Comparison of Single-Line Rate for Dedicated Protection on WDM Optical Network Topologies

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***Abstract*—Wavelength division multiplexing (WDM) divides the huge bandwidth available on a fiber into several non-overlapping wavelength channels and enables data transmission over these channels simultaneously. Failure of the optical fiber causes loss of huge amount of data which can interrupt communication. There are several approaches to ensure network survivability. In survivability, we consider dedicated protection in this paper in which backup paths are configured at the time of establishing connections. If a primary path is failed, the traffic is rerouted through backup path with a short recovery time. In this paper, we investigate the performance by calculating the spectrum efficiency variation for dedicated protection in WDM networks. Spectrum efficiency is calculated by dividing the total traffic bit rate by the total spectrum used. In this paper, we carry out the investigation with detailed simulation experiments on different single-line rate (SLR) scenarios such as 100 Gbps, 400 Gbps, and 1Tbps. In addition, this paper focuses on four standard network topologies which consist of different number of links to identify how the spectrum efficiency varies for each network. Our findings are as follows. (1) Spectrum efficiency for each SLR are almost similar and comparable in all the network topologies. (2) Unlike network topology with low number of links, the spectrum efficiency for network topology with high number of links are higher, therefore, the spectrum efficiency increases when the number of links are increased. (3) The spectrum efficiency is lower when the number of primary links are higher even though in all the network topologies.**

Keywords*—*wavelength division multiplexing; dedicated protection; single-line rate; spectrum efficiency.

I. INTRODUCTION

Optical networking with wavelength division multiplexing (WDM) has been considered to be a promising solution for handling the explosive growth of Internet traffic [1]. Furthermore, it is very likely that this trend will continue due to the massively increasing number and use of internet services such as Video on Demand (VoD), high definition Internet Protocol (IP) TV, cloud computing and grid applications requiring high amount of data rate. The ever increasing demand for bandwidth is posing new challenges for transport network providers. A viable solution to meet this challenge is to use optical networks based on WDM technology. WDM is a method of data transmission in which it divides the vast transmission bandwidth available on a fiber into several non-overlapping wavelength channels and enables data transmission over these channels simultaneously [2]. WDM is similar to frequency division multiplexing (FDM). However, instead of taking place at radio frequencies (RF), WDM is done in the electromagnetic spectrum. In this technique the optical signals with different wavelengths are combined, transmitted together, and separated again. It uses a multiplexer at the transmitter to join the several signals together, and a demultiplexer at the receiver to split them apart. It is mostly used for optical fiber communications to transmit data in several channels with slightly different wavelengths. This technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity. In this way, the transmission capacities of optical fiber links can be increased strongly. Therefore, the efficiency will be increased. WDM systems expand the capacity of the network without laying more fiber. WDM technique has mainly been used in optical backbone networks. To meet these high data rate demands, modulation formats installing higher number of bits per symbol into 50 GHz fixed grid spaces as standardized by International Telecommunication Union (ITU) along the bandwidth spectrum were brought in [3, 4]. For instance, 100 Gbps-based transmission systems have been fit into 50 GHz fixed grid space and commercialized [5]. Theoretically, a single fiber is capable to support over 1000 optical channels or wavelengths at a few Gbps in speed [6]. We have focused on survivability particularly traditional dedicated protection approach in WDM optical networks that received much attention in the research community. We realized more opportunities for further research in these areas.

Failure of the optical fiber in terms of fiber cut causes loss of huge amount of data which can interrupt communication

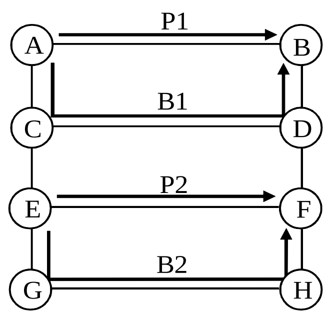

Fig. 1: A scenario of traditional dedicated protection.

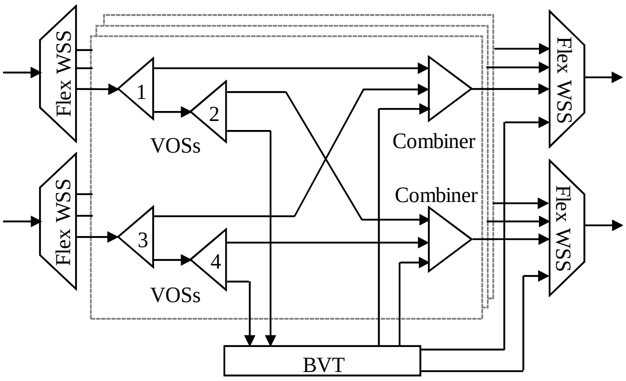

Fig. 2: A switch architecture used for dedicated protection in WDM.

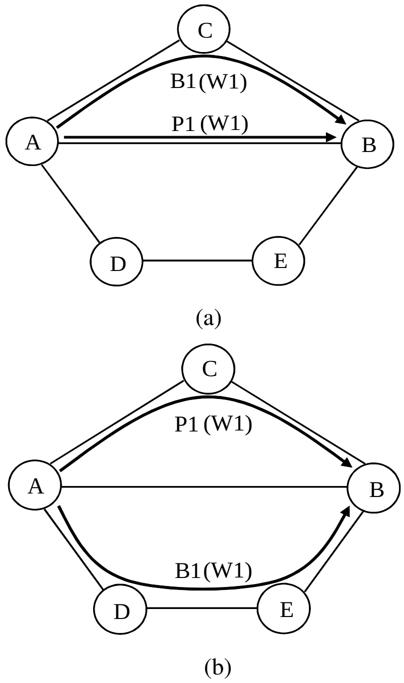

Fig. 3: A scenario of traditional dedicated protection using (a) one primary link and (b) two primary links in WDM networks.

services. There are several approaches to ensure mesh fiber network survivability. In survivability, the path through which transmission is actively realized is called working path or primary path whereas the path reserved for recovery is called backup path or secondary path. One of the survivability approaches in optical networks is protection in which pre-assigned backup paths are established or reserved at the time of admitting a request which are link-disjoint with their corresponding primary paths. Further, dedicated protection is one of the traditional protection methods in which backup resources are reserved dedicatedly as shown in Fig. 1 with the network topology of eight nodes and ten links [7]. Pre-configured paths (primary (P) or backup (B)) are denoted by solid arrows. In the dedicated protection shown in Fig. 1, backup paths B1 and B2 are configured at the time of establishing primary paths P1 and P2 respectively (B1 and B2 are pre-configured). In the event of a link failure on a primary path P1, this approach requires no further switch configuration to set up the backup path B1. Therefore, traffic is rerouted through B1 in short recovery time in this method. However, resources for backup paths B1 and B2 cannot be shared as achieved in traditional shared protection [8] which method requires more recovery time for switch configuration if a primary path is brought down by a failure.

Spectrum efficiency is the optimized use of spectrum or bandwidth so that the maximum amount of data can be transmitted with the fewest transmission errors. Spectrum efficiency can be calculated by dividing the total traffic bit rate by the total spectrum used in the particular network. The total traffic bit rate can be calculated by multiplying the data rate by the number of connections (lightpaths). The total spectrum would be the multiplication of the frequency used for a single wavelength and the total number of wavelengths (bandwidth slots) used in the network [9, 10]. Therefore, spectrum efficiency for a particular number of connections in a particular network topology depends on the primary paths and their backup paths from each source to each destination of the connections. In this paper, we investigate the performance by calculating the spectrum efficiency for traditional dedicated protection in WDM optical networks using single-line rate (SLR) such as 100 Gb/s, 400 Gb/s, and 1 Tb/s. Further, we investigate by comparing the above mentioned scenario for various network topologies in which the number of links are different. This is because, the number of links can be depended on the evaluation of spectrum efficiency. Finally, we compare traditional dedicated protection in WDM optical networks using SLR with different number of primary links as shortest path from the source to the destination.

To the best of our knowledge, this is the first paper that is investigating the traditional dedicated protection and WDM optical networks using SLR in various network topologies in terms of spectrum efficiency. Our findings are as follows. Approximately the same and comparable spectrum efficiency is seen for all SLR in all traffic bit rates. Unlike lower number of links in a network topology. The spectrum efficiency is higher in higher links network topology. Therefore, the spectrum efficiency can be performed higher in large geographical area such as core networks. Further, the spectrum efficiency increases when the primary links from the source to the destination are increased.

II. Related Work

In this section, we review some related work that have been done on evaluating performance in WDM optical networks. These works include analyzing power efficiency and spectrum efficiency by applying different modulation techniques and algorithms. The work in [11], an efficient algorithm called semelightpath has been introduced and applied to ARPANET and NSFNET to estimate the blocking probability with and without link failure. The authors in [12] propose a new protection scheme, which they term as partial path protection (PPP), to select end-to-end backup paths using local information about network failures. To evaluate the performances of the protection scheme, the blocking probability has been estimated over NSFNET, Sprint's OC-48 and New Jersey LATA network. In [13], the authors present Optical Transport Network (OTN) switching for improved energy and spectral efficiency in WDM Networks. In this study, the authors considered the Spanish core network with various MLR such as 40 Gbps, 100 Gbps, 200 Gbps, and 400 Gbps. Spectral efficiency and the power efficiency have been compared for Mixed-Line Rate (MLR) method in WDM transport network in [14]. In this paper, various data rates such as 10 Gbps, 40 Gbps, and 100 Gbps have been considered. Similarly, in [15], spectral efficiency and power efficiency have been compared for end-to-end connections in different wavelengths over WDM networks. However, in addition to MLR such as 10 Gbps, 40 Gbps, and 100 Gbps, SLR method are also investigated. Similar work has been carried out in [16] as they have done in [14] and [15]. In addition, they have considered three various cases such as, high transmission capacities, long connection distances, and MLR systems. Finally, the authors have concluded the relevance between the spectral and power efficiencies. However, in [14], [15], and [16], no protection methods are investigated. In addition, low data rates are considered in these works.

III. Spectrum Efficiency Evaluation

The traditional dedicated protection in WDM networks for the various number of primary links is illustrated in Fig. 3, with a network topology of five nodes and six links. Solid arrows denote primary (P) and backup (B) paths which are pre-configured. Primary path P1 and its corresponding backup path B1 are shown with their wavelength W1. (Note that, primary path and its backup path can also consume different wavelengths). In case of a component failure, say, failure on P1, configuration is not needed as B1 is pre-configured (Note that P1 and B1 are link-disjoint). Therefore, with short recovery time, backup traffic is rerouted. To enable such pre-configuration of backup path with faster performance (unlike slow switches that have high response or switching time such as micro electromechanical systems (MEMS)), a recently proposed switch architecture shown in Fig. 2 [17, 18] has been used in our investigation. The switch uses components such as flexible wavelength selective switches (Flex WSS), bandwidth variable transponders (BVTs), 1x2 variable optical splitters (VOSs) and combiners. Further, less power consumption caused by the components can be achieved in the switch architecture (Fig. 2). Therefore, we use switch architecture in a network topology shown in Fig. 3, to illustrate dedicated protection in WDM networks for the various number of primary links.

In Fig. 3(a), a primary path P1 (A → B) and its corresponding backup paths B1 (A → C → B) are configured at their appropriate nodes at the time of connection established. As explained above, traffic is rerouted through B1, when a link or component failure occurs at P1. In this scenario, the number of primary link is limited to one as shortest path for primary link

Algorithm 1 Compute spectrum efficiency for dedicated protection in WDM optical networks.

Input: $G = (V, E)$, V: network nodes, E: bi-directional links, Request $i = (s, d, R)$ with backup under single component failure model, $npl_{threshold}$: (*npl*-number of primary link), GB: guardband.

Output: Finding primary lightpaths (according to npl) and backup lightpaths in order to compute total data rate TDR, total bandwidth spectrum TBS, spectrum efficiency SE, or Block if no primary and backup lightpaths found.

Step-1
Find primary path P_i from K paths $(i = 1, 2, .., K)$
if $P_i = npl_{threshold}$ is available **then**
  For all links in a primary path P_i
  Find, range of wavelength slots wP_i
  if $wP_i > 0$ **then**
    Go to: **Step-2**
  else
    if P_i is not end of path list **then**
      Repeat **Step-1** for $P_{i+1} = npl_{threshold}$
    else
      Discard primary path P_i
    end if
  end if
else
  Discard primary path P_i
end if
Step-2
Find backup path B_i using link disjoint condition with P_i
if B_i is available **then**
  For all links in a backup path B_i
  Find range of wavelength slots wB_i
  if $wB_i > 0$ **then**
    Allow backup path B_i and Go to: **Step-3**
  else
    if B_i is not end of path list **then**
      Repeat **Step-2** for B_{i+1}
    else
      Discard primary path P_i
    end if
  end if
else
  Discard primary path P_i
end if
Step-3
For all assigned data rate in primary links and backup links
Compute total data rate TDR and total bandwidth spectrum TBS
Compute spectrum efficiency SE = TDR/TBS

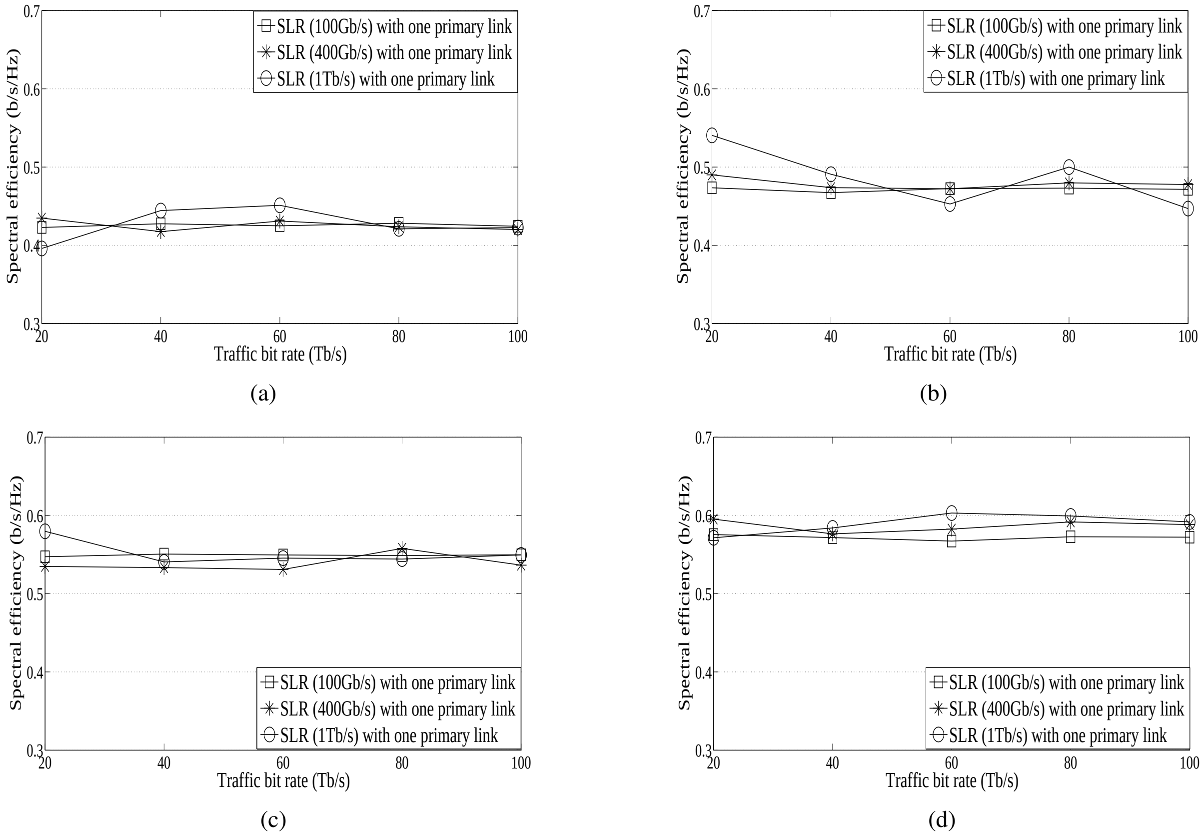

Fig. 4: Spectral efficiency of traditional dedicated protection in WDM networks using one primary link in (a) 21-link NSFNET, (b) 30-link Deutsche network, (c) 35-link Spanish Telefonica network, and (d) 43-link US network.

is one hop, that is A $\rightarrow$ B. This is because to standardize the total spectrum used by the primary link. However, two links that is A-C and C-B are used for backup path B1. In Fig. 3(b), a primary path P1 (A $\rightarrow$ C $\rightarrow$ B) and its corresponding backup paths B1 (A $\rightarrow$ D $\rightarrow$ E $\rightarrow$ B) are configured at their appropriate nodes at the time of connection established. In case of a link or component failure at P1, traffic is rerouted through B1. In the same way, the number of primary link is limited to two in this scenario as shortest path for primary links are two hops, that is A $\rightarrow$ C and C $\rightarrow$ B. However, three links that is A-D, D-E, and E-B are used for backup path B1.

Further, to implement limiting the number of primary links, we propose an algorithm shown in Algorithm 1. This algorithm consists of setting up primary and backup paths and their wavelength slots. Source, destination, and the data rate are the inputs. This is used to accommodate lightpaths and to calculate the spectrum efficiency using various number of primary links.

IV. Performance Study

We simulate the traditional dedicated protection approach in WDM optical networks using recently proposed switch architecture. We use (a) NSFNET (14 nodes and 21 bi-directional links), (b) Deutsche network (21 nodes and 30 bi-directional links), (c) Spanish Telefonica network (21 nodes and 35 bi-directional links), and (d) US Network (24 nodes and 43 bi-directional links) topologies for our study. We consider 88 wavelength slots each of which consists of 50 GHz fixed grid spacing. Request arrival process follows Poisson distribution and holding time of requests follow exponential distribution with unit mean. Traffic requests arrive in dynamic network environment. Source node and destination node of each request follow uniform distribution. We consider SLR, therefore, data rates such as 100 Gbps, 400 Gbps, 1 Tbps for their bandwidths 50 GHz, 200 GHz, 600 GHz follow the uniform distribution respectively. We assume the guard band is 50 GHz, which is one wavelength slot. Each experiment is simulated with various request arrivals in order to compute the total amount of bit rate and bandwidth used.

In this study, we consider traditional dedicated protection with various number of primary links (one hop and two hops as shortest path from the source to the destination) in WDM optical networks. This is because to regulate the number of primary links in a uniform manner, hence, to measure the efficiency caused by both primary and backup links. In Fig. 4, each of the SLR such as 100 Gbps, 400 Gbps, and 1 Tbps are compared by considering one primary link as shortest path from the source to the destination in various network topologies such as NSFNET, Deutsche network, Spanish Telefonica network, and US Network. Similarly, the same comparisons

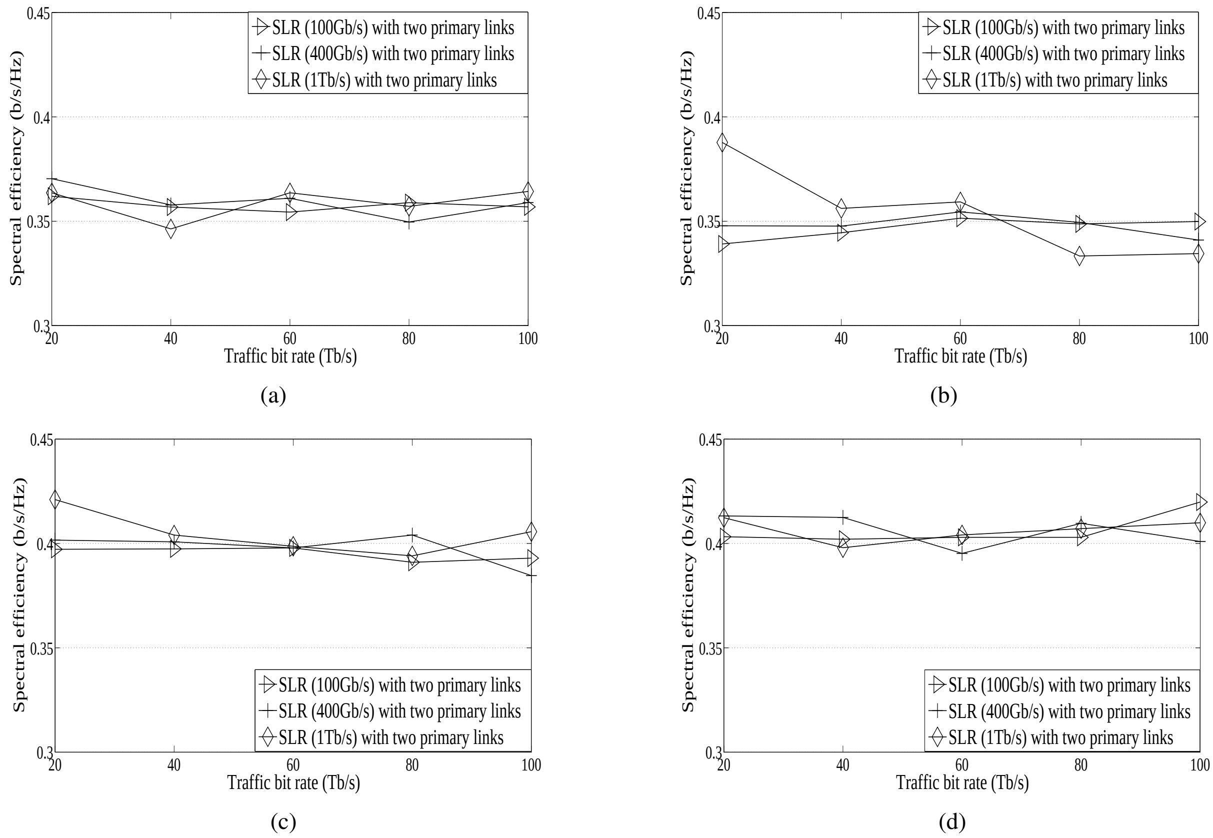

Fig. 5: Spectral efficiency of traditional dedicated protection in WDM networks using two primary links in (a) 21-link NSFNET, (b) 30-link Deutsche network, (c) 35-link Spanish Telefonica network, and (d) 43-link US network.

for two primary links as shortest path from the source to the destination are shown in Fig. 5. We select the traffic bit rate ranges from 20 Tb/s to 100 Tb/s for all comparisons that are being assigned to calculate spectrum efficiency. Such that they provide approximately the same spectrum efficiency (range). This helps us find and compare the relative impact of the performance on different network topologies with different SLR and different number of primary links. Our performance study is considered in threefold. Firstly, we compare the different SLR in a particular network topology, secondly, we compare the performance of the entire SLR in various network topologies, and finally, we compare the performance of the entire SLR in various network topologies with the different number of primary links which are explained below.

Firstly, we consider the spectrum efficiency for SLR 100 Gb/s with one primary link in NSFNET topology as shown in Fig. 4(a). It can be observed that through all the range from 20 Tb/s to 100 Tb/s, the spectrum efficiency is approximately constant. Similarly, the same pattern can be observed in SLR 400 Gb/s as observed for SLR 100 Gb/s. However, when we consider SLR 1 Tb/s, it is significantly fluctuated in traffic bit rate from 20 Tb/s to 80 Tb/s and remained constant in traffic bit rate 80 Tb/s and 100 Tb/s. Secondly, in addition to NSFNET topology, we simulate this scenario in Deutsche network, Spanish Telefonica network, and US Network as shown in Fig. 4(b), Fig. 4(c), and Fig. 4(d) respectively. In Fig. 4(b), similar performance can be achieved as observed in Fig. 4(a) when considering SLR 100 Gb/s and 400 Gb/s. However, the pattern is significantly fluctuated through all the ranges from 20 Tb/s to 100 Tb/s when considering SLR 1 Tb/s. In Fig. 4(c) and Fig. 4(d), for all the SLR such as 100 Gb/s, 400 Gb/s, and 1 Tb/s, approximately the similar spectrum efficiency can be observed through all the traffic bit rate. Specifically we note that, it can be observed that the spectrum efficiency for all SLR is increased in US network when compared to NSFNET topology. Therefore, the spectrum efficiency is increased while the number of links are increased in a network topology. This observation can be justified by considering the performance of other intermediate network topologies such as Deutsche network and Spanish Telefonica network as shown in Fig. 4(b) and Fig. 4(c) respectively.

Thirdly, in addition to considering one primary link, we simulate this scenario for two primary links in all the network topologies as shown in Fig. 5. In Fig. 5(a), it can be observed that all the SLR are approximately similar through all the traffic bit rate. However, the spectrum efficiency in all the traffic bit rate are decreased when compared in one primary link as shown in Fig. 4(a). Further, in Fig. 5(b), Fig. 5(c), and

Fig. 5(d), it can be observed the similar pattern as observed in Fig. 5(a). In addition, unlike the performance observed in Fig. 4 in terms of number of links, approximately the similar spectrum efficiency can be observed in both NSFNET and Deutsche network and in both Spanish Telefonica network and US Network. Specifically we note that, it can be observed that the spectrum efficiency for all SLR using NSFNET in two primary links are decreased as shown in Fig. 5(a) when compared for all SLR using NSFNET in one primary link as shown in Fig. 4(a). Further, this performance can be observed in all other network topologies. Therefore, the spectrum is more efficiently used when considering one primary link as a shortest path from the source to the destination.

V. Conclusions

In this paper, we addressed the comparison of spectrum efficiency for dedicated protection in WDM optical networks. Therefore, we considered four standard network topologies such as NSFNET, Deutsche network, Spanish Telefonica network, and US Network. We investigated the performance of various single-line rate (SLR) such as 100 Gb/s, 400 Gb/s, and 1 Tb/s in various number of primary links as shortest path from the source to the destination. Our findings are as follows. Firstly, we compared the performance of various SLR in a particular network topology with one primary link. We observed that almost similar performance is achieved in data rates such as 100 Gb/s and 400 Gb/s. However, the performance is fluctuated when the data rate is higher such as 1 Tb/s. Secondly, we compared the spectrum efficiency in various network topologies with the same scenario mentioned above. We observed that the performance increases when the number of links are increased in all the SLR, as higher number of links can achieve higher spectrum efficiency. Further, we compared the performance of various SLR in all the network topologies with one primary link against various SLR in all the network topologies with two primary links. In this comparison, we observed that the spectrum efficiency is reduced when considering two primary links compared to one primary link. This performance can be observed in all network topologies with one primary link against their appropriate network topology with two primary links.

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