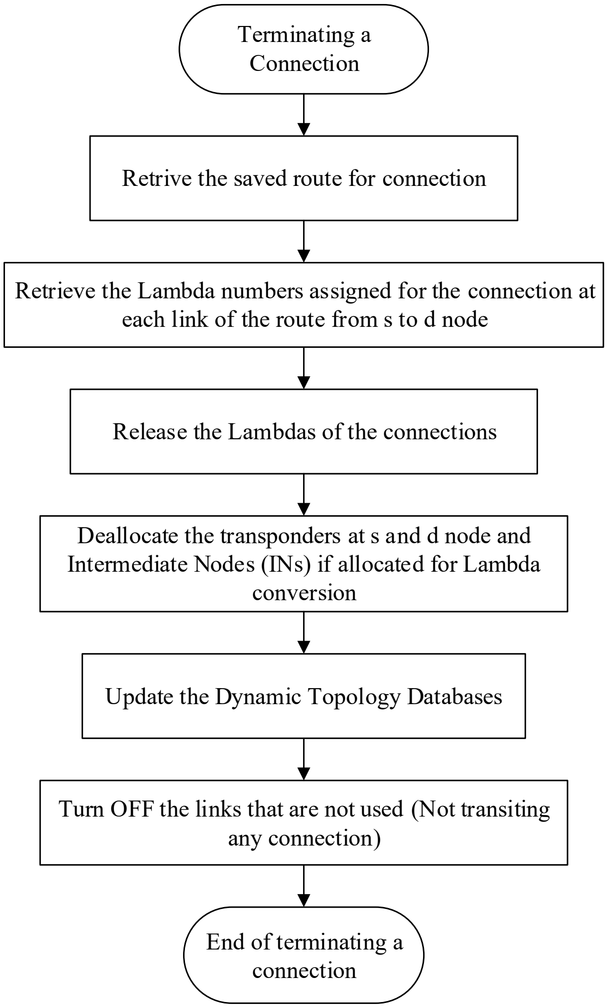

Figure 5-5. Terminating an established lightpath

5.4. Multi-Constrained Shortest Path (MCSP)

Multi-Constrained Shortest Path in equation (5-10) is a simple and very intuitive non-green shortest path mechanism that would be used if no emission information were available. This routing mechanism, not surprisingly, aims at finding the shortest route that complies with both ASLA and DSLA. The Binary Linear programming formulation of the MCSP subject to the same constraints of CLE is as follows:

$$min\, z = \sum_i \sum_j C_{ij} \cdot x_{ij} \tag{5-10}$$

In which C_{ij} is the administrative or Link-State cost of each optical link. In this chapter by considering $C_{ij}=1$, MCSP performs the “Shortest Hop Count” operation.

CLE is compared against the EE, EASB, and MCSP with various performance metrics of upcoming sections. CLE, CLE-C, and MCSP are constrained shortest path routing methods. Therefore, their level of complexity is in order of O^2.

The next section details the testbed information and the performance metrics for the analysis of this chapter.

5.5. Analysis and Simulation Environment

5.5.1. The Network

The same network of Figure 1-1 is used in this chapter and each link has 96 numbered Lambdas to assign without the continuity constraint, using First Fit (except for CLE-C), to be consistent with regenerated routing mechanisms of EE and EASB. The availability of optical links is randomly assigned a number from 0.9999 to 1 and is assumed to be constant for the entire duration of simulations. Request for route or connection is simulated with a Poisson process and is exponentially distributed with an arrival rate of 20 connections per hour and mean duration of 10 hours. The ASLA for connection requests ranges from 0.999 to 0.99999, and DSLA is a multiple of 12.5 ms per time zone difference as illustrated in Section 5.3.2. The optical links and elements of the forwarding plane may be placed in the OFF state if they have no established lightpath. Each link and node is turned ON by a mixture of green and non-green sources of energy resulting in overall energy dirtiness as mentioned in Section 5.3.1.

5.5.2. Performance Metrics Used in This Chapter

Although some of these performance metrics have already been defined, they are revisited here for sake of completeness.

ASLS

ASLS is the satisfaction rate of the ASLA. This metric is a ratio of the number of connections that were served with a route that met their ASLA to the total number of the served connections. CLE, CLE-C, MCSP and EASB that consider ASLA in finding a route for a connection request, result in 100% ASLA satisfaction.

DSLS

DSLS is the satisfaction rate of the DSLA. This metric is a ratio of the number of connections that were served with a route that met their DSLA, to the total number of the served connections. CLE, CLE-C, and MCSP that consider DSLA in finding a route for the connection request are expected to have higher satisfaction compared to other routing mechanisms. Unlike ASLS, DSLS may or may not be 100% since the route which is not complying with DSLA is not blocked.

Success Rate

The success rate is a ratio of the number of served requests over the total number of requests.

Success Satisfaction

Success Satisfaction is the product of Success Rate, ASLS, and DSLS of a routing method. This metric helps to analyse the overall satisfaction rate. Routing mechanisms such as CLE, CLE-C, and MCSP that consider ASLA and DSLA in finding a route are expected to have higher Success Satisfaction.

Lambda per Connection

This metric is the average length of the lightpath of the served connections in units of hops. A lower number is preferred for this metric. A lower number indicates better resource efficiency. Since the Traffic Engineering in GMPLS is in bidirectional fashion, the return path is also considered in this graph. Therefore, the actual average length of the TE lightpath in units of hops is the half of the number presented by this metric.

Emission per Lambda

This metric is the amount of emission emitted to the atmosphere to establish a unit resource, Lambda. A lower number is preferred for this metric, and this metric shows the emission reduction capability of a routing mechanism. The value of the emission per Lambda will be lower for the routing mechanisms that have a higher success rate as the emission is divided by more number of resources in operation. Because of this reason, emission reduction must be evaluated and analysed for routing methods that have about the same success rate.

Node Power

In this chapter, the node power is the power drawn by the optical forwarding layer of the network. For each node, this power is the sum of energy used by transponders to add or drop a Lambda as well as the energy used by transponders that perform the Lambda conversion operation. Since adding and dropping a Lambda in a source node and a destination node is the fixed part of the energy used by a node, the change in the value of the energy usage for each node depends on the number of Lambda conversions. The value of node power will be higher for the routing mechanisms that have higher success rate, and therefore this metric must be evaluated for routing mechanisms that have the same success rate.

Conversion Count

This metric is the total number of Lambda conversions in the network. In other words, the sum of all Lambda conversions in every node of the network. With this metric, we can observe the effect of using the combination of different routing and assignment methods.

Link Power

This metric is the power drawn by all turned ON links of the network. Since the power drawn by the link does not change after being turned ON (since inline amplifiers and signal leveling amplifiers amplify the entire spectrum or Lambdas), a lower value for this means a lower number of links (inline amplifiers) are in operation.

The next section details the results of the analysis for CLE, CLE-C, MCSP, EASB and EE using the introduced performance metrics.

5.6. Results

5.6.1. Graphical Presentation of the Obtained Results for Performance Metrics

As we can see in Figure 5-6, the success rate of EE is 100% since it does not consider any SLA in serving a request and no blocking occurs due to SLA violation. 100% success rate for this routing mechanism also means that there were enough resources to handle the given traffic intensity and no connection request is blocked due to lack of resources. As we can see in Figure 5-6, adding the delay constraint in finding a route reduces the success rate by only 2% compared to EASB. In this figure CLE, CLE-C and MCSP are overlapping point by point. With the same success rate for CLE, CLE-C, and MCSP and only 2% difference compared to EASB, it is fair to compare these routing mechanisms against each other using the remaining performance metrics. Figure 5-7, shows the ASLS percentage. As we can see in this graph, without considering the ASLA in finding a route by EE, the ASLS drops to 65% which may not be acceptable. As mentioned earlier the routing mechanisms that serve the connection requests by considering the ASLA have a 100% ASLS which is the case here for CLE, CLE-C, MCSP, and EASB. Figure 5-8, shows the results of analysis for DSLS. As we can see in Figure 5-8, without considering the DSLA in finding a route, DSLS can drop by more than 15% among routing methods that have about the same success rate. As we can see in Figure 5-8, CLE is about 17% and 23% more DSLA compliant compared to EASB and EE respectively. The non-green method of MCSP is about 2% more DSLA compliant compared to CLE, because as we will see in later graphs, it has a lower average hop length for the lightpaths. Therefore, MCSP has a lower chance of Lambda conversion which may incur node delays. CLE-C is 100% DSLA compliant since there is no Lambda conversion delay in the transit nodes of the lightpaths. Therefore, CLE and CLE-C are better options compared to the hybrid green method of EASB and pure green method of EE, regarding DSLA compliance. The results in Figure 5-9 for Lambda per connection shows that the entire difference in resource efficiency of the green-aware mechanism of CLE, CLE-C, EE and EASB is about 0.15 hops or 3%. Therefore, regarding resource efficiency, these mechanisms are comparable and are about the same. Not surprisingly, MCSP that aims at reducing the number of hops by performing constrained shortest path has lower average Lambda per Connection and is about 10% or 0.4 hops more resource efficient. In Figure 5-10 interesting results are obtained for link power that represents the number of links in use. As we can see in this Figure, CLE, CLE-C, and EE that performs constrained or direct shortest emission first routing, use fewer links and have lower energy consumption in the links compared to EASB and MCSP. The reason is, CLE, CLE-C and EE try to use most of the greener links and form a “Highway” across the greener links, leaving the less green links in OFF state. On the other hand, MCSP performs constrained shortest path, and EASB just chooses a route that has the lowest hybrid cost. Therefore, they use more links. About 3 kW less power with the same SLA Satisfaction on the network that has a total of 21 bidirectional links is desirable. Based on this graphs CLE and CLE-C use less energy in the links compared to EASB and MCSP. Results of power consumption of nodes in Figure 5-11 show that EE has the highest power consumption in nodes. However, this is because EE has 100% success rate and establishes more connections. Among CLE, MCSP and EASB that have about the same success rate and use FF in Lambda assignment, MCSP uses about 4 kW less power because MCSP has lower average route length as shown in Figure 5-9, and therefore, routes in MCSP transit less number of nodes on an average. CLE-C with continuity constraint draws about 55% less energy compared to MCSP because no Lambda conversion is performed in nodes as we will see in the upcoming figure. With these observations, it is possible to conclude that CLE-C is more energy efficient among other routing mechanisms compared in this Figure. Figure 5-12 shows the results for the number of Lambda Conversion. As we can see in this figure, CLE-C has zero number of Lambda conversions since it assigns the Lambdas with a continuity constraint. MCSP, CLE, and EASB almost repeat the results of Figure 5-11, and as we can see MCSP has a lower number of the Lambda conversions since again, the average route length in MCSP is about 10% shorter and therefore less number of Lambda conversions can happen. Therefore, CLE-C with the continuity constraint in the assignment of Lambdas, and zero conversion, is more energy efficient than MCSP, EASB, CLE and EE. The results for emission reduction in Figure 5-13 show that CLE is about 6% more emission efficient than MCSP and about 3% more efficient than EASB. Not surprisingly EE has a lower average because the total amount of emission is divided by more number of established lightpaths and Lambdas as EE has 100% success rate. In this Figure, CLE-C has about 37% less emission per unit resource Lambda compared to the non-green MCSP, because as we saw, it a has a lower link and node power consumption and it chooses the greener routes. The last graph in this section of analysis is the percentage of the Success Satisfaction in Figure 5-14. As we can see in this Figure, although EE has 100% success rate, because in has a poor ASLS and DSLS, it shows the lowest of the Success Satisfaction percentage compared to other routing methods in this chapter. Among EASB, CLE, CLE-C, and MCSP that have about 80% success rate CLE-C has the highest Success Satisfaction rate as it has 100% ASLA satisfaction and 100% DSLA satisfaction. After CLE-C, MCSP and CLE show about the same (1% difference) in success satisfaction since they have acceptable DSLS and ASLS satisfaction. EASB although has 100% ASLS but because of poor DSLS value, sits at 12% less Success Satisfaction compared to CLE.

Based on obtained results we can say that Constrained Shortest Path MCSP and Constrained Least Emission CLE improve the DSLS by at least 15% compared to EASB, using the constraint in Equation (5-6). The continuity constraint added to CLE (to come up with CLE-C) provides the full 100% DSLS. Routing based on emission information lowered the link energy usage and overall emissions. Routing based on shortest path lowered the total node energy. However, the saving in energy and emission is much more significant using continuity constraint. The difference of less than 10% in emission per unit resource Lambda among CLE, EASB and MCSP is due to the fact that there is no 100% pure green or non-green link. This result is in a big contrast to results of the paper in [11,12,34,45,51] that use the concept of 100% green or 100% non-green energy for the links.

In summary, the proposed CLE method with continuity constraint (CLE-C) has the best emission reduction, highest Success Satisfaction rate, an acceptable resource usage, and provides 100% Satisfaction for both ASLA and DSLA compared to other routing mechanisms of this chapter. With continuity constraint and lower number of conversions in CLE-C, a Service Provider can operate with a lower number of transponders used in operation and have a more economical operation or lower Total Cost of Ownership (TCO).

This is added to the 55% less energy usage in nodes compared to the traditional non-green routing mechanism of MCSP.

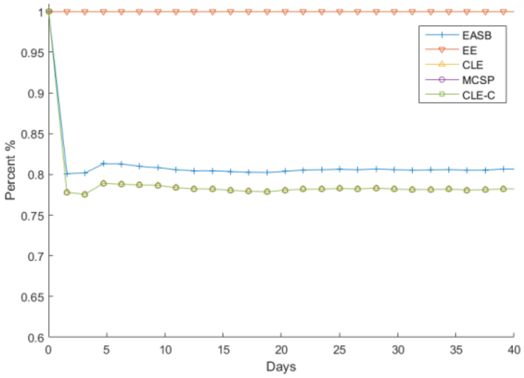

Figure 5-6. Success rate

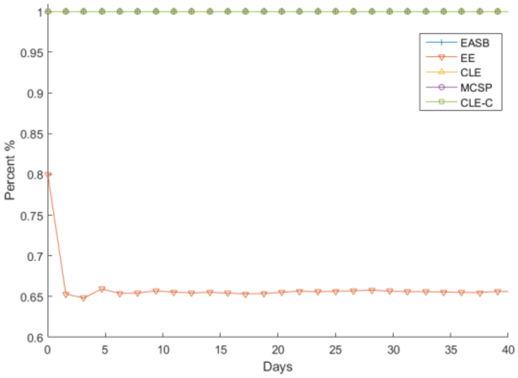

Figure 5-7. ASLS

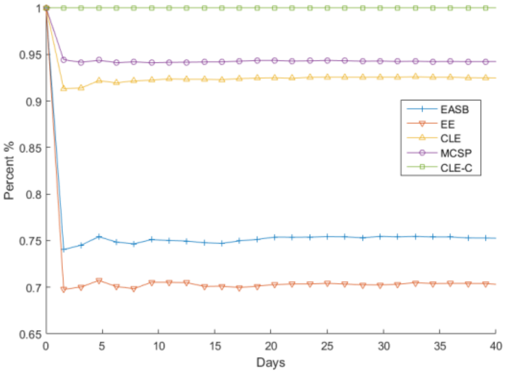

Figure 5-8. DSLS

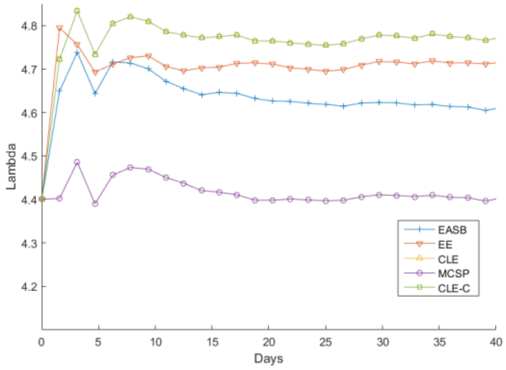

Figure 5-9. Lambda per connection

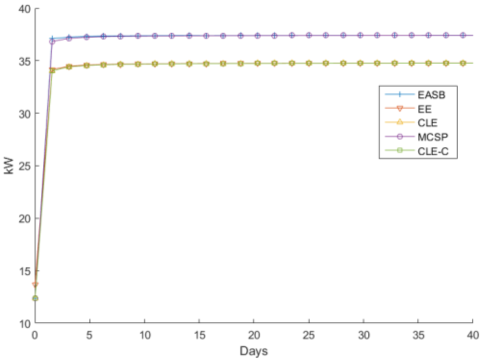

Figure 5-10. Total link power

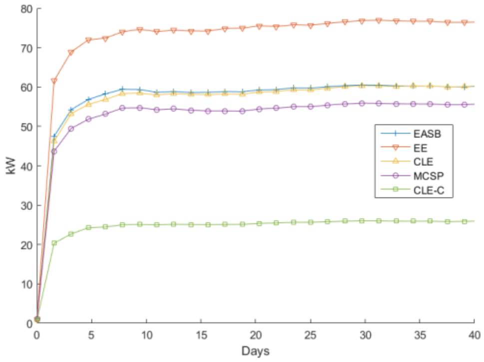

Figure 5-11. Total node power

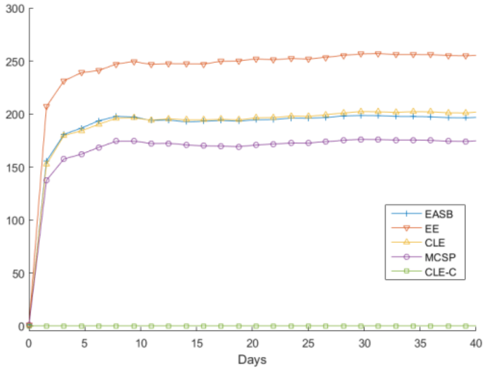

Figure 5-12. Total Lambda conversions

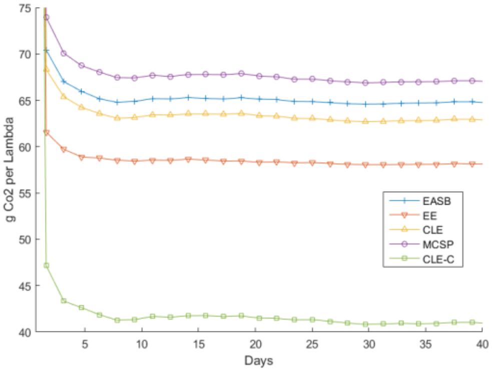

Figure 5-13. Emission per Lambda

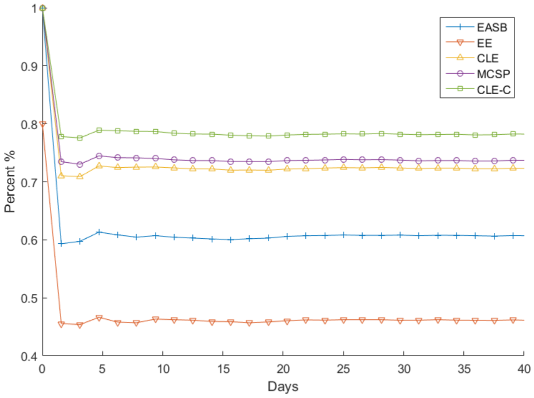

Figure 5-14. Success Satisfaction

5.6.2. Confidence Interval Analysis

Although the previous section provided a comprehensive analysis on the performance of the CLE-C, this section is added to the study of the performance of CLE-C, to eliminate any randomness. Since the availability of the links, availability of the green energy and arrival of connection requests and their characteristics are random and simulated, the simulation is repeated 100 times, processing 2 million connection request and building a 95% confidence interval over the mean of the average of some key performance metrics. Based on results of Table 5-1, the success rate is about the same (1% difference) for EASB, CLE, CLE-C and MCSP and their 95 % confidence interval has an overlapping section which is desired.

Table 5-1. 95% Confidence interval over mean of success rate

Variable	Mean	StDev	SE Mean	95% CI
EASB	0.80235	0.09194	0.00919	(0.78410,0.82059)
EE	1	0	0	(1.000,1.000)
CLE	0.79269	0.08779	0.00878	(0.77527,0.81010)
MCSP	0.79269	0.08779	0.00878	(0.77527,0.81010)
CLE-C	0.79269	0.08779	0.00878	(0.77527,0.81010)

The 95% confidence interval on the mean of Success Satisfaction in Table 5-2 repeats the graphical results of this metric, and CLE-C with about 80% Satisfaction has the highest Success Satisfaction rate. Moreover, 95% confidence interval of CLE-C does not have any overlapping section with any other routing mechanism compared in this chapter. CLE and MCSP have overlapping sections in their 95% confidence interval which is desired. This shows that the Success Satisfaction of CLE can be as good as the traditional non-green mechanism of MCSP.

Table 5-2. 95% Confidence interval over mean of Success Satisfaction

Variable	Mean	StDev	SE Mean	95% CI
EASB	0.58462	0.04436	0.00444	(0.57581,0.59342)
EE	0.47309	0.04175	0.00418	(0.46481,0.48138)
CLE	0.7254	0.0708	0.00708	(0.71135,0.73945)
MCSP	0.74362	0.07492	0.00749	(0.72875,0.75848)
CLE-C	0.79269	0.08779	0.00878	(0.77527,0.81010)

Based on results of Table 5-3, CLE-C provides 100 % DSLS rating which is about 6% and 9% higher than MCSP and CLE respectively. CLE-C has no overlapping section in 95% confidence interval compared to MCSP which is highly desired.

Table 5-3. 95% Confidence interval over mean of DSLS

Variable	Mean	StDev	SE Mean	95% CI
EASB	0.73353	0.05489	0.00549	(0.72264, 0.74442)
EE	0.716511	0.003825	0.000382	(0.715752,0.717270)
CLE	0.91699	0.02832	0.00283	(0.91137, 0.92261)
MCSP	0.93965	0.02835	0.00284	(0.93402, 0.94527)
CLE-C	1	0	0	(1.000, 1.000)

Table 5-4 shows us that ASLS is 100 % for CLE-C and CLE, in all 100 experiments

Table 5-4. 95% Confidence interval over mean of ASLS

Variable	Mean	StDev	SE Mean	95% CI
EASB	1	0	0	(1.000,1.000)
EE	0.65105	0.05797	0.0058	(0.63955,0.66256)
CLE	1	0	0	(1.000,1.000)
MCSP	1	0	0	(1.000,1.000)
CLE-C	1	0	0	(1.000,1.000)

Table 5-5, for an average of emission per Lambda, shows us that there is no overlapping between 95% confidence interval of CLE-C and any other routing mechanism in this chapter. The average of emission of CLE-C is about 36% less than MCSP. The other point noticed is that EASB averaged about the same as CLE with 4% less emission compared to MCSP.

Table 5-5. 95% Confidence interval over mean of emission per Lambda

Variable	Mean	StDev	SE Mean	95% CI
EASB	65.478	6.414	0.641	(64.206,66.751)
EE	59.5193	0.3717	0.0372	(59.4455,59.5930)
CLE	65.775	4.83	0.483	(64.816,66.733)
MCSP	68.658	5.356	0.536	(67.595,69.721)
CLE-C	44.025	5.701	0.57	(42.894,45.156)

Finally, Table 5-6 shows us that CLE-C could establish the lightpaths with zero conversion for all 100 experiments and MCSP with lower average route length operated with 11% less number of conversions, very similar to the results obtained in the graphical representation of the performance metrics.

Table 5-6. 95% Confidence interval over mean of Lambda Conversion count

Variable	Mean	StDev	SE Mean	95% CI
EASB	208.68	54.32	5.43	(197.90,219.46)
EE	246.825	4.345	0.434	(245.962, 247.687)
CLE	201.35	42.12	4.21	(192.99,209.71)
MCSP	181.35	39.53	3.95	(173.51,189.19)
CLE-C	0	0	0	(0.000000,0.000000)

This section confirmed the validity of graphical results obtained in the last section.

5.7. Summary and Future Work

This chapter introduced a multi-SLA aware routing mechanism that could provide 100% DSLS and ASLS while operating at 55 % less node energy and 36% less emission compared to tradition non-green mechanism. In this chapter, it was observed that minimizing the emission of the route is as effective as (4 to 6) % in reducing the total emission of the network when realistic emission values are used in the simulation and analysis. The better and significantly more reduction of around 36% in emission emitted by the network resulted by using continuity constraint that consumes 55% less energy. The next chapter studies the performance of the continuity constraint on blocking rate of the network.

Chapter 6 NHOPAKIND RESOURCE ASSIGNMENT METHOD

6.1. Introduction

The last chapter stated that continuity constraint might increase the blocking rate of the network and it separated the routing step from the assignment step. This chapter introduces a new energy efficient resource assignment method and compares it against FF and FF with continuity constraint with five performance metrics. The introduced method aims at reducing the energy usage at the forwarding layer of the nodes by reducing the number of Lambda conversions. The assignment method introduced in this chapter can be an "add-on" to any routing mechanism. For the analysis section of this chapter, The new assignment method will be added to the process of serving a connection requests using Shortest Path Routing mechanism. The testbed and the way that lightpaths are established are the same as last chapter, except for the fact that each link is limited to have 16 available to assign Lambdas to be able to simulate the congestion condition of the network easier. The organization of this chapter is as follows: Section 6.1 introduces the new method. Section 6.2 provides a review of the performance metrics, details the test environment and explains the traffic intensity scenarios. Section 6.3 elaborates the results with graphs and building the Confidence Intervals. Section 6.4 provides the summary and states the future work. Introduction to the assignment method comes next.

6.2. NHopAKind Resource Assignment

This section introduces the new proposed method for resource assignment called "N Hop A Kind", after a winning combination in the game of Poker. This method tries to find a lightpath that has a zero or minimum Lambda conversion when no continuous lightpath to the destination (assignment with continuity constraint) is available. When establishing a lightpath with Lambda conversion, each group of Lambdas of the route are "N Hop A Kind" before (each) conversion. The upcoming figures explain the process with an example. In Figure 6-1, S is the source node, and D is the destination node. Each Intermediate Node or (IN) is followed by a number that shows the place of the IN in the route. Therefore, the first intermediate node in the path from S to D is IN1. The next hop is IN2 in the route and so on. NHopAKind assignment method consists of two major steps.

The first step tries to find a direct and continues lightpath from S to D which is called "Advancing". Advancing will check each available to assign Lambda in the first hop between S and IN1 in the hope of finding a Lambda which will be able to "Advance" to D. If there is such a Lambda number, the lightpath is established and no Lambda conversion is needed. If there is a continuous Lambda, then NHopAking assignment is stopped, and the process finishes. This condition is shown in Figure 6-1. However, if there isn't such a Lambda number, the NHopAkind initiates the second step. The second step of NHopAkind gathers the (Lambda, End-Point) pairs as demonstrated in Figure 6-2, and sorts them based on highest IN. An End-Point of a Lambda is a point or hop at which advancing to D was blocked or stopped, as the Lambda was not available in the next link of the route. After sorting, the combinations with the repeated End-Points are purged from the list. The second step, therefore, is called "Sorting and Purging". The Purging sub-step significantly reduces the number of combinations to try out in the next "Round". At the end of this process NHopAkind has finished the first Round of the attempt to find a minimum conversion lightpath from S to D. The second Round is started with the Advancing, from the End-Point with the highest IN which is (40, IN4) in example of Figure 6-3, which is closer to D and has a lower chance of needing another conversion. If the Advancing with the first (Lambda, End-Point) pair results in a direct lightpath with no conversion, the process is stopped and the overall lightpath of (40,40,40,40,23) is obtained, which has 1 conversion only. In Figure 6-3 the IN4 is the last hop to D, and if there is such an End-Point, the entire lightpath will have only 1 conversion. The reason is, the routing process is decoupled from the assignment method, and there would be no hop from IN4 to D if no resource were available in the dynamic network. In other words, if there were no available-to-assign Lambda from IN4 to D, then the hop from IN4 to D would not exist for the assignment and the route from S to D would not transit through the node of IN4. Now let us imagine that the combination pair (40, IN4) does not exist. Therefore, the "Advancing" step would start from the (15, IN3) combination pair. If the Advancing results in a direct lightpath from IN3 to D, then the process is stopped, and the overall lightpath combination of (15,15,15,44,44) is obtained as seen in Figure 6-4. This combination has only 1 conversion as well, and therefore, uses the same amount of energy in conversion. If there is no direct lightpath to D at the end of Round 2, then the process of Sorting and Purging is performed for each

End-Point of Round 2 and the NHopAkind method enters the Round 3. In Round 3 at each End-Point of Round 2, the highest (or the nearest to D) End-Point or IN is selected for Advancing to D and finding a direct lightpath. Advancing continues to find a direct lightpath as we will see in Figure 6-5. To explain the process in Round 3 and later Rounds, let us number each End-Point. For example, Lambda 20 from S is stopped at IN3 and gets R1E1 denoting Round 1 End-Point 1. R2E3, therefore, is the 3rd End-Point in Round 2. As we can see in Figure 6-5, Advancing is started from End-Points of the last Round to find a continuous lightpath. When a continuous lightpath is found, the Lambda numbers of the entire route can be found by "Reversing" to S by knowing the "Parent" of the End-Point that resulted in the continuous lightpath. For example, in Figure 6-5 Lambda number 3 with End-Point of R3E2 reached to D and to find the Lambdas for the entire route we need to "Reverse" back to S. The Parent of the End-Point R3E2 is R2E2, whose parent is R1E1. By knowing the Parents of the Endpoints Lambdas of the path can "Compiled", as we can see in Figure 6-5. As soon as finding a direct lightpath in Round 3 or any Round, in general, the process is stopped, and there is no need to check the other combinations. This significantly improves the resolution time of NHopAkind method. It can be concluded that at the end of each round R, a lightpath with R-1 conversions may be found. The network testbed in this chapter has an average route length of around 2.5 hops (as we will see in the results section). Therefore, NHopAkind may do up to 3 Rounds on an average.

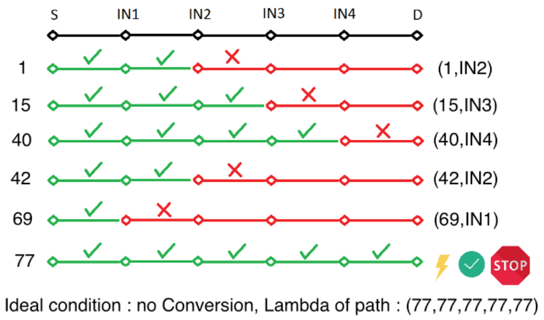

Figure 6-1. Advancing step

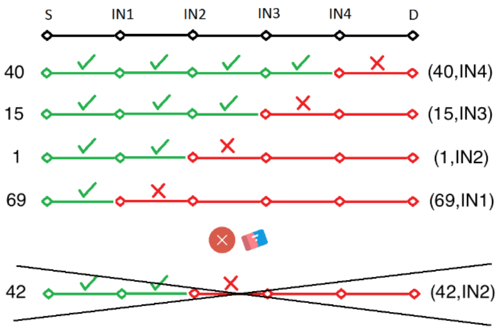

Figure 6-2. Sorting and Purging step

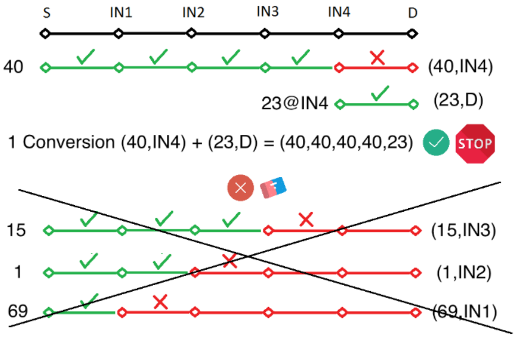

Figure 6-3. 1 conversion in last IN

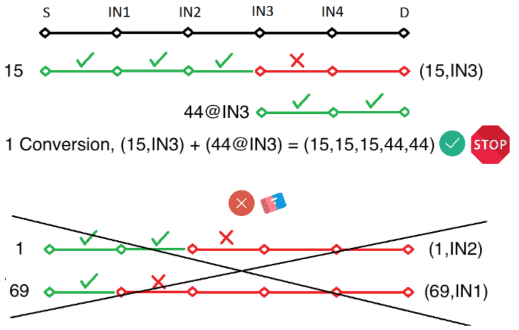

Figure 6-4. Equivalent alternate lightpath with 1 conversion

Fot this chapter SP routing method is paired with the First Fit, First Fit with continuity constraint and the NHopAkind and calls the combinations SP, SPCont and SPNHK respectively.

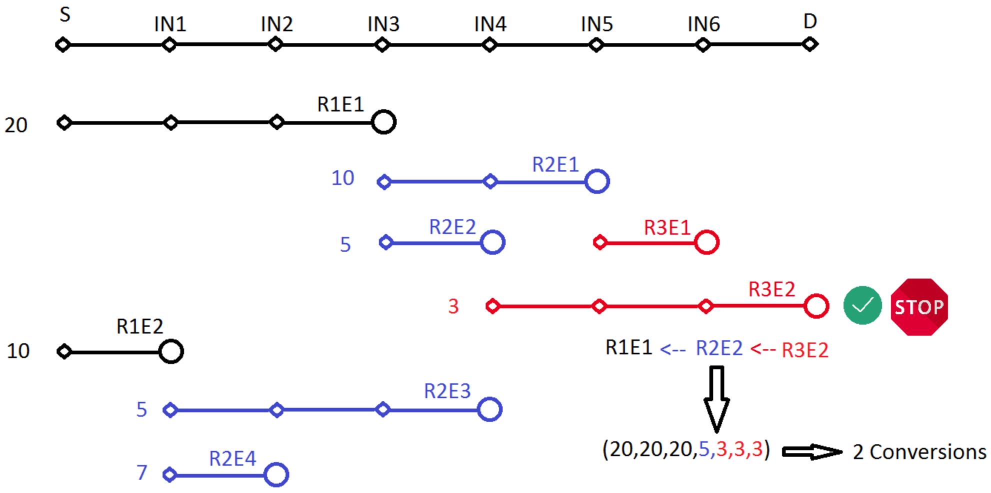

Figure 6-5. Advancing step in Round 3

Table 6-1. shows the algorithm of the NHopAking in form of pseudocode.

Table 6-1. NHopAkind Algorithm

```
INPUT : Route; Lambda  : Resource matrix; LAM_NUM : Max available Lambda per link;
Flag : Resource availability flag;

OUTPUT : RET_Flag: Updated resource availability flag;
RT : Route Lambdas; Connum : Number of Lambda conversions;

Function [RET_Flag,RT,Connum] =AssignNHopAkind(Route,Lambda,LAM_NUM,Flag)
    MAX_COL=2;SORT_COL=2; NODENUM=14;
    RTlambda=[]; %the lambda assignment to return
    R_len=length(Route)-1;
    Continuous=0;
    End_Point2_NUM(1:NODENUM)=0;
    offset=1; %the reference point for howmany hops to go to get blocked
```

```
   Initialize(End_Points,0)
   End_Point=[];
   [l,Continuous,Flag,End]= Advance(Lambda,Route,Flag,End,LAM_NUM);
   %this is the location of Lambdas crossed or stopped and need  conversion
   if Continuous
      RT(1:r_len)=l;
      Connum=0;
   else
      End_Point=Sort(End,Route,LAM_NUM,MAX_COL,SORT_COL,Lambda);
      End_point2=purgeRepeatedEnd(End_Point);
      End_point2_set{1,1}=End_point2;
      End_Point2_NUM(1)=1;
      i=1;Round=2;
      while i<NODENUM && ~Continuous
         s=1;j=1;
         while (j<=End_Point2_NUM(Round-1) && ~Continuous)
            End_Point2_NUM(Round-1);
            pretempcrosspoint2=End_point2_set{Round-1,j};
            Sizepretemp=size(pretempcrosspoint2);
            k=1;
            while (k<=Sizepretemp(1) && ~Continuous)
               temproute=Route(pretempcrosspoint2(k,2):length(Route));
               offset=pretempcrosspoint2(k,2);
               [l,Continuous,Flag,End]= Advance(Lambda,temproute,Flag,End,LAM_NUM);
               End_Point=[];
               if ~Continuous
                  End_Point=cross2point(End,temproute,LAM_NUM,MAX_COL, SORT_COL,Lambda);
                  End_point2=purgeRepeatedEnd(End_Point);
                  cross_point3=addOfsetNode(End_point2,offset);
                  End_point2_set{Round,s}=cross_point3;
                  Crosspoint2_parent{Round,s}=[Round-1,j,k];
                  End_Point2_NUM(Round)=End_Point2_NUM(Round)+1; % number of cross points existing
               end
               s=s+1; k=k+1;
            end
            j=j+1;
         end
         Round=Round+1; i=i+1;
      end
      RTlambda=[RTlambda,ones(1,length(pretempcrosspoint2(k-1,2):length(Route)))*l];
      tempC=[];tempC(1)= Round-2 ;tempC(2)= j-1; tempC(3)=k-1; Finalpoints=[];
      %Since with lower rounds Crosspoint2_parent is not defined then we will
      %make a dummy one here so loop does not break
      if (Round<=3)
        Crosspoint2_parent{tempC(1),tempC(2)}=[];
      end
      while (Round-2)>=1
         temp=End_point2_set{tempC(1),tempC(2)}(tempC(3),:);
         Finalpoints=[Finalpoints;temp];
         tempC=Crosspoint2_parent{tempC(1),tempC(2)};
         Round=Round-1;
      end
      RT=[];
      Finalpointslen=size(Finalpoints);
      Startnode=1;
   if Finalpointslen(1)>1
      Finalpoints=flip(Finalpoints);
   end
      start=1; temp=[];
      for i=1:Finalpointslen(1)
         temp(start:Finalpoints(i,2)-1)=Finalpoints(i,1);
         start=Finalpoints(i,2);
      end
      RT=[temp,RTlambda(1:length(RTlambda)-1)];
      Connum=Finalpointslen(1)+1;
   End
   for k=1:( R_len)
       RET_flag=UpdateFlag(Route,Flag,Lambda)
   end
end
```

Figure 6-6 demonstrate the process of serving a connection request which is similar to the workflow of the last chapter. When a connection request arrives, first a route using SP method is computed. With SPCont the assignment process attempts to assign the resource of Route continuously, and if it succeeds, the lightpath is established in the next upcoming step. If the assignment is not successful, the connection request is blocked. With SP and SPNHK the resources of the route are assigned by corresponding assignment methods which give the Lambdas of the route and the number and place (INs) of the Lambda conversions. Regardless of the assignment method, after assigning the resource, the dynamic topology table is updated, and if a link is in the OFF state, it is turned ON. If a link just assigned its last resource and can not take any more lightpaths, it is removed from the dynamic topology, so no new route is computed using that link. As the last step the transponders of S, D, and INs (if Lambda conversion is needed) are allocated, and the lightpath is established. This concludes the serving a connection request. The process of releasing a lightpath is the same as in the last chapter and is not repeated here.

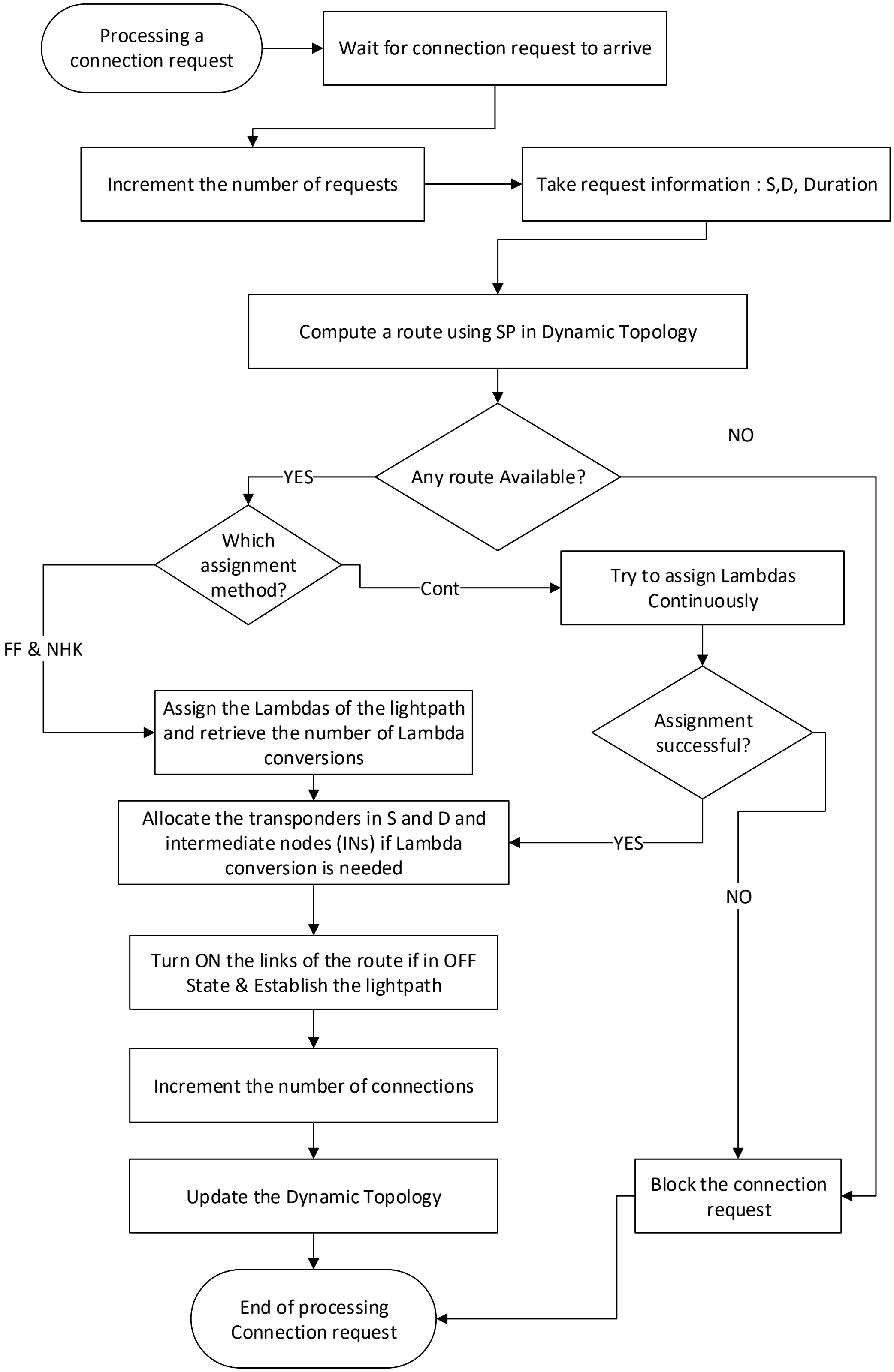

Figure 6-6. Serving connection request

6.3. Analysis

6.3.1. Testbed Network

The network of the last chapter is used in this chapter with the same optical elements. The behaviour of the traffic is simulated with a Poisson process with an arrival rate of 20, 80 and 125 connection requests per hour, for scenario 1 scenario 2 and scenario 3, respectively. The duration of the connections or lightpaths also follows an exponential distribution with a mean duration of 30 mins. Each link has 16 available to assign Lambdas. The simulation to obtain the results of each routing and assignment pair is performed in parallel and independently using MATLAB Parallel Toolbox [18]. Introduction to the performance metrics used in this comes next.

6.3.2. Performance Metrics

Number of Conversions

This metric simply shows the total number of current Lambda conversions at each time of the day. Depending on the traffic scenario and the assignment method used, this number can be different for each routing-assignment pair. Obviously, a lower value is preferred for this metric. It is expected that continuous and NHopAkind methods have zero Lambda conversion in scenario 1, since there are enough resources to establish the lightpaths "continuously."

Lambda per Edge

This metric is the average number of the connections per each link of the network. This metric shows how congested the network links are on an average.

6.4. Results

6.4.1. Analysis for Scenario 1: The Light Traffic

As we can see in Figure 6-7, The success rate of the network for all routing mechanism of SP, SPCont and SPNHK is the same. The reason is that there are enough resources to establish the lightpaths regardless of assignment mechanism used. As we can see in Figure 6-8, the average utilization of the links of the network is 2.5 out of 16 available-to-assign Lambdas and the network is not congested at all with the light traffic of scenario 1. As we can see in Figure 6-9, since there is no congestion on the links due to the light traffic, SP, SPNHK and SPCont give the same route length on an average. Figure 6-10, for this scenario, shows that the Continuous and NhopAkind become the same, as NHopAkind assigns the resources with minimum Lambda conversion, which is zero for this scenario. This fact is shown with overlapping SPCont and SPNHK in Figure 6-10. SP with FF in this case assigns the resources of the lightpaths with a total of 16 Lambda conversions. With a lower number of conversions, the total node energy is about 50% less for SPNHK and SPCont compared to SP as we can see in Figure 6-11. The results of analysis for scenario 1 concludes that continuous assignment and NHopAkind assignment are the same when the traffic intensity and utilization of the links are low. The same analysis is performed for scenario 2 and 3.

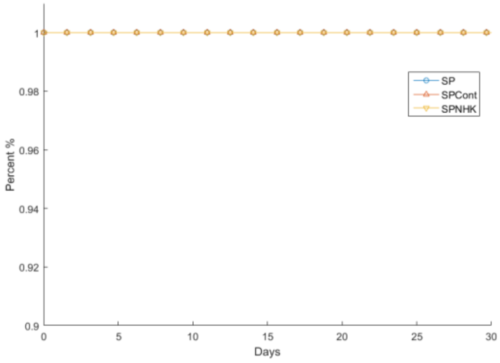

Figure 6-7. Success rate

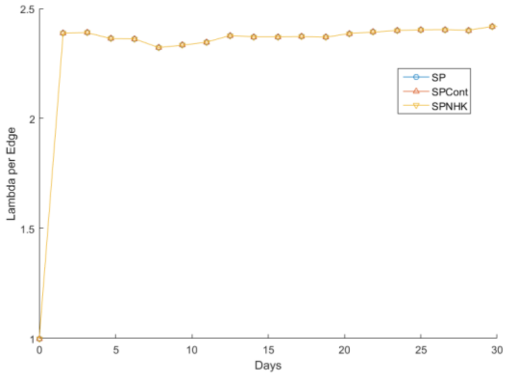

Figure 6-8. Lambda per edge

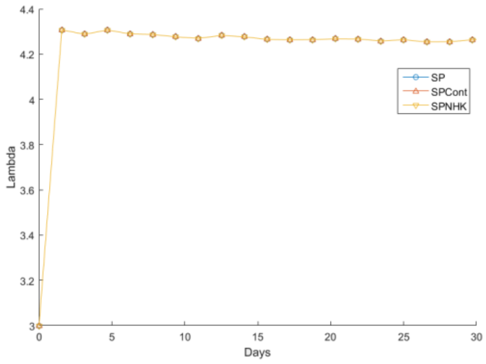

Figure 6-9. Lambda per connection

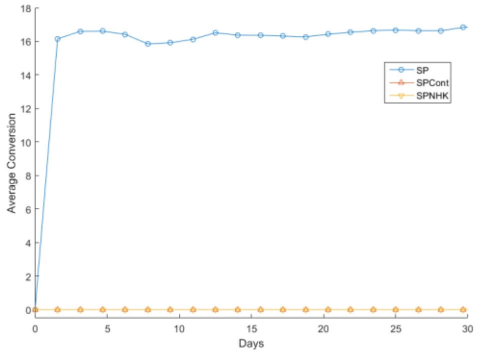

Figure 6-10. Lambda conversions count

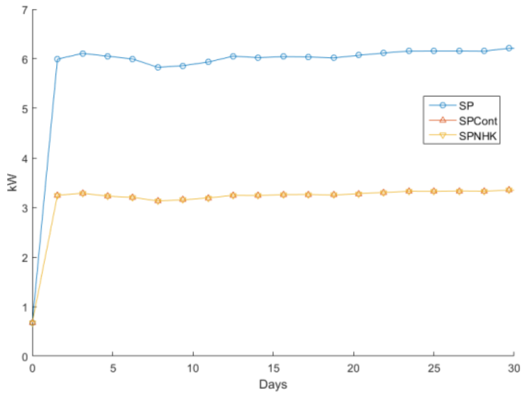

Figure 6-11. Total node power

6.4.2. Analysis for Scenario 2: The Moderate to Heavy Traffic

As we can see in Figure 6-12, the success rate of SPCont drops by 6%. SPNHK and SP still provide almost 100% success rate and are overlapping in this figure. Therefore, the 6% drop in the success rate of SPCont is due to lack of continuous lightpaths and not lack of available resources. Results of Figure 6-13, shows that the average congestion of the links of the network is around 50% of the 16 available to assign Lambdas per each link or edge. In Figure 6-13 SPNHK and SP have higher link utilization, first, because they have a higher success rate, and because they assign the resources to the routes that bypass the congested links and are longer on an average. The fact that the routes assigned by SP and SPNHK are longer than SPCont is clearly shown in Figure 6-14. As we can see in Figure 6-14, the overlapping value of average route length for SP and SPNHK is about 8% higher compared to SPCont. Therefore, routes are 8% longer on an average trying to establish the lightpath through the links that still have the resources (Lambdas to assign). With the results of Figure 6-15 for Lambda conversion count, we can see that SPNHK is minimizing the Lambda conversion by 72%. Therefore, SPNHK performs 72% less Lambda conversions and gives the same route length to provide 100% success rate compared to SP. SPCont (not surprisingly) gives zero Lambda conversion count. The lower Lambda conversion number with SPNHK compared to SP is also reflected in results of Figure 6-16 for node power consumption, and SPNHK consumes about 44% % less energy compared to SP.

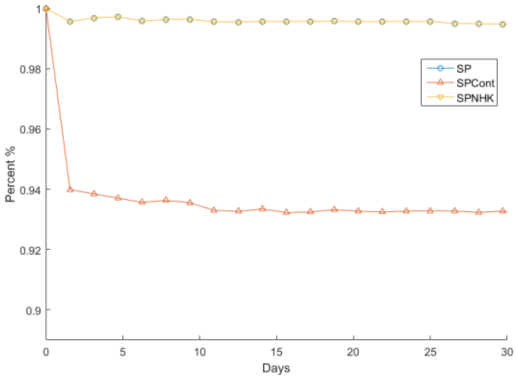

Figure 6-12. Success rate

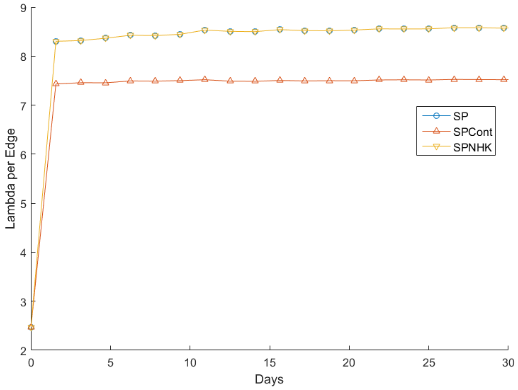

Figure 6-13. Lambda per edge

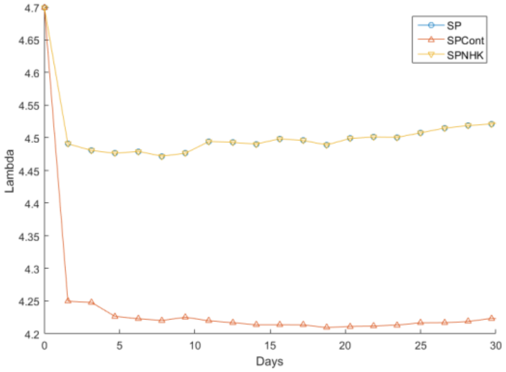

Figure 6-14. Lambda per connection

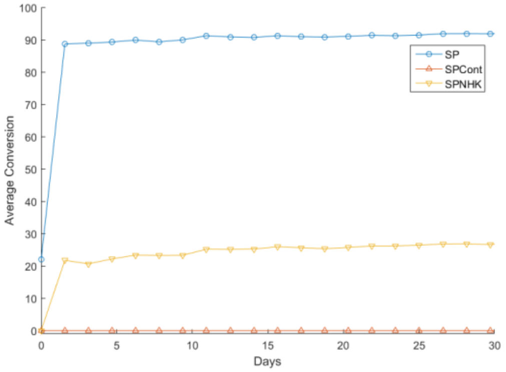

Figure 6-15. Lambda conversion count

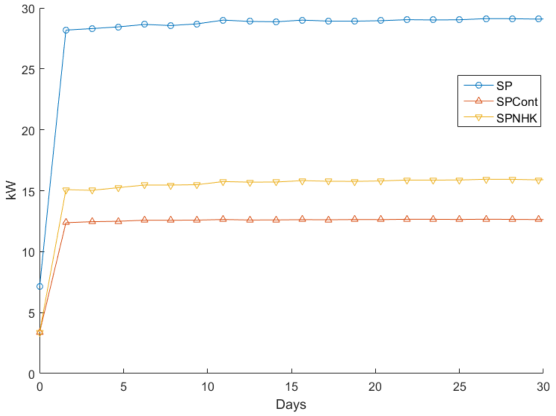

Figure 6-16. Node power

6.4.3. Analysis for Scenario 3: Heavy Traffic

As we can see in Figure 6-17, the success rate of the network drops quite a bit by about 20%. However, the overlapping success rate of SP and SPNHK is about 3% higher compared to the SPCont. SPNHK and SP try to use any possible route and resource to establish the lightpath. The level of congestion in Figure 6-18, shows that the network is almost completely congested as the average of 13 out of 16 available to assign Lambdas of the links are already established and taken. As mentioned earlier this situation happens when SP and SPNHK assign the resources for the routes that are longer on an average trying to bypass the congested links and establish the lightpath. As we can see in Figure 6-19, SP and SPNHK chose any remaining route and available resources to establish the lightpaths and therefore, the average route length is about 38% longer compared to SPCont. By increasing the route length, the probability of having more Lambda conversion is increased and therefore SPNHK behaves almost the same as SP with only 14% less conversion as we can see in Figure 6-20. However, SPNHK consumes about 26% less energy to give the same success rate of SP which is about 2.5% to 3% higher than SPCont as shown in Figure 6-21. Depending on the value of the connections requests, 3% more success rate may or may not be reasonable to spend 38% more resources and 47% more energy compared to SPCont. However, since the assignment process is separated from the routing process, depending on the congestion condition of the network different assignment mechanisms can be used that are more energy and resource efficient than FF. We can conclude that it is reasonable to use NHopAking when the traffic intensity of the network is low to moderately high, to gain more success rate and save energy. However, it may be reasonable to switch to the continuous assignment of resources when traffic intensity is higher, and the network is congested. The average number of assigned Lambdas for a link is a good indication of the congestion level of the network.

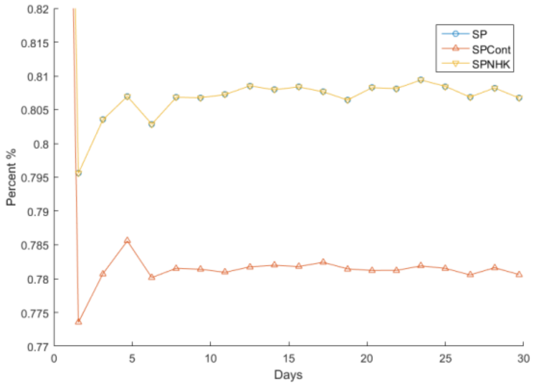

Figure 6-17. Success rate

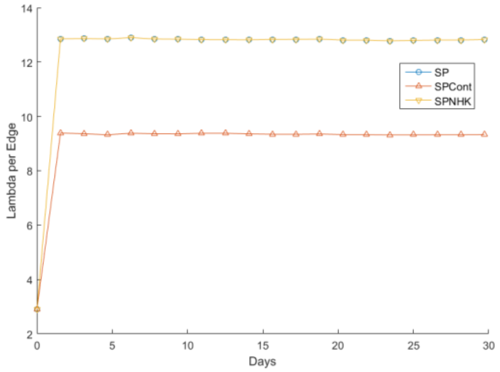

Figure 6-18. Lambda per edge

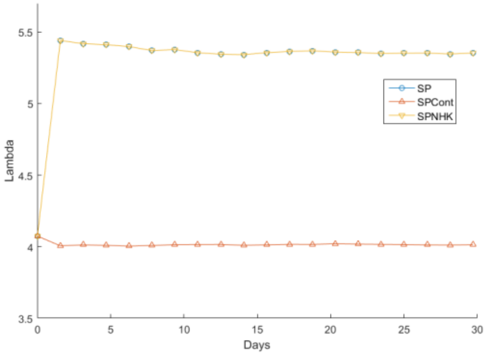

Figure 6-19. Lambda per connection

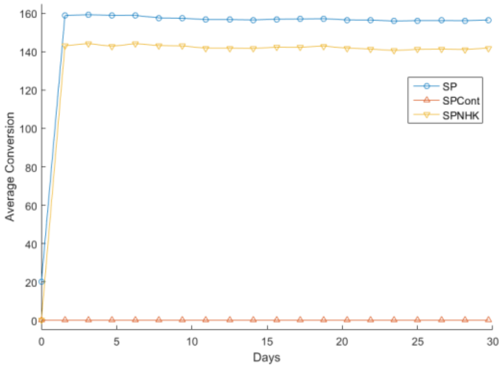

Figure 6-20. Lambda conversion count

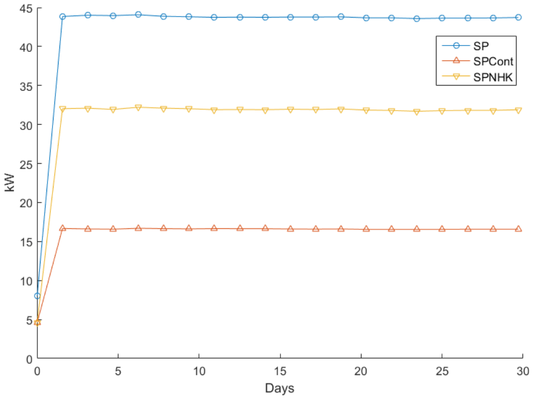

Figure 6-21. Node power

6.4.4. Confidence Interval Analysis

It is understood that the reader of this chapter may argue that many aspects of the simulation section are random and there may be no guarantee to observe the same results by repeating the simulation. Therefore, this text-based section presents the analysis on Confidence Intervals (CIs) of the performance metric. Using Minitab in [21], the mean and the 95% CI over the average of the mean is computed for four important performance metrics with 70 independent and parallel runs of the simulation, equivalent to processing and analyzing 5.6 million connection requests. The traffic intensity chosen for this analysis is the arrival rate of 100 connections per hour with the same 30-minute average duration. 100 connections per hour was chosen to push the network to even more congestion level of scenario 2 but avoiding almost the complete congestion of scenario 3 with more than 20% drop in success rate. The analysis for an average of mean success rate in Table 6-2 shows about 8% more success rate for SPNHK compared to SPCont in the "busy time". It is also important to notice that the 95% CIs of SPNHK and SPCont do not overlap at all which means SPNHK will have a higher success rate at 100 connections per hour. The analysis for route length average in Table 6-3 shows that SPNHK will increase the length of the routes on an average to use all available resources and ensure higher success rate of the network. The CI of the SPNHK for average route length confirms that resources of longer routes will be assigned. The results of CI analysis for node power in Table 6-4 shows that SPNNHK is about 35% more energy efficient compared to SP. There is no overlapping between CIs of the SP and SPNHK. Finally, for the number of Lambda Conversion in Table 6-5, we can see that SPNHK has about 33% less number of conversions compared to SP. The CIs of SPNHK and SP do not overlap.

Table 6-2. 95% Confidence interval over mean of success rate

Variable	Mean	StDev	SE Mean	95% CI
SP	0.938834	0.002763	0.00033	(0.938175, 0.939492)
SPCont	0.864415	0.002121	0.000254	(0.863909, 0.864921)
SPNHK	0.938834	0.002763	0.00033	(0.938175, 0.939492)

Table 6-3. 95% Confidence interval over mean of route length

Variable	Mean	StDev	Mean	95% CI
SP	4.98931	0.02615	0.00313	(4.98308, 4.99554)
SPCont	4.13763	0.00996	0.00119	(4.13526, 4.14001)
SPNHK	4.98931	0.02615	0.00313	(4.98308, 4.99554)

Table 6-4. 95% Confidence interval over mean of node power (kW)

Variable	Mean	StDev	Mean	95% CI
SP	37.6009	0.2301	0.0275	(37.5460, 37.6557)
SPCont	14.533	0.0527	0.0063	(14.5205, 14.5456)
SPNHK	24.2334	0.2444	0.0292	(24.1751, 24.2917)

Table 6-5. 95% Confidence interval over mean of number of Lambda conversions

Variable	Mean	StDev	Mean	95% CI
SP	128.494	1.186	0.142	(128.211,128.776)
SPCont	0	0	0	(0.000000, 0.000000)
SPNHK	86.678	2.067	0.247	(86.185, 87.171)

6.5. Summary and Future Work

Based on results obtained in this chapter, it can be concluded that NHopAking is as good as a Continuous method regarding the success rate and resource utilization when traffic intensity is light. With higher traffic intensity NHopAking uses more resources to keep the success rate higher, compared to the continuous method. Although NHopAkind is using longer routes to establish the lightpaths, it uses (35-50)% less energy to give the same success rate of the First Fit method. In any case, the number of Lambda conversions performed by NHopAkind is lower than the First Fit for the same success rate. In the busy times of the network, NHopAKind gives up to 8% more success rate compared to the continuous method which can be considered as 8% more income for the service provider.

NHopAkind method will be tested with different average durations of the lightpaths and a higher number of the available resources per link, in future.

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Chapter 7 SUMMARY AND FUTURE WORK

This chapter summarizes the contributions of this thesis. With the stateless routing mechanisms of Chapter 3, the throughput of the control plane of the GMPLS network can be increased by 6-fold when compared to traditional routing mechanisms that perform the routing operation on arrival of the connection request. The FL-EASB introduced in Chapter 3 can use the futuristic information to handle the maintenance windows (Not using a link in maintenance window). Furthermore, T-EASB and FL-EASB are examples of the routing mechanisms to be used with a stateless mechanism. Any other routing such as the routing mechanism introduced in Chapter 5 can be used to populate the routing table on the fly or use the predicted information. As the resource assignment is done separately, any resource assignment such as the one introduced in Chapter 6 can perform the resource assignment with the stateless approach. As future work, the success rate of T-EASB and FL-EASB will be tested with the newly proposed resource assignment of Chapter 6. The Table Driven Constrained Least Emission T-CLE routing mechanism will also be developed to improve the throughput of the control plane that is using CLE-C mechanism.

Chapter 4 showed the importance of developing effective green routing mechanisms as they perform better than traditional routing mechanisms that adopt the GSLA for reducing the emission of the network. Chapter 4 also showed that by adopting GSLA by traditional non-green mechanism would not give the accepted resource efficiency and will have increased resource utilization, again, in return for an unacceptable reduction in emission. It was shown that by as low as 20% increase in the amount of available green energy in the network connection requests with much higher GSLA requests of up to 80% can be accommodated with 90% success rate. The effect of adding Green SLA (using the realistic energy and emission information of Chapter 5) on the behavior of key performance metrics of the optical network will be evaluated.

Chapter 5 introduced a Multi-SLA aware routing mechanism which is more practical to be implemented in the control plane of the GMPLS network. The CLE and EE outing mechanism form a highway over greener links. CLE-C provides 100% Satisfaction for ASLA and DSLA and emits the least emissions compared to other routing mechanisms. By analyzing the outcome of simulation for 2 million connection requests and performing the CI analysis it can be confirmed that the obtained results are acceptable. Chapter 5 also computed the realistic information for the testbed. Table A-1 is the result of gathering more that 50,000 records and it is expected that this energy table will be used by other papers that need the set of realistic information for energy and emission in any networking field. The results of Chapter 5 have been obtained by interfacing MATLAB with a state of the art optimization solver, Gurobi. For connecting these two softwares, Chapter 5 used a newly developed code in MATLAB that is going to be shared in "MATLAB Central" for public use. Future work will add a set of new device and energy specific constraints to the formulation of CLE to make it even more practical and usable. For example, the constraint of the maximum energy draw possible per node will be added. The performance of CLE with NHopAkind resource assignment method for the higher intensity of the traffic will also be evaluated.

Chapter 6 developed and tested a new assignment mechanism that can increase the success rate of the network when traffic intensity is higher than normal. The NHopAKind resource assignment provided up to 8% more success rate compared to FF with continuity constraint while using 37% less energy compared to FF that provides the same success rate. Chapter 6 suggested switching between resource assignment mechanisms depending on the congestion level of the network. Similar to Chapter 5 for performing the CI analysis Chapter 6 combined and used the data resulting from processing 5.6 Million connection requests. With this analysis, it was confirmed that results obtained for the performance of NHopAKind are comparable or better than FF with the continuity constraint. The success rate of the network when pairing NHopAkind with different routing mechanisms will be studied in future work.

The routing and assignment mechanism provided in the thesis can be used with any Link-State environment and can be ported to other controller based systems such as SDN controllers.

Appendix A. Total Generation Capacity in the US in 2011

Numbers in units of MW.

Table A-1. Total generation capacity in the US in 2011

States\Source	Pumed	Wind	Hydro	Solar	Nuclear	Geo Thermal	Coal	Natural Gas	Other Gas	Bio Mass	Wood	petroleum
AK	0	0	0	0	0	7.4	413.95	0	0	881.25	698.95	110.95
AL	0	0	0	593.15	0	0	3221.8	5089.25	82.8	12609.55	45.05	11478.65
AR	28	21.1	0	311.2	0	0	1336.2	1844	0	8038	22	4535
AZ	216.3	6.8	0	28	128.55	138.1	2720.4	3937	0	14017.55	100.7	6227.5
CA	3839.45	407.15	2055.95	640.5	589.25	3768.4	10123.95	4390	212.6	41775.9	527.45	411.7
CO	562.5	13.6	0	0	85.5	1792.9	657	0	0	5510.1	188.5	5605.2
CT	29.2	174.6	0	0	0	0	123.6	2109.5	0	3083	3278.55	566.45
DC	0	0	0	0	0	0	0	0	0	10	790	0
DE	0	8	0	0	12.5	2	0	0	135	2286	116.8	794
FL	0	666.85	0	359	64.6	0	54.5	3970.5	0	34962.8	10970.75	10253.5
GA	1861.5	24.2	0	623.9	0	0	2046.25	4061	0	15009.45	1390.1	13007.75
HI	0	222.25	31	0	2.2	91.6	23.55	0	12.2	0	2001.4	180
IA	0	14.6	0	0	0	4206.55	141.5	611.75	0	2501.05	1071.1	6947.9
ID	0	12.3	11.1	75.8	0	611.3	2654.2	0	0	879.25	5.4	17.2
IL	0	127.8	0	0	9	2737.3	34.1	11560.5	117.7	14562.8	943.4	14956.05
IN	0	53.75	0	0	0	1339.7	60.1	0	535.3	5993.85	472.05	19013.4
KS	0	7.1	0	0	0	1271.8	2.65	1190	0	4661.2	550.9	5188.2
KY	0	16.8	0	57.85	0	0	792.9	0	0	5327.85	73.4	15395.85
LA	0	13.9	0	311.35	0	0	192	2145	33.3	19390.65	997.9	3419
MA	1680	270.85	0	25.7	11.3	29.65	263.25	684.7	0	6430.65	3230.6	1579.55
MD	0	137.9	0	2.1	4.4	120	590	1719.5	152.35	2106.95	2998.45	4890
ME	0	91.15	0	609.85	0	322.5	743.8	0	0	1725.2	1016.1	90
MI	1851.3	184.55	0	263.8	0	374.6	235.35	4044.1	0	11687.15	707.3	11514.15
MN	0	210.9	0	162.15	0	2576.6	197.45	1633.5	0	5188.25	852.3	4713.1
MO	667	7.7	0	0	0	458.5	567.65	1215	0	5811.3	1316.7	12486.1
MS	0	0	0	228.6	0	0	0	1195.5	4	11979.55	37.5	2546
MT	0	0	0	0	0	378.2	2742.3	0	1.5	390.5	55.5	2442.3
NC	76.75	43.1	0	480	39.1	0	1956.9	5073	0	8492.95	596	12370.95
ND	0	9.8	0	0	0	1422.9	508	0	8.4	10.1	72.05	4151.3
NE	0	10.9	0	0	0	332.5	278.2	1244.5	0	1776.3	363.2	4108.3
NH	0	29.8	0	128.85	0	24	495.2	1246.45	0	1284.9	508.9	549.95
NJ	400	213.75	0	0	145.65	7.5	5.25	4192.6	0	10618.15	1472.75	1992.85
NM	0	6.5	0	0	129.5	750.2	82.9	0	0	3365.55	4.4	3990
NV	0	0	358.8	0	125	0	1051	0	0	7511.7	11.4	2873.8
NY	1400	363.9	0	86.1	31.5	1398.9	4334.95	5253.75	0	19618.1	5390.5	2815.55
OH	0	58.3	0	63.65	22.4	159.7	104.65	2155	116.2	8747.55	1095.15	21300.4
OK	260	15.7	0	57.8	0	1810.8	858.2	0	0	13607.8	69.3	5312
OR	0	35.9	0	243.35	2.6	2208	8426.35	0	0	3151.65	0	585
PA	1521	433	0	107.2	17.95	789.3	772.6	9784	105.2	10308.05	4473.7	18181.1
RI	0	23.7	0	0	0	1.5	2.7	0	0	1836.8	17.4	0
SC	2716	33.7	0	257	0	0	1337.6	6572.5	0	5698.85	736.5	7284.25
SD	0	0	0	0	0	780	1594	0	0	730.6	247.25	496.6
TN	1616.3	6.8	0	185.25	0	29.1	2525.75	3456.1	0	5042.5	39.6	8657.1
TX	0	127.2	0	215.15	43.5	10361.75	689.3	4990	310.9	70802.35	208.85	23258.4
UT	0	9	45.5	0	0	324.4	251.8	0	0	2061.35	27.8	4903
VA	3241	295.1	0	363.65	0	0	892.05	3596.5	0	8666.05	2448.65	5905.95
VT	0	3.2	0	76.75	2.2	45.1	324.65	624.15	0	0	116.55	0
WA	314	64.6	0	319.7	0.5	2453.5	20969.9	1117.5	0	4026.1	15.2	1340
WI	0	88.1	0	236.1	0	615.45	383.95	1756	0	6416.9	800.7	8440.1
WV	0	2.2	0	0	0	528.1	289.2	0	0	1098.9	13	15527.1
WY	0	0	0	0	0	1412.4	305.65	0	99.15	130.7	5.8	6499.4

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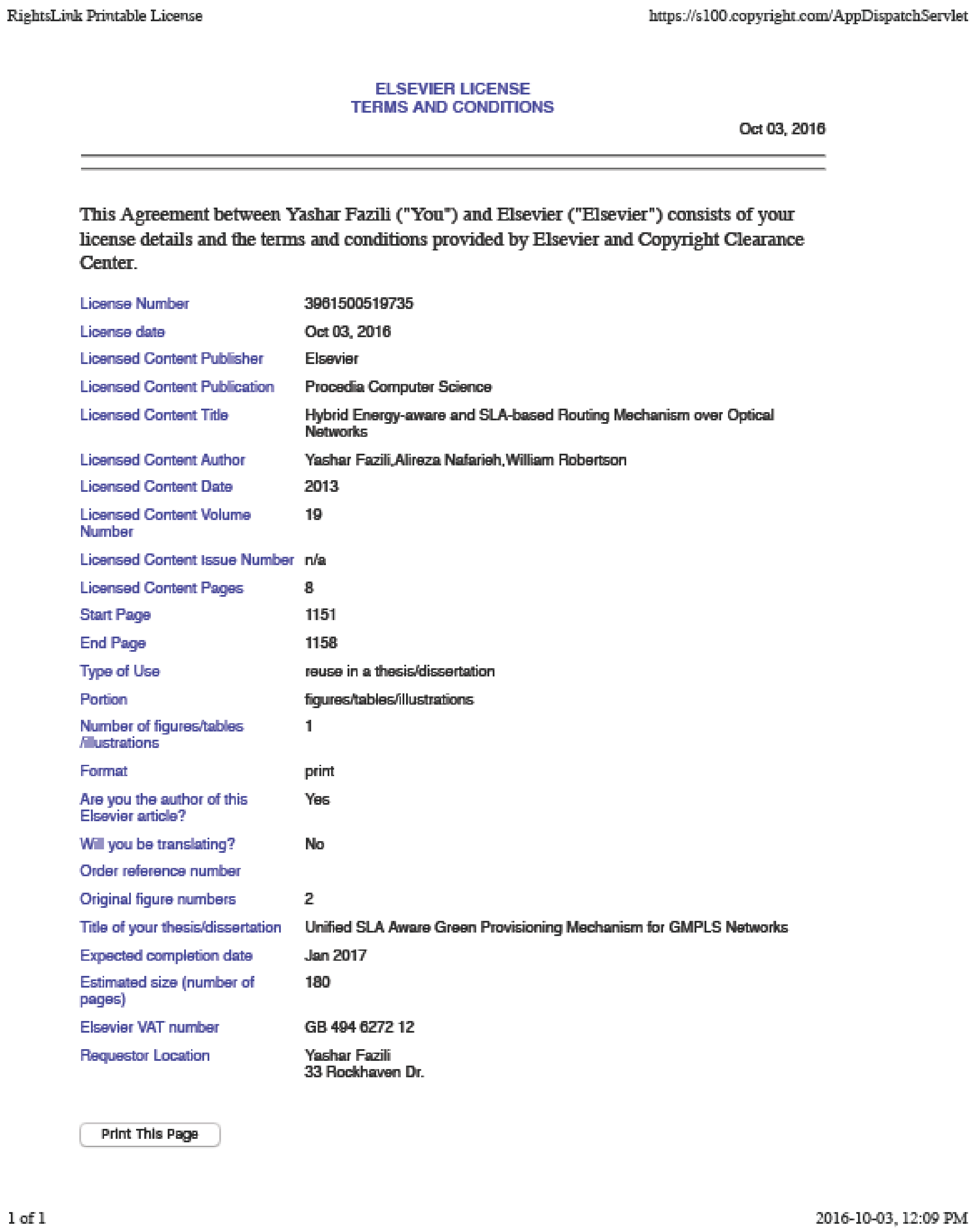

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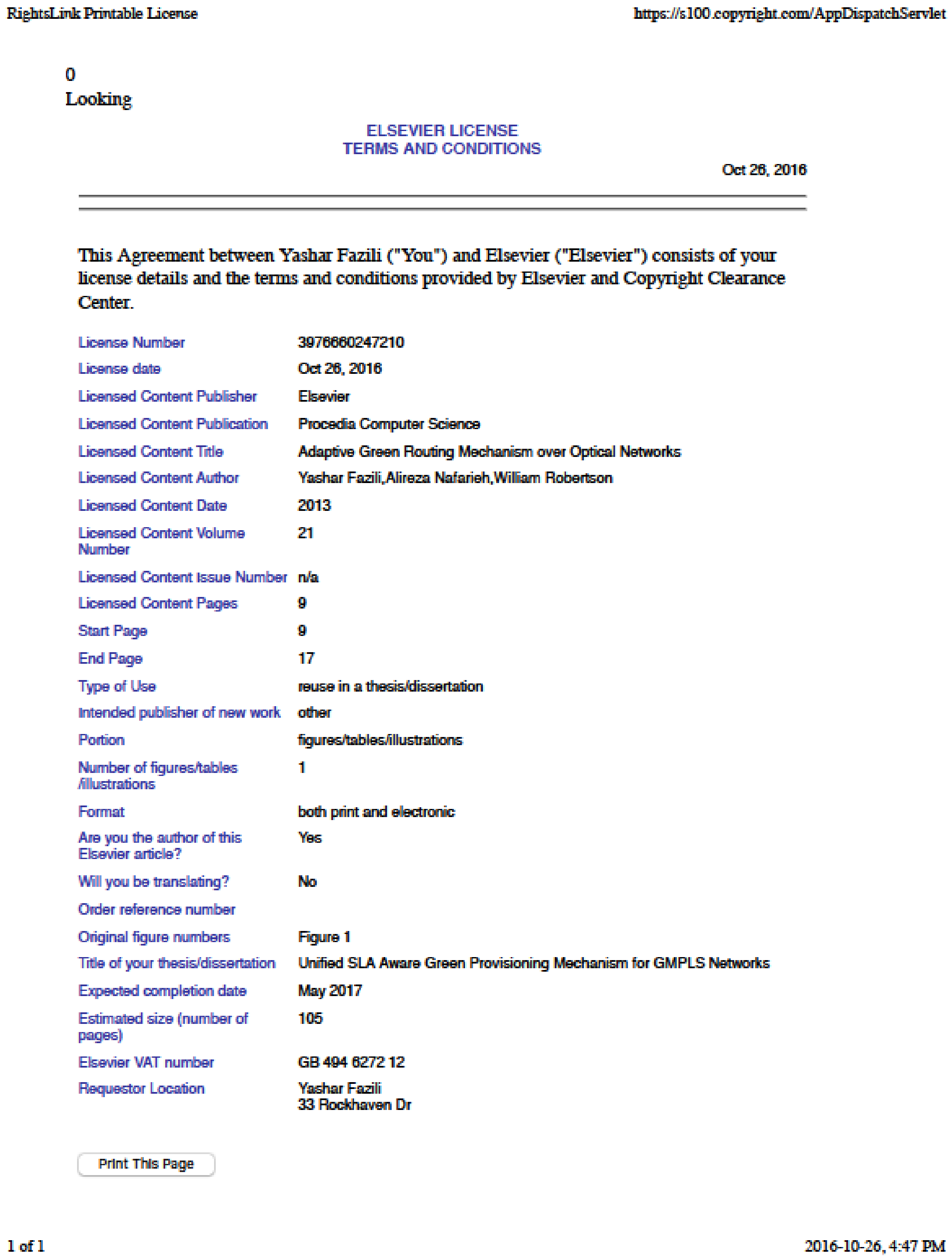

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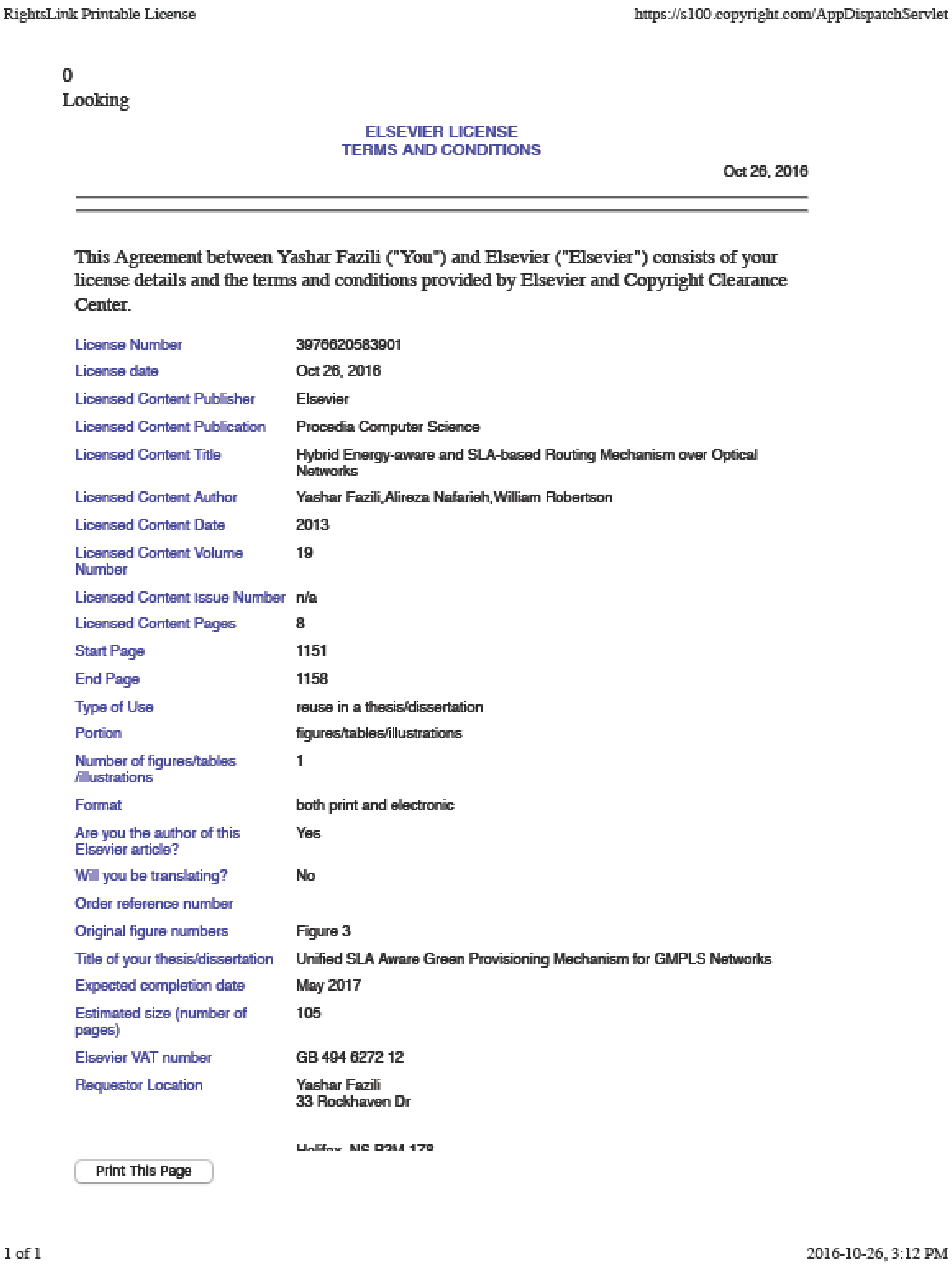

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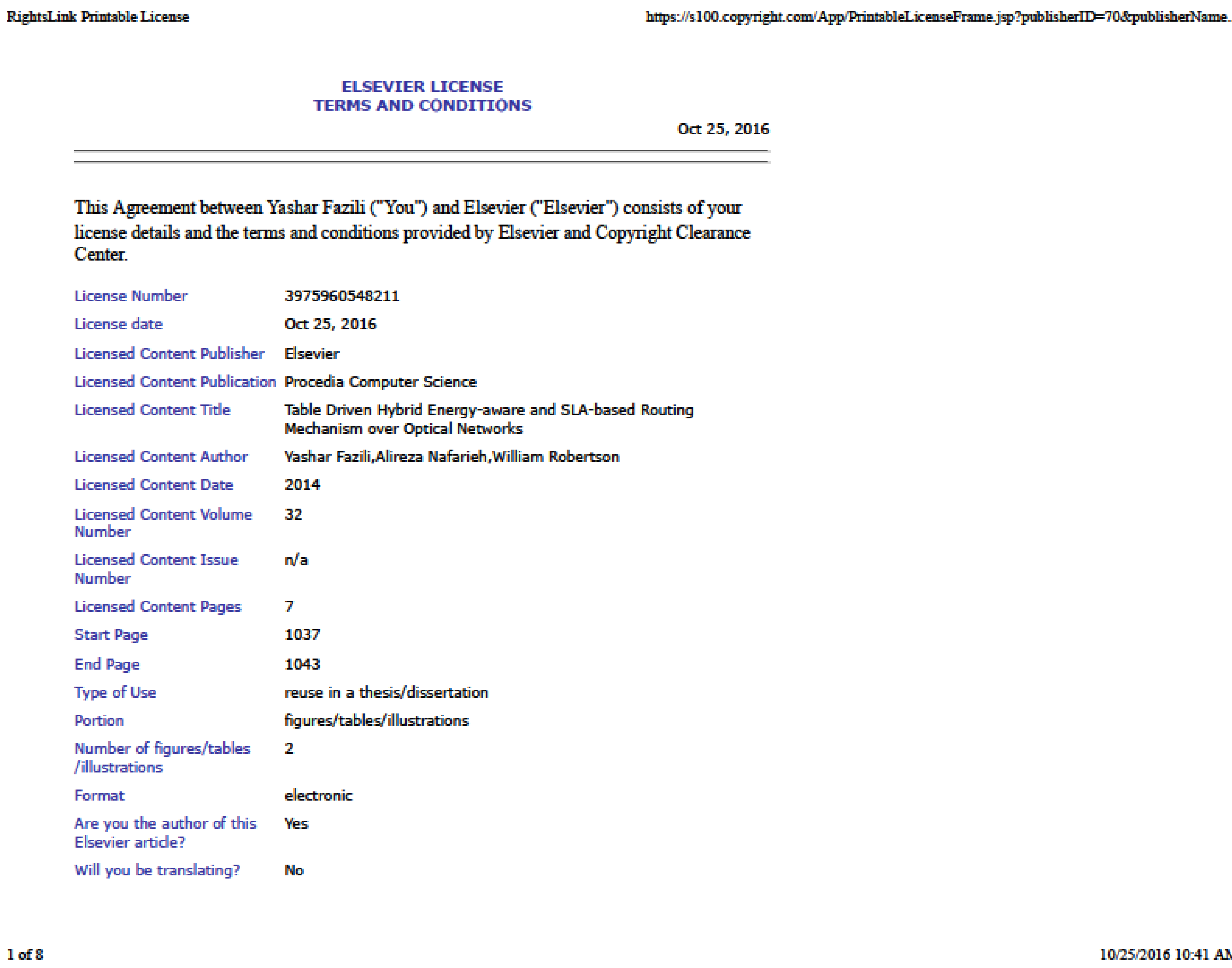

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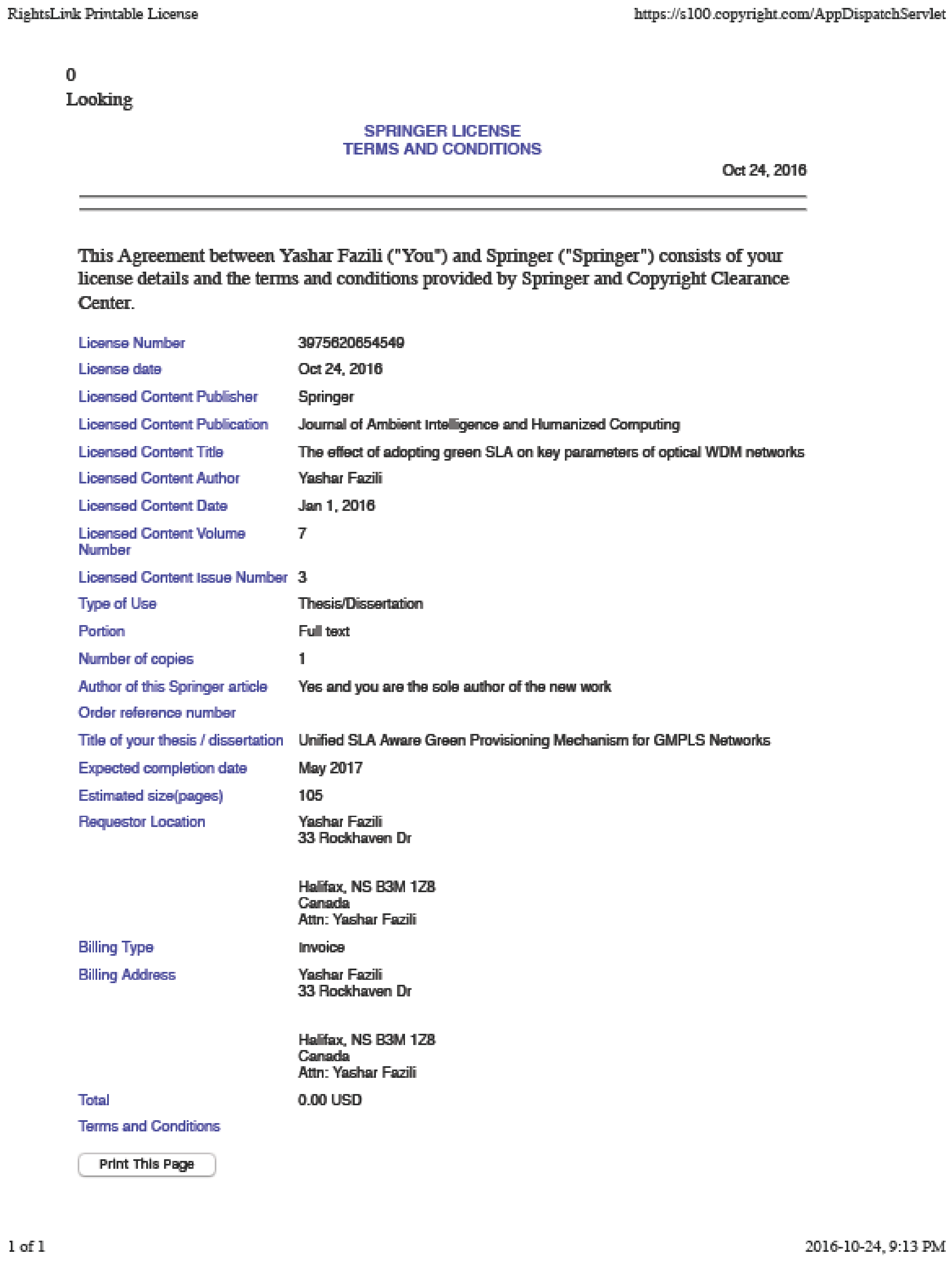

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