Cost-effective Network Capacity Enhancement with Multi-band Virtual Bypass Links

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Abstract: A cost-effective network expansion method through the use of virtual links in which multi-band transmission is introduced. Network capacity enhancement reaches over 10% just with the introduction of a few virtual links on each topology.

1. Introduction

The ever-growing traffic volume in communication networks demands the substantial and ceaseless capacity expansion of optical transport networks. The capacity of a single-mode fiber (SMF) has been successfully enhanced with the introduction of dense wavelength-division multiplexing and digital coherent technologies. As the SMF-capacity expansion using the C-band is saturating [1], space-division multiplexing and multi-band transmission are being intensely studied [2,3]. Although both transmission technologies will realize substantial fiber capacity enhancement, they demand the installation of novel fibers or devices to support the higher spatial parallelism or wider frequency bands. In addition, higher transmission loss at additional frequency bands shortens repeater-spans or the maximum transmissible reach in multi-band transmission networks [4]. Therefore, relatively long time and significant expense are incurred to adopt these technologies for upgrading all currently operating networks [5].

The general objective of optical network design and control is to bridge the gap between given fiber distributions and optical path distributions. Numerous algorithms for routing and wavelength/spectrum assignment (RWA/RSA) to optical paths have been proposed so far to fulfill given requirements such as network capacity maximization, path blocking ratio minimization, better resiliency, and so on [6]. However, even if the number of optical path demands between each node pair is same for all node pairs and a sophisticated network design algorithm is adopted, links will not be equally utilized; most paths are obliged to go through the center area while few paths utilize the surrounding area. Thus the largest link utilization ratio in the network determines the network capacity bound and the capacity enhancement of such links without installing additional fibers will contribute the cost-effective network capacity enhancement within reasonable time.

In this paper, we propose a novel multi-band transmission scheme named multi-band virtual bypass links (MB-VBLs) that aims at cost-effective network capacity expansion. To that end, multi-band transmission will be introduced only to the most congested links. The frequency bands (e.g., S/L-bands) newly used on these links are regarded as additional links, MB-VBLs, overlaid on the original links. Optical paths in the original band (e.g., C-band) will go through the MB-VBLs through the wavelength conversion function at their ingress and egress portions. Thus the multi-band transmission area is isolated and concealed to maintain full compatibility with existing facilities. In order to find the links on which MB-VBLs have to be installed, we adopt our congested-link finding algorithm which estimates expected utilization of all links through link cut-set analysis [7]. Numerical simulations on three real topologies in dynamic path operation scenarios elucidate that the introduction of multi-band transmission only to most congested links enhances their capacity by over 10%. Furthermore, the numbers of paths going through MB-VBLs are quite small in all cases. These results confirm that network capacity upgrade, which is cost-effective, immediate, and fully compatible to current configuration, is possible by the supplemental use of multi-band transmission.

2. Multi-band Virtual Bypass Links for Cost-effective Network Capacity Enhancement

The aim of this paper is to enhance the capacity of currently operating fully transparent networks cost-effectively. The network topology will be a connected bipartite graph. In order to simplify notations, we regard the C-band as the currently used band. Moreover, we suppose that all paths are of the same bitrate and occupy the same frequency bandwidth; however, the generalization to non-uniform bitrate/frequency bandwidth cases is straightforward. Optical paths are located on a uniformly spaced frequency grid in the C-band and a different spacing grid is used in newly used bands. Optical paths are dynamically operated considering the expected introduction of transport software-defined-network (SDN) technologies. Their distribution on the network topology is represented by a traffic matrix T whose (i, j) component represents the average number of paths expected to exist from node i to node j.

Table 1. MB-VBL Configurations with Wavelength Converters

Network converter interface	Converter-VBL interface	Restriction in RWA/RSA	Loss [dB] (in/outside of MB-VBL)	Remarks
Splitter or Coupler	Coupler or Splitter	None	>10 dB for N=10 / >10 dB for N=10	• The parameter N stands for the number of wavelength converters. • Loss at $1\times N$ / $N\times 1$ couplers/splitters is $10\log_{10} N$ dB + excess loss. • Losses of $1\times N$ WSSs and $1\times N$ AWGs are assumed to be 7 and 5 dB [10,11].
WSS	Coupler or Splitter	None	7 dB / >10 dB for N=10	
Splitter or Coupler	AWG	Network-converter interface	>10 dB / 5 dB	
WSS	AWG	Network-converter interface	7 dB / 5 dB	
AWG	AWG	Network-converter and converter-VBL interface	5 dB / 5 dB	

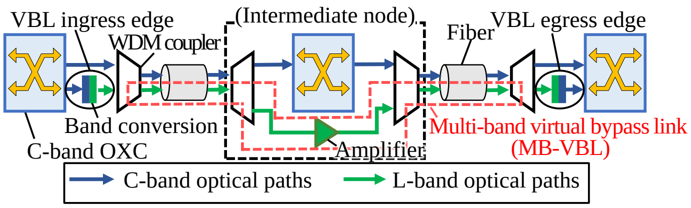

Fig. 1. MB-VBL configuration.

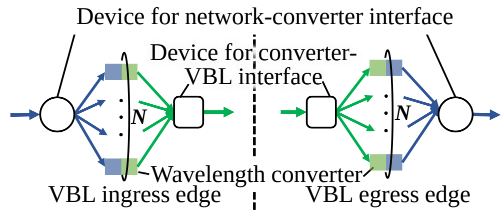

Fig. 2. Configuration of band conversion with 2N wavelength converters.

The mandatory requirement for cost-effective network capacity expansion will be to guarantee perfect compatibility with networks using C-band transmission. For this, we propose to partially introduce the transmission in the S/L-bands only to a small number of links. As amplifiers/transponders for the L-band are commercially available, we focus on the L-band transmission to enhance the fiber capacity; however, we can also adopt the transmission on the other bands in the same way. L-band transmission is implemented as virtual links, named multi-band virtual bypass links (MB-VBLs), that directly bridge pairs of nodes; L-band signals on these links are converted from/to C-band signals at their input and output sides (Fig. 1). The signal frequency conversion can be done by frequency-band converters or wavelength converters placed at both sides of MB-VBLs [8,9]. The former converts all incoming signals simultaneously as bundles while the latter can only convert one of these. Hereafter, we discuss the implementation of MB-VBLs with wavelength converters, as sufficient network capacity enhancement can be derived with the detour of just a few optical paths to the L-band; this property will be elucidated in Sec. 4. Thus, we can assume very sparse accommodation of optical paths with broad frequency spacing in the L-band, which eases the filtering operation necessary to demultiplex and multiplex paths. Figure 2 and Table 1 show some examples of how to implement MB-VBLs with wavelength converters and typical devices. Signals are distributed to wavelength converters and converted signals are bundled at the ingress edge of an MB-VBL and the inverse operations are applied at the egress edge. For the distribution and bundling operations, we can use arrayed waveguide gratings (AWGs), WSSs, and splitters/couplers. WSSs and splitters/couplers are equivalent in terms of path routing capability and the signal power loss and cost differentiate these devices. The use of an AWG at the distribution/bundling part of the ingress/egress edge imposes a restriction such that a wavelength converter can convert a signal in the corresponding passband of the AWG. On the other hand, the use of an AWG at the bundling/distribution part of the ingress/egress edge, the VBL-network interface portion, does not impose any restriction in path routing. Moreover, the broad frequency spacing allows us to use AWGs with broad pass-bands which can be compact and inexpensive.

3. Installation of MB-VBLs and Dynamic Path Control on Networks with MB-VBLs

In order to find appropriate locations to install MB-VBLs, we search for links likely be heavily congested subject to the pair of given topology and traffic distribution T [7]. For each link cut-set of given topology, 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. The MB-VBL installation scheme and dynamic path control considering the existence of MB-VBLs are summarized below.

Phase 1 (MB-VBL setup): For each link likely to be heavily congested and identified by the cut-set analysis, search for short (1-2 hops) routes across the link. Select one short route so that the node degrees of ingress/egress nodes, which are the number of directly connected nodes to these nodes, are large. Establish an MB-VBL on the route.

Phase 2 (Dynamic path operation): Each path setup request that arrives is processed as follows. Search for a route with vacant wavelength/frequency on all links traversed in ascending order of hop counts of routes. The hop counts to traverse each MB-VBL is set to "the number of physical links traversed by the MB-VBL"+1 to encourage the use of the conventional frequency band. If this fails, block the request. If a path teardown request arrives, then the path is removed immediately.

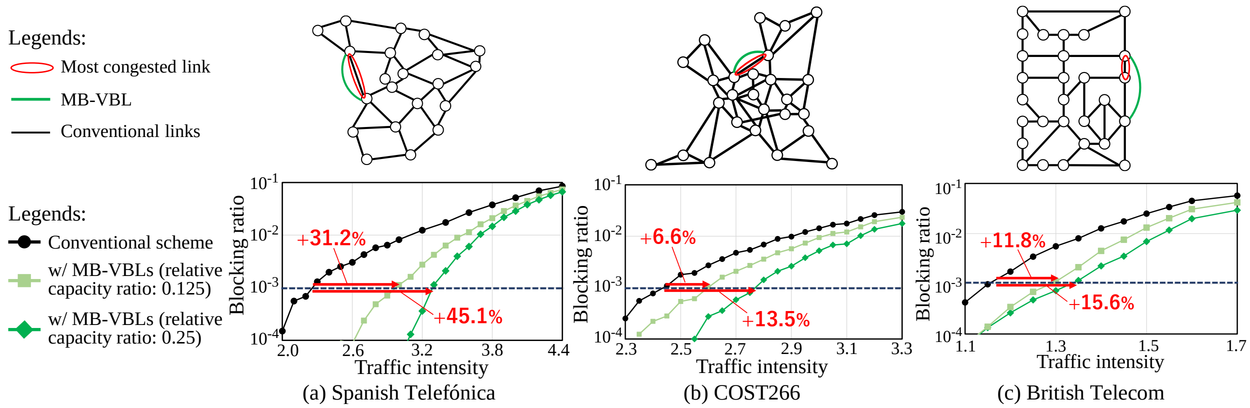

Fig. 3. Examined network topologies (upper) and variation in path blocking ratio (lower).

4. Numerical Simulations

Three physical topologies, Spanish Telefónica, Pan-European COST266, and British Telecom network, with 21/26/27 nodes and 35/51/40 links, respectively, are used to evaluate performance. Upper of Fig. 3 shows each topology with the congested link and MB-VBL locations determined by the above method. A pair of fibers is laid on each link of all networks. The frequency bandwidth currently used is 4.8 THz in the extended C-band. All paths use the most popular bitrate, 100 Gbps, and the conventional 50 GHz spaced grid both for C- and L-bands. The relative capacity of MB-VBLs is 0.125 and 0.25 times of current fibers. We assume WSS or coupler/splitter for network-converter interface, in which MB-VBLs can carry optical paths of any wavelength/frequency. This flexibility substantially mitigate wavelength/frequency contentions at the corresponding congested links. Thus the capacity enhancement ratio may exceed the relative MB-VBL capacity. A baseline for comparison is the conventional networks without MB-VBL. The uniform traffic distribution is assumed; the (i, j) $(i \neq j)$ component of traffic matrix T is same for all node pairs. In the dynamic path control stage, optical path setup demands are generated according the Poisson distribution and the time to tear down follows the negative exponential distribution. The source and destination nodes of each path are randomly and uniformly selected due to the uniformity assumption.

Lower of Fig. 3 plots overall the blocking ratio variation subject to traffic intensity in these physical topologies. For the target blocking ratio of 10^{-3}, the introduction of MB-VBLs with 0.125/0.25 times relative capacity of current fibers allows the networks to accommodate more traffic: 31.2/45.1% (Telefónica), 6.6/13.5% (COST266), and 11.8/15.6% (British). In Telefónica, the load calculated by cut-set analysis concentrates on the most congested link, resulting in significant enhancement of network capacity boosted by the mitigation of wavelength/frequency contention on the link. Although the other topologies show about 10% enhancement of network capacity, the ratio of paths going through MB-VBLs out of the total paths is only 0.6/1.1% (Telefónica), 0.6/1.0% (COST266), and 0.4/0.7% (British), respectively. This observation shows that significantly fewer wavelength converters are needed to realize MB-VBLs than all transponders of the entire network. In summary, network capacity can be expanded over 10% by installing a limited number of wavelength converters, about 1% of all transponders.

5. Conclusion

In this paper, we proposed a cost-effective capacity enhancement technology that introduces multi-band transmission only to heavily congested links of optical networks. The transmission on additional frequency bands is implemented as virtual links, named MB-VBLs, that are isolated from the other part of networks to keep perfect compatibility with existing facilities for transmission on the conventional frequency band. Numerical simulations on dynamic path operations in three real topologies, Spanish Telefónica, Pan-European COST266, and British Telecom network, showed that the proposed scheme enhances capacity by 45.1/13.5/15.6%, respectively. Few paths go through the MB-VBLs, so the use of multi-band transmission devices is minimized.

6. References

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