Cost-Effective Capacity Enhancement of Survivable Optical Networks by Supplemental Band Expansion and Backup Resource Sharing

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Abstract: A novel cost-effective capacity enhancement method for resilient optical networks is proposed that introduces supplemental multi-band transmission and sharing of extended bands by backup paths. Numerical simulations confirm 17.7-35.3% enhancement on three real topologies.

1. Introduction

The ever-growing traffic loads on communication networks demand the substantial and ceaseless capacity expansion of optical transport networks. As single-mode fiber capacity expansion in the C-band is saturating, multi-band transmission is being intensely studied [1,2]. While this approach will realize substantial fiber capacity enhancement, it demands devices that can support the wider frequency bands. In addition, higher transmission loss in the new frequency bands shortens repeater spans or the maximum transmissible reach in multi-band transmission networks [3]. Therefore, relatively long time and significant expense are incurred in upgrading all currently operating networks [4]. To resolve this problem, we proposed a network capacity enhancement scheme in which the frequency bands (e.g., S/L-bands) newly used on a few links are regarded as additional links, named multi-band virtual bypass links (MB-VBLs), overlaid on the original links [5]. We introduce MB-VBLs only to the most congested links and then divert paths going through these links to the MB-VBLs, thereby achieving network capacity enhancement. Substantial capacity improvement with relatively few wavelength converters placed at the ends of MB-VBLs is verified, and hence, it will be a cost-effective way of enhancing network capacity.

Resiliency is another key requirement for optical networks as they are now the infrastructure of our information society. A simple but effective way to guarantee resiliency against single failure is to introduce path protection; for each path request, a pair of disjoint working and backup paths is established [6,7]. A drawback of path protection is the substantial increase in network resource utilization which results in severe network capacity deterioration. Network resource sharing as shared path protection has been studied; however, shared risk group independence between corresponding working paths is required and the same wavelength / spectrum has to be assigned to backup paths on shared resources.

To adapt the steep traffic growth and to satisfy the need for resiliency, we propose a novel capacity enhancement scheme for optical networks with dedicated path protection. As we proposed in [5], MB-VBLs are introduced to the most congested links in the network. The wavelength converters of MB-VBLs are shared by multiple backup paths considering the risk sharing between corresponding working paths. Different wavelengths / spectra can be assigned to backup paths traversing the same MB-VBL and each MB-VBL can be shared as a bundle of backup paths. Thus, the restriction imposed by resource sharing between backup paths is relaxed relative to conventional shared path protection. Numerical simulations on three real topologies elucidate that the introduction of MB-VBLs enhances their capacity by over 10%. Furthermore, in all cases, due to the sharing among backup paths, wavelength converters at MB-VBLs are fewer than the backup paths passing through the MB-VBLs. These results confirm that capacity upgrade in resilient network is cost-effectively possible as the supplemental use of MB-VBLs requires only a limited number of wavelength converters.

2. Capacity Enhancement in Survivable Optical Path Networks with Multi-band Virtual Bypass Links

In this paper, we assume that network topologies are represented by 2-connected graphs to assure survivability against a single failure. The frequency assignment follows the ITU-T flexible grid; the center frequency of a path is located on the 6.25-GHz-spaced grid and the frequency bandwidth is a multiple of 12.5 GHz. In order to simplify the notations, we regard the C-band as the currently used band and we assume L-band transmission is used to enhance the network capacity; however, the discussion is valid for any combinations of frequency bands such as the S+C+L-bands. The L-band transmission will be implemented to few links and defines multi-band virtual bypass links (MB-VBLs) which directly connect their end nodes without consuming C-band frequency resources (Fig. 1).

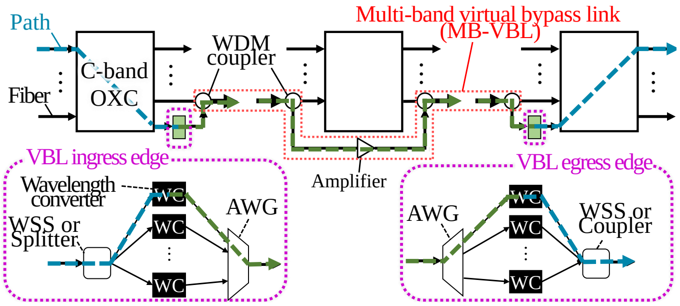


Fig. 1. MB-VBL configuration.

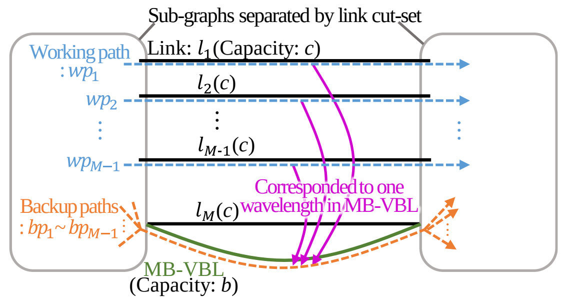


Fig. 2. Behavior of paths between link cut-set in network with MB-VBL.

The signal frequency conversion can be done by wavelength converters placed at both sides of the MB-VBLs [8]. Signals are distributed to wavelength converters by wavelength selective switches (WSSs) or splitters. The converted signals in the corresponding passband of the arrayed waveguide gratings (AWGs) are bundled at the ingress edge of an MB-VBL. The inverse operations are applied at the egress edge. In optical networks without protection, the number of paths that can be carried by an MB-VBL is bounded by the number of wavelength converters. However, in path protected optical networks, wavelength converters can be shared by multiple backup paths by bounding the degree of risk sharing.

Suppose that an MB-VBL is installed on one of the links in a link cut-set, a set of links separating the original network topology graph into two connected sub-graphs [9]. Let the number of links in the cut-set be M and the capacity of each link be c (Fig. 2). The capacity of the MB-VBL, b, can be shared by up to $M-1$ backup paths whose working paths are distributed to the other $M-1$ links. Thus, the maximum numbers of path pairs that can traverse the cut-set with and without the MB-VBL are proportional to $Mc/2$ and $(Mc+(M-1)b)/2$, respectively. The ratio of enhancement is $\frac{(M-1)b}{Mc}$. If the number of links in a cut-set M is 4 and the MB-VBL uses wavelength converters that can process 33% of paths in a link, then the capacity of the cut-set is enhanced by up to 25%.

The above observation gives a method of estimating the number of wavelength converters necessary. Suppose we have a network with an MB-VBL and several backup paths traversing the MB-VBL. The number of corresponding working paths going through a link or node gives the number of wavelength converters to be activated on the MB-VBL. Thus, to guarantee the resiliency against single node/link failures, the maximum number of corresponding working paths going through a link or node defines the number of converters necessary on each side of the MB-VBL. If we only count the number of such paths on all links, then resiliency against single link failures is assured. Although additional signaling to identify which backup paths have to be carried by MB-VBLs and changing switch status at ingress/egress nodes and edges of MB-VBLs is necessary, resource sharing is introduced only at MB-VBLs.

With the MB-VBL implementation in Fig. 1, different wavelengths / spectra have to be assigned to backup paths to be activated at the same time as backup paths share the fibers bridging optical cross-connects (OXCs) and VBL edges. Different MB-VBL implementations using add/drop functions at ingress/egress nodes are possible; the restriction on wavelength / spectrum assignment is relaxed but we omit further discussion due to the space limitation.

3. Installation of MB-VBLs and Design Algorithm of Resilient Networks

For each link cut-set of given topologies, the load of the cut-set is represented by the ratio of the number of paths, whose source and destination nodes lie on opposite sides of the cut-set, to the total capacity of fibers laid on the cut-set. MB-VBLs will be installed to the cut-set with the highest load, named critical cut-set. The MB-VBL installation and path accommodation schemes to suppress the largest index of frequency slots are summarized below.

Phase 1 (MB-VBL setup): If the critical cut-set includes three or more links that do not share their end nodes, select one of these links. Otherwise, select a pair of links that do not share their end nodes (Fig. 3(a)). For each selected link, search for a short (2-3 hops) route traversing it and find the one shown by numerical evaluations to be most effective. Establish MB-VBL(s) along the routes found.

Phase 2 (Path setup): For each node pair, find a set of node and link disjoint route pairs between these nodes and let the set be a route candidate set for the node pair. Sort all path setup requests in descending order of the product of hop counts of the shortest routes and numbers of frequency slots necessary to traverse these shortest routes. For each request, select the route pair in the route candidate set that minimizes the index of frequency slots used. If multiple route pairs have the same minimum, then select the one with shorter route length. Establish a pair of working and backup paths on the route pair. If the selected route pair traverses an MB-VBL, a back-up path is established on the route through the MB-VBL. Repeat this procedure until all requests are processed. Find the number of wavelength converters necessary at ingress/egress edges of each MB-VBL by counting the number of corresponding working paths traversing each link / node.

Network topology	(a) JPN25	(b) British Telecom	(c) pan-European
# of nodes	25	27	28
# of links	43	40	41
Max. node degree	5	4	5
Ave. node degree	3.4	3.0	2.9

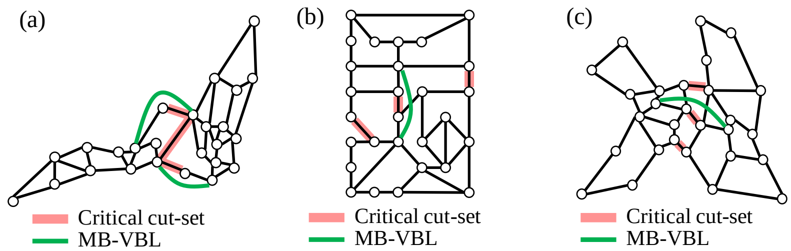
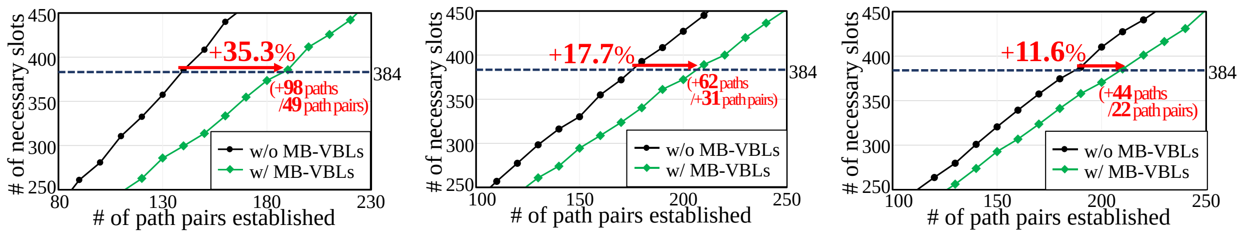


Fig. 3. Examined network topologies.



(a) JPN25 (b) British Telecom (c) pan-European Optical Transport Network

Fig. 4. Variation in number of necessary slots.

4. Numerical Simulations

Three physical topologies, JPN25, British Telecom network, and pan-European Optical Transport Network, with 25/27/28 nodes and 43/40/41 links, respectively, were used to evaluate performance [10-12]. Fig. 3 shows each topology with the critical cut-set and MB-VBL locations as determined by the above method. A pair of fibers is laid on each link of all networks. Resiliency against single link failure is assumed. We assume three path capacities; 100 Gbps, 400 Gbps, and 1 Tbps that occupy 4, 7, and 15 12.5GHz-width slots, respectively [13]. Traffic demand is given by a set of optical path setup requests, where the source and destination nodes are randomly and uniformly distributed. The occurrence probability of each capacity is 1/3. A baseline for comparison is the path-protected conventional network without MB-VBL. For each configuration, simulations were repeated 100 times and the results are the averages.

Fig. 4 plots the number of necessary slots versus the number of paths established. The number of established optical path pairs yields a linear increase in the number of necessary slots. Installing the MB-VBLs suppresses the number of necessary slots. For the threshold value of 384, which corresponds to 4.8 THz / extended C-band configuration, MB-VBL introduction enhances the capacity by 35.3%, 17.7%, and 11.6%, respectively, on JPN25, British, and pan-European. The numbers of wavelength converters for 4/7/15 slots at MB-VBL ingress/egress edges are 16/18/18, 8/8/9, and 7/8/9 respectively on these topologies, while the total number of accommodated working and backup paths is increased by 98, 62, and 44, respectively. With the introduction of one converter to the edges of an MB-VBL, 1.6-2.3 working and backup paths can be additionally accommodated by the network. We also verified the ratio of the number of wavelength converters at edges of MB-VBLs and the number of backup paths traversing MB-VBLs on each topology. The ratios reach 1.2, 1.8 and 1.8, respectively, on JPN25, British, and pan-European topologies. The substantial capacity enhancement and resource sharing among backup paths confirm the cost-effectiveness and efficiency of the proposed MB-VBL scheme.

5. Conclusion

In this paper, we proposed a cost-effective capacity enhancement method for resilient optical networks. The supplemental introduction of multi-band transmission to a few links was implemented as MB-VBLs and the extended bands of MB-VBLs are shared by multiple backup paths. Numerical simulations on three real topologies, JPN25, British Telecom network, and pan-European network, showed that the proposed scheme can successfully enhance network capacity by 35.3/17.7/11.6%, respectively.

6. References

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