

A Novel Strategy to Optimize Capacity Utilization in Optical Networks

Anand Raj Gautam^a, Brijendra Mishra^a, Ashish Kumar Pandey^b, Ashutosh Kumar Singh^{c*}

^aDepartment of Electrical & Electronics Engineering, Vikrant University, Gwalior, India – 474006

^bDepartment of Computer Science & Engineering, I.E.T., Dr. Rammanohar Lohia Avadh University, Ayodhya, India -224001

^cDepartment of Electronics & Communication Engineering, I.E.T., Dr. Rammanohar Lohia Avadh University, Ayodhya, India -224001

E-mail: anandrajgautam@gmail.com (A. R. Gautam), soet_brijendra@viirantuniversity.ac.in (B. Mishra), ashishkumpandey@rmlau.ac.in (A. K. Pandey), and aksinghelectronics@gmail.com (A. K. Singh)

Abstract— Reducing costs is a primary objective in optical fiber network design. Multiwavelength optical devices represent an innovative technology that increases network capacity while lowering expenses, offering a more cost-effective alternative to installing traditional equipment. In this article we discuss the different capacity optimization technique in a survivable optical network. The spare capacity allocation (SCA) techniques for node-arc formulation of link restoration (NAFLR) model, and joint capacity allocation (JCA) model have been thoroughly discussed and compared in this manuscript. The obtained results show that the JCA model utilizes minimum spare capacity in compare with NAFLR model.

Keywords— Spare capacity allocation, Optical networks, Link restoration and Survivability.

Introduction

Over the past two-three decades, capacity requirement and reliability have remained essential constants in the architectural evolution of optical networks. Optical amplifier technology, along with wavelength division multiplexing (WDM) and dense WDM (DWDM), play a crucial role in fulfilling scalability and capacity needs in a cost-efficient way. Due to the ability of each individual wavelength to transmit data at speeds greater than 10 Gbps and the capacity of the commercial systems to multiplex up to 164 wavelengths on a single fiber strand, the extensive capabilities greatly increase the consequences of physical link failures [1]. Consequently, the failure of one fiber strand can disrupt millions of users, resulting in substantial revenue losses. In optical networks, a single wavelength channel can support transmission rates of several Gbps, the failure of a fiber link can result in the loss of numerous connection streams. Therefore, guaranteeing survival has turned into a crucial necessity in the design of WDM based optical networks [1].

Network survivability refers to a telecommunication networks capacity to maintain service during failure, encompassing both planning and operational dimensions [2]-[4]. Survivability planning involves several protection techniques that allocate spare capacity to be utilized when a failure occurs. Operationally, these protection techniques are executed through restoration mechanism that activate to restore service to all affected customers during link failure.

Previously several research works have been done in the field of capacity allocation and survivability techniques. In [5], the authors present a step-by-step process designed to enhance fixed alternate shortest path routing in the framework of dynamic RAW techniques in wavelength routed optical networks. The effectiveness of this strategy is evaluated against the Yen and Dijkstra based algos, along with the newly developed most efficient shortest path

algo, particularly in relation to blocking probability. Research finding indicate that it is indeed possible to select a suitable route for each node pair from the shortest paths, thereby effectively balancing the network load.

In [6], a dynamic resilience model has been introduced, aimed at routing flows to minimize the total bandwidth utilized for both protection and working paths. This strategy employs path protection; this leads to decrease costs and is highly appropriate for worldwide optimization. If a link stop working, all traffic that relies on that link will be rerouted to specific paths that were decided in advance. The obtained results suggest that this model is considerably more efficient and delivering enhanced QoS regarding utilization of network resource and other metrics when compared to traditional restoration and protection methods.

In [7], a survivability plan called DHMBC for optical networks was presented to reduce network blocking probability, resource usage, and enhance throughput. This technique selects the suitable method for backup paths allocation depending on where the failure occurs in the telecommunication network. The obtained results demonstrate that the presented fault recovery methods are more effective than traditional protection techniques regarding various network performance metrics. This approach combines the advantages of both restoration and protection model, making it feasible for implementation to ensure resilience in future high speed optical networks.

In [8], the research paper presents a dual link-based fault recovery strategy that utilizes a protection cycle based technique. This approach employs a replica property for p-cycle ring to enhance the path base protection (PR). These techniques are employed to protect the network node when a similar protection cycle or ring exists within the network. In [9], the authors presented a novel method for calculating both working and spare capacity through a mathematical ILP model referred to as the JCA model. In this proposed model, working and restored traffic are routed together. Consequently, the JCA model necessitates less capacity compared to other optimization models. In [10], the authors have introduced an enhanced technique using link state and path prediction analysis for efficient slots of frequency allocation and recycle the bandwidth for all the data centers linked directly via elastic optical networks.

In [11], the authors have introduced a novel WDM architecture that incorporates optical add drop multiplexers (OADMs), system performance monitoring, and dynamic bandwidth allocation to ensure optimal use of telecommunication systems. The dynamic allocation strategies of an optical resources, facilitated by the adjustability of wavelength division multiplexing, allows for greater flexibility in bandwidth and leads to lower operation costs. In [12], the authors tackle the challenge of survivability techniques within mixed grid or heterogeneous networks. The study introduced a mathematical technique, relevant constraints, and simulation outcomes for recovery of connection utilizing DPP and partial path protection (PPP) techniques.

This research paper introduces the fundamental optimization techniques for spare capacity allocation in optical network to guarantee network resilience. The main concern is the optimal distribution of this capacity within an existing network to support specific restoration and protection strategies, assuming the network topology has already been established. In this study, we explore various methods for optimizing capacity in a survivable telecommunication network based on mesh topology. The spare capacity allocation (SCA) techniques for NAFLR model, and JCA model have been are thoroughly discussed and compared in this manuscript. The remaining part of the paper is structured in the following manner. A mathematical programming based SCA model for NAFLR model, and JCA model have been presented in Section II. Section III presents the results analysis of example networks, NFSNET, and European Network for model, and JCA model. Finally, conclusions are drawn in section IV.

Problem Formulation

A mathematical programming based SCA model for NAFLR model, and JCA model have been presented in this section. The fiber networks consist of set of links and nodes. For both SCA models, a link represents a two-way connection between pair of nodes. Hence a node has the ability to transmit messages bidirectionally, either from source i to destination j or j to i . A graph is defined by $[N, L]$, with N denoting the nodes in the set and L indicating the connections between these nodes. A directed graph that represents a network is usually symbolized

as $G = [N, A]$. An arc, which corresponds to a link, is represented by A . The notation d_{ij} signifies the demand from i to j , while D represents the demand pair sets across each link.

The variable c_{ij} indicate the working or operational traffic on connection (i, j) , and variable h_{ij} represents the spare capacity allocated to link (i, j) . The flow restoration on arc (i, j) when the link (s, t) cut or fail is denoted by variable r_{ij}^{st} . If link (s, t) cut or fails, f_{st} flow units need to be rerouted form s to t and vice versa from t to s . In the NAFLR model, the requirement is expressed as follows:

$$q_i^{st} = \begin{cases} f_{st}, & \text{if } i = s, \\ -f_{st}, & \text{if } i = t, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

SCA technique for NAFLR technique is expressed as:

Total capacity optimization:

$$\sum_{(i,j) \in L} (c_{ij} + h_{ij}) \quad (2)$$

Case of conservation of flow:

$$\sum_{(k,j) \in A} r_{kj}^{st} - \sum_{(i,k) \in A} r_{ik}^{st} = q_i^{st} \quad \forall k \in N \quad \forall (s, t) \in L, \quad (3)$$

Normal and reverse direction capacity:

$$r_{ij}^{st} \leq h_{ij} \text{ and } r_{ji}^{st} \leq h_{ij} \quad \forall (i, j) \in L \quad \forall (s, t) \in L, \quad (4)$$

Case of link failure:

$$r_{st}^{st} + r_{ts}^{st} = 0 \quad \forall (s, t) \in L, \quad (5)$$

Let $T = U_{(i,j \in D)} P_{ij}$, here U signifies the set of cycles and P_{ij} represents the collection of directed routes form i to j . The flow along path p is indicated by Y_p and the paths form node i to j are represented by K_{ij} . In the event of a link (s, t) failure, the flow of restoration on path p is denoted as w_p^{st} and set V_{ij}^{st} represents the directed paths for restoration form i to j . The mathematical representation of the SCA technique for NAFLR model is as follows:

Total capacity optimization: (Use equation 1)

Equation for demand across the link:

$$\sum_{p \in P_{ij}} Y_p = d_{ij} \quad \forall (i, j) \in D \quad (6)$$

Equation for normal and reverse direction capacity:

$$\sum_{p \in K_{ij}} Y_p = c_{ij} \text{ and } \sum_{p \in K_{ji}} Y_p = c_{ij} \quad \forall (i, j) \in L \quad (7)$$

Equation for spare demand 1 and demand 2 across the link:

$$\sum_{p \in V_{ij}^{st}} w_p^{st} = \sum_{p \in \bar{V}_{ij}^{st}} Y_p \text{ and } \sum_{p \in V_{ji}^{st}} w_p^{st} = \sum_{p \in \bar{V}_{ji}^{st}} Y_p \quad \forall (s, t) \in L \quad \forall (i, j) \in D \quad (8)$$

Equation for normal and reverse direction spare capacity:

$$\sum_{p \in K_{ji}} w_p^{st} \leq h_{ij} \text{ and } \sum_{p \in K_{ji}} w_p^{st} \leq h_{ij} \quad \forall (s, t) \in L \quad \forall (i, j) \in L \quad (9)$$

Non-negativities are expressed as:

$$\begin{aligned} c_{ij} &\geq 0 \quad \forall (i, j) \in L, \\ h_{ij} &\geq 0 \quad \forall (i, j) \in L, \\ r_{ij}^{st} &\geq 0 \quad \forall (s, t) \in L \quad \forall (i, j) \in A, \end{aligned}$$

$$w_p^{st} \geq 0 \quad \forall (s, t) \in L \quad \forall p \in T.$$

NAFLR model, and JCA model for SCA planning was evaluated using five types of networks: Network A, Network B, Network C, NFSNET, and European Network. Fig. 1 illustrates Network A, which comprises 06 nodes and 09 links, while table 1 provides the corresponding demand matrix.

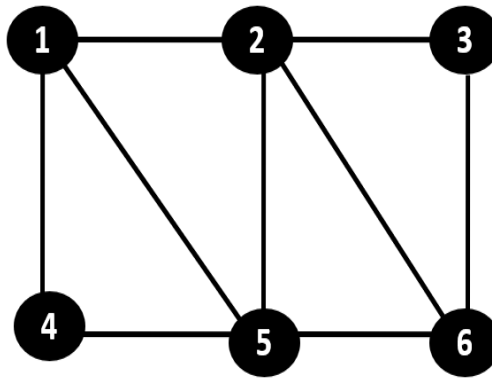


Figure 1. Example Network A

Table 1. Demand matrix table for Network A.

Node	1	2	3	4	5	6
1	--	10	0	10	10	0
2	0	--	10	10	10	10
3	0	0	--	0	10	10
4	0	0	0	--	10	0
5	0	0	0	0	--	10
6	0	0	0	0	0	--

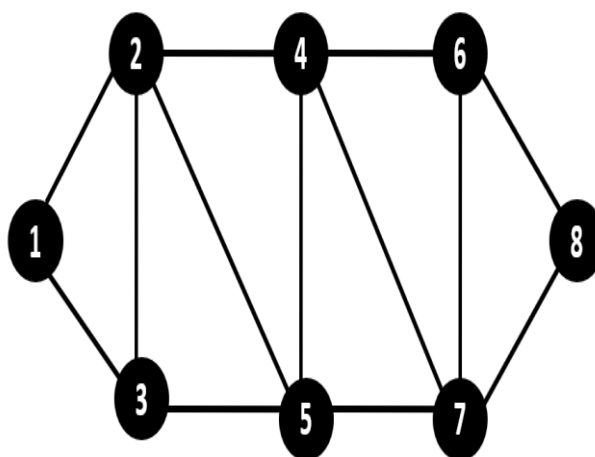


Figure 2. Example Network B

Table 2. Demand matrix table for Network B.

Node	1	2	3	4	5	6	7	8
1	--	20	20	0	0	0	0	0
2	0	--	20	20	20	0	0	0
3	0	0	--	20	20	0	0	0
4	0	0	0	--	20	20	20	0
5	0	0	0	0	--	20	20	0
6	0	0	0	0	0	--	20	20
7	0	0	0	0	0	0	--	20
8	0	0	0	0	0	0	0	--

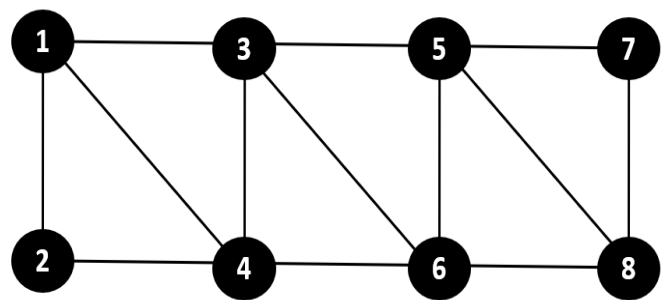


Figure 3. Network C

Table 3. Network C demand matrix.

Node	1	2	3	4	5	6	7	8
1	--	20	20	20	0	0	0	0
2	0	--	20	20	0	0	0	0
3	0	0	--	20	20	20	0	0
4	0	0	0	--	20	20	0	0
5	0	0	0	0	--	20	20	0
6	0	0	0	0	0	--	20	20
7	0	0	0	0	0	0	--	20
8	0	0	0	0	0	0	0	--

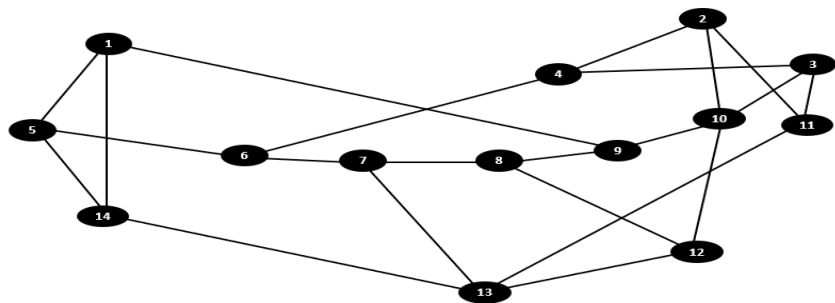


Figure 4. NFSNET

Table 4. NFSNT demand matrix.

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	---	0	0	0	10	10	0	10	10	10	0	0	10	10
2	0	---	10	10	0	10	0	0	10	10	10	10	10	0
3	0	0	---	10	0	10	0	0	10	10	10	10	10	0
4	0	0	0	---	10	10	10	0	0	10	10	0	0	0
5	0	0	0	0	---	10	10	0	10	0	0	0	10	10
6	0	0	0	0	0	---	10	10	0	0	0	0	10	10
7	0	0	0	0	0	0	---	10	10	0	0	10	10	10
8	0	0	0	0	0	0	0	---	10	10	0	10	10	0
9	0	0	0	0	0	0	0	0	---	10	0	10	0	0
10	0	0	0	0	0	0	0	0	0	---	10	10	10	0
11	0	0	0	0	0	0	0	0	0	---	10	10	10	10
12	0	0	0	0	0	0	0	0	0	0	---	10	10	10
13	0	0	0	0	0	0	0	0	0	0	0	---	10	10
14	0	0	0	0	0	0	0	0	0	0	0	0	---	10

Figure 2 illustrates Network B, which includes 13 links and 8 nodes. Table 2 displays the demand chart for Network B. Figure 3 illustrates Network C, which also use 13 links and 8 nodes, while table 3 displays the demand chart for Network C. Figure 4 illustrates NFSNET, which includes 22 connections and 14 nodes. Table 4 displays the demand matrix for NFSNET.

RESULTS AND DISCUSSIONS

The optimization models for the proposed example networks were solved using the AMPL programming language together with CPLEX Solver 12.2. Fig. 5 illustrates the optimal solution of Network A for NAFLR model. The spare capacity of every connection in Network A has been assessed and is shown in figure 5. The result shows the Network A utilizes a total of 100 units of spare capacity. The optimal solution of Network A for JCA model is shown in fig. 6. In the JCA model, Network A has utilized a total of 66 units of spare capacity. Results show that the JCA model utilized 34% less spare capacity in compare with NAFLR model for Network A.

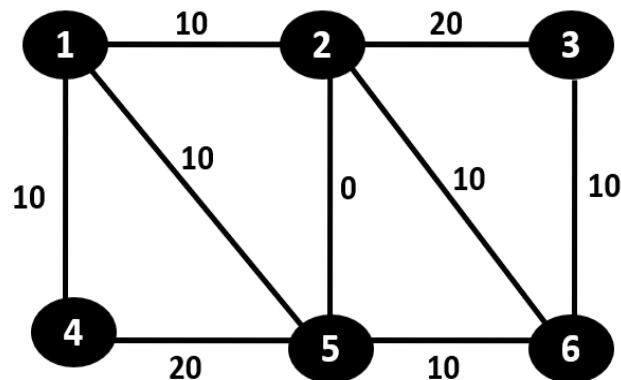


Figure 5. Optimal solution of Network A for NAFLR model.

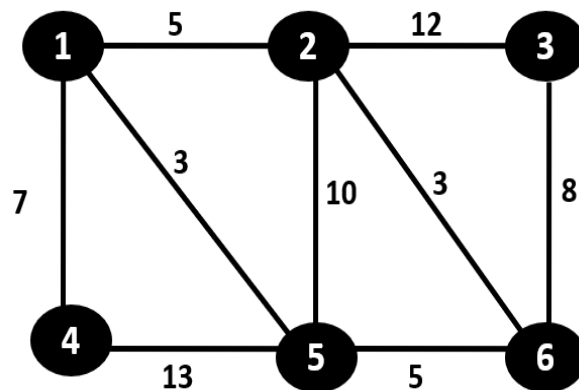


Figure 6. Optimal solution of Network A for JCA model.

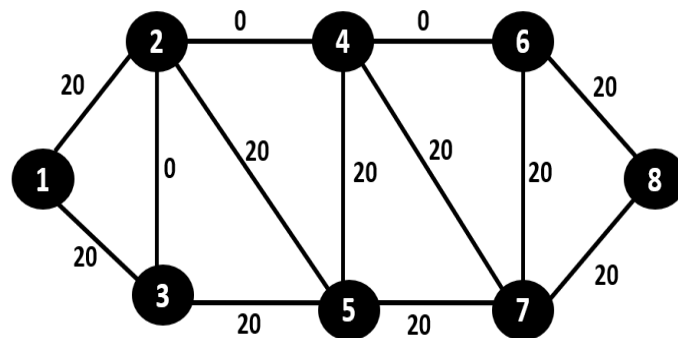


Figure 7. Optimal solution of Network B for NAFLR model.

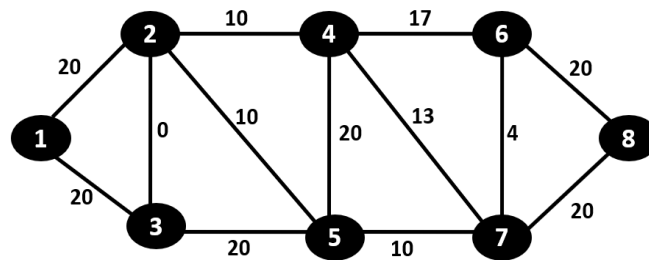


Figure 8. Optimal solution of Network B for JCA model.

Fig. 7 illustrates the optimal solution of Network B for NAFLR model. The spare capacity of every connection in Network B has been assessed and is shown in figure 7. The result shows the Network B utilizes a total of 200 units of spare capacity. The optimal solution of Network B for JCA model is shown in fig. 8. For JCA model, the total spare capacity used by network B is 184 units. Results show that the JCA model utilized 8% less spare capacity in compare with NAFLR model for Network B.

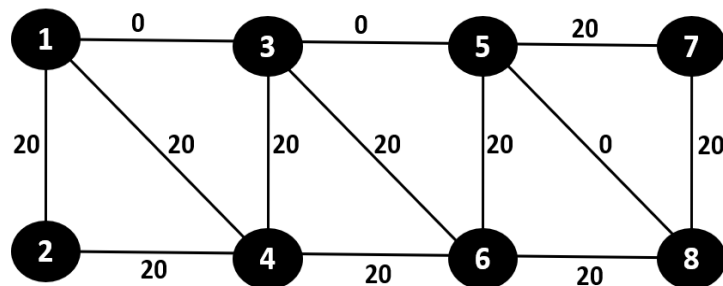


Figure 9. Optimal solution of Network C for NAFLR model.

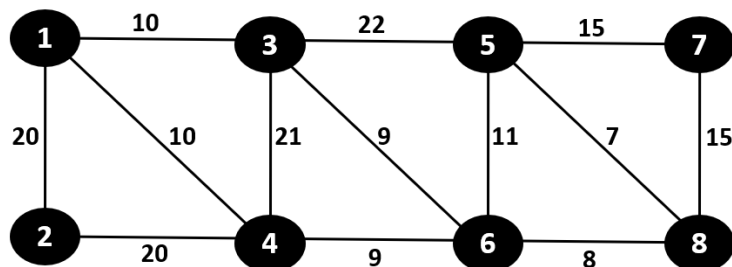


Figure 10. Optimal solution of Network C for JCA model.

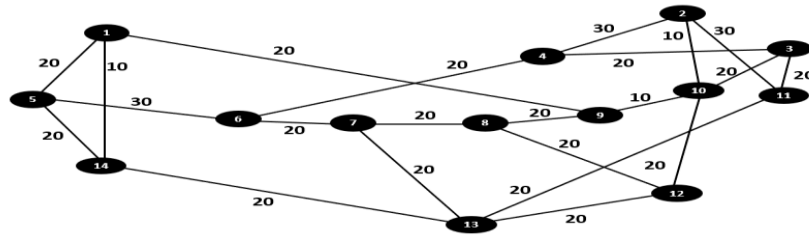


Figure 11. Optimal solution of NSFNET for NAFLR model.

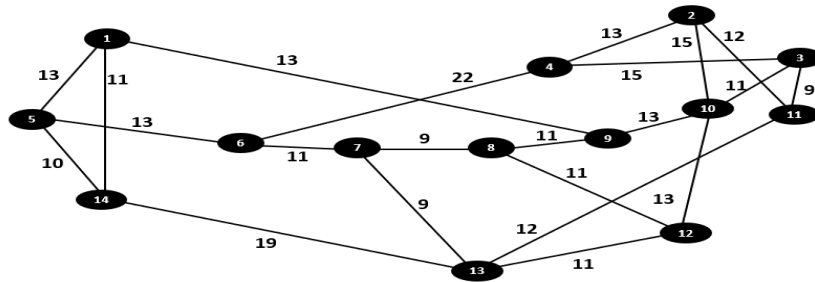


Figure 12. Optimal solution of NSFNET for JCA model.

Fig. 9 illustrates the optimal solution of Network C for NAFLR model. The spare capacity of every connection in Network C has been assessed and is shown in figure 9. The result shows the Network C also utilizes a total of 200 units of spare capacity. The optimal solution of Network C for JCA model is shown in fig. 10. In the JCA model, Network C has utilized a total of 177 units of spare capacity. Results show that the JCA model utilized 11.5 % less spare capacity in compare with NAFLR model for Network C.

Table 5. Summary of spare capacity utilization for different example networks.

Example Networks	Spare Capacity Utilized by NAFLR Model	Spare Capacity Utilized by JCA Model
Network A	100	66
Network B	200	184
Network C	200	177
NSFNET [9]	450	276
European Network [1]	206	168

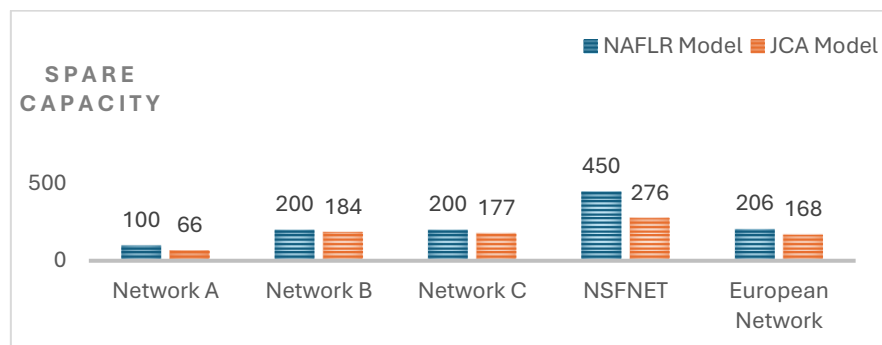


Figure 13. Spare capacity utilization for NAFLR model JCA model.

Fig. 11 illustrates the optimal solution of NSFNET for NAFLR model. The spare capacity of every connection in NSFNET has been assessed and is shown in figure 11. The result shows the NSFNET utilizes a total of 450 units of spare capacity [9]. The optimal solution of NSFNET for JCA model is shown in fig. 12. In the JCA model, NSFNET has utilized a total of 276 units of spare capacity. Results show that the JCA model utilized 38.6 % less spare capacity in compare with NAFLR model for NSFNET. The utilization of spare capacity by European network for NAFLR model and JCA model have been examined in paper [1]. The overall spare capacity employed by the European network for the NAFLR model is 206 units and JCA model utilized 168 units of spare capacity. Results show that the JCA model utilized 18.4 % less spare capacity in compare with NAFLR model for European network. Summary of spare capacity utilization for different example networks (Network A, Network B, Network C, NFSNET, and European Network) are shown in table 5. Comparison of spare capacity utilization for NAFLR model JCA model are shown in figure 13. Clearly, it has been observed that JCA model utilizes minimum spare capacity in compare with NAFLR model.

1. Conclusions

This manuscript introduces the fundamental optimization techniques for spare capacity allocation in optical network to ensure network survivability. In this paper we have discussed the different capacity optimization technique in a WDM base survivable network. SCA techniques for NAFLR model, and joint capacity allocation (JCA) model have been are thoroughly discussed and compared in this manuscript. The obtained results show that the JCA model utilized 34 % less spare capacity in compare with NAFLR model for Network A, 8 % less spare capacity in compare with NAFLR model for Network B, 11.5 % less spare capacity in compare with NAFLR model for Network C, 38.6 % less spare capacity in compare with NAFLR model for NSFNET and 18.4 % less spare capacity in compare with NAFLR model for European network. JCA model typically requires less spare capacity compare with NAFLR model base restoration technique.

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