Techno-Economic Potential of Wavelength-Selective Band-Switchable OXC in S+C+L Band Optical Networks

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Abstract: Techno-economic performance of an S+C+L-band network employing the wavelength-selective band-switchable optical cross-connect is investigated. Numerical results verify that a significant cost-per-bit reduction can be achieved compared to conventional multi-band and multi-fiber solutions under realistic conditions. © 2022 The Author(s)

1. Introduction

In recent years, considerable research efforts have been dedicated to multi-band (MB) optical networking to keep up with continuous traffic growth [1–3]. This approach utilizes MB spectrum resources on existing fiber infrastructure, which can be a cost-effective solution for network capacity scaling. Please note that new fiber deployments are very costly [3], and thus MB networking is absolutely essential especially in cases of limited fiber availability. Moreover, its practical benefits have recently been studied in terms of network capacity (accommodated traffic) and network cost [4,5]. In [5], it has been shown that C+L-band operation provides a cost benefit compared to a 2-fiber (parallel C-band) one on large networks even when fiber cost is low. However, to the best of our knowledge, there is little work that explores the cost benefit beyond C+L-band (e.g., S+C+L-band) operation at this moment, and discussions towards S+C+L-band networks are open. Therefore, to evolve from C+L to S+C+L-band (and beyond) in a cost-effective manner, further studies considering both optical cross-connect (OXC) node architectures and network performance are required. In particular, the use of components other than C-band can affect the network cost since such components are potentially costly. Furthermore, the stimulated Raman scattering (SRS) can cause degradation and imbalance in transmission quality over multiple bands, which influences network capacity especially on large networks. Note that a smaller capacity can lead to increase in the cost-per-bit value. To address these issues, we recently proposed “wavelength-selective band-switchable” MB-OXC that potentially maximizes the use of C-band components and experimentally demonstrated its feasibility [6]. Although we also showed that our approach can improve network performance [7], the impact of our approach on network cost remains to be elucidated. Note that such an investigation is important for clarifying whether S+C+L-band networks make economical sense.

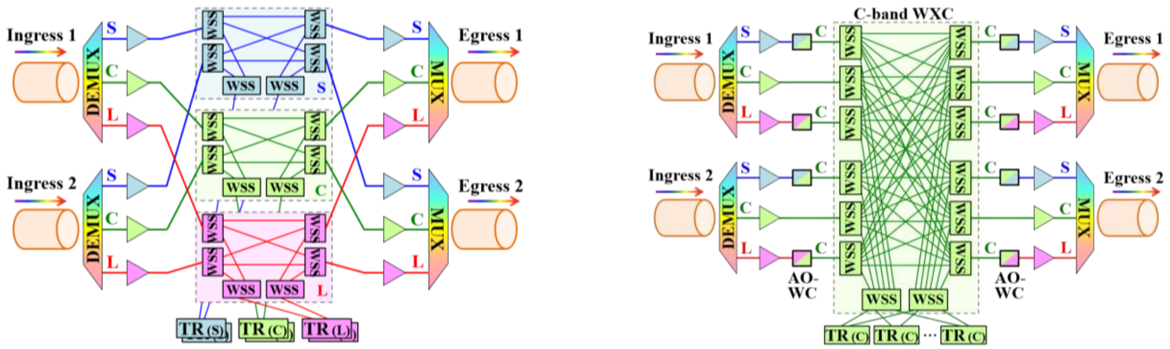
In this paper, we present a techno-economic analysis in which two S+C+L-band networks (with the conventional and our proposed MB-OXC) are compared to a 3-fiber C-band network in the cost-per-bit metric. Specifically, the impacts of optical components other than C-band and our wavelength-selective band switching capability are numerically investigated. Results reveal that more than 10% lower per-bit cost can be achieved with our approach even when fiber cost is low and band switching induced penalties are considered.

2. Optical Node Architectures for Multi-Band Optical Networks

This section describes MB-OXC architectures used in the analysis. We first review the conventional MB-OXC (presented in [1]) as a baseline architecture for S+C+L-band networks and then present our proposed one [6].

As shown in Fig. 1(a), a conventional MB-OXC takes a straightforward approach that deploys wavelength cross-connect (WXC) for each band in a parallel fashion. Specifically, it consists of band de-/multiplexers, amplifiers, WXCs, and transponders (TRs). For each WXC, each band component, i.e., wavelength selective switch (WSS) is naturally required. Moreover, TRs for each band are also required, and individual optical signals are transported transparently within each band.

In contrast, our proposed wavelength-selective band-switchable MB-OXC (shown in Fig. 1(b)) leveraging all-optical wavelength converters (AO-WCs) enables to maximize the use of well-established C-band technologies. Specifically, in this configuration, AO-WCs convert the spectrum from/to S- or L-band to/from C-band, and C-band signals are handled by a high-port-count C-band WXC. Consequently, although high-port-count C-band WSSs (e.g., instead of 1×9, 1×20 WSSs) are used for the WXC, WSSs of other than C-band are no longer required. In addition, optical add/drop operations can be executed on C-band and the use of TRs of other than C-band can be eliminated, which can potentially be less costly because a large number of TRs are generally deployed in large networks. Note that our MB-OXC enables each incoming optical signal to be output to any direction on any band. In other words, unlike the conventional one, the transmission band can be switched at intermediate nodes without the need for 3R



(a) conventional MB-OXC (b) wavelength-selective band-switchable MB-OXC

Fig. 1. MB-OXC node architectures (in the case of 2-degree node).

regenerators. This wavelength-selective band switching capability can significantly enhance optical-layer flexibility.

The key component of the proposed MB-OXC is the AO-WC that enables multiple-wavelength conversion and bit-rate/modulation-format agnostic wideband operation. Note that thanks to recent intensive studies [8,9], AO-WCs are becoming available. For instance, compact devices for AO-WC based on highly-nonlinear fibers or periodically-poled lithium niobate waveguides can be employed. Moreover, the impact of transmission penalty caused by AO-WCs on the network performance has recently been discussed in [7]. In particular, extensive simulations in [7] have revealed that wavelength-selective band switching capability can significantly improve network performance even when AO-WC induced transmission penalty is explicitly considered.

3. Numerical Analysis

We present numerical evaluations to clarify the benefits of the proposed MB-OXC and explore the potential of S+C+L-band optical networks. In this work, techno-economic performance comparisons are conducted using the cost-per-bit metric, just as in [5]. For this paper, two S+C+L-band network scenarios (employing the conventional MB-OXC or the proposed MB-OXC) and a 3-fiber (parallel C-band) network scenario are compared using the NSFNET topology. As shown in Fig. 2, this topology has 14 OXC nodes and 21 bi-directional links where the average link length is about 1080 km. Moreover, assumed physical parameters for optical transmission are the same as in [7]. In network performance simulation, we assume the incremental traffic model where connection requests are sequentially generated. Request generation follows uniform random distribution, and each request demands 100-Gbps capacity. In response to such requests, path provisioning operations are executed, and we apply a path provisioning algorithm presented in [7] for utilizing wavelength-selective band switching capability. Please note that 0.5 dB of GSNR penalty per band switching is considered in this paper, according to recent experiment [6]. The modulation format candidates used are summarized in Table 1. In addition, Table 2 summarizes the relative cost of each component (normalized by the cost of a C-band EDFA) for network cost calculation, which is according to recent work [5,10]. Just as in [5], costs of L-band components are assumed to be 20% higher than those of C-band. Here, we define the cost parameters α, β, and γ to understand the parameter sensitivity. α is a multiplicative factor of S-band component cost, which indicates the cost increase from C-band. β is a scaling factor of AO-WC cost, where the AO-WC cost is estimated by the product of TR cost and β. Moreover, fiber cost strongly depends on not only country and network size but also assumed operation period. This cost is expressed by γ in this work.

We first measure the accommodated traffic volume when the blocking probability is 1% and obtain the required amount of each component for traffic accommodation. Note that the volume attained by each (conventional and proposed) S+C+L-band network normalized by that of a 3-fiber case is about 0.71 and 0.94, respectively. This exhibits the potential of wavelength-selective band switching capability on MB network performance, as discussed in [7]. Then, the total cost is divided by the accommodated traffic volume to derive the cost-per-bit value. Calculated per-bit costs for various conditions are shown in Fig.3, where the value is normalized by the total “node” cost of a 3-fiber network. When comparing two S+C+L-band scenarios, employing the proposed MB-OXC always shows better

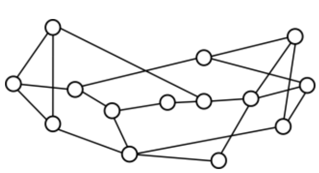


Fig. 2. NSFNET topology.

Table 1. Modulation Format Candidates for 100-Gbps Capacity

Modulation format	Req. spectrum	Req. GSNR
2-carrier 32 Gbaud DP-BPSK	100 GHz	4.2 dB
32 Gbaud DP-QPSK	50 GHz	7.2 dB
16 Gbaud DP-16QAM	25 GHz	13.8 dB

Table 2. Relative Component Costs

Component	Rel. cost
EDFA (C-band)	1
EDFA (L-band)	1.2
TDFA (S-band)	α
MUX/DEMUX	0.04
1×9 WSS (C-band)	5
1×9 WSS (L-band)	6
1×9 WSS (S-band)	5α
1×20 WSS (C-band)	7.5
9×18 WSS (C-band)	20
9×18 WSS (L-band)	24
9×18 WSS (S-band)	20α
18×9 WSS (C-band)	20
TR (C-band)	36
TR (L-band)	43.2
TR (S-band)	36α
AO-WC	36β
Fiber (per fiber per km)	γ

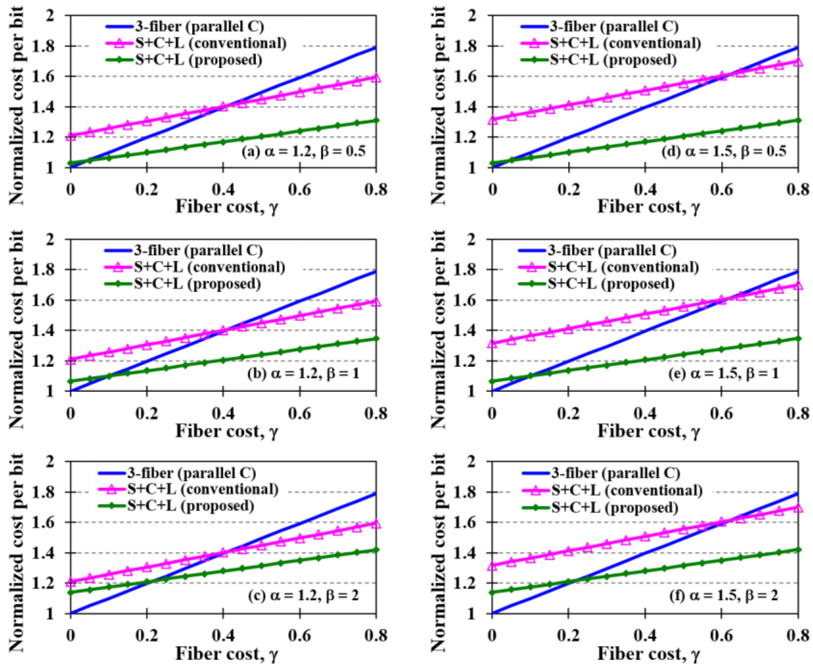


Fig. 3. Normalized cost-per-bit values.

cost-per-bit performance. This is not only because the conventional S+C+L-band one has lower capacity but also because the impact of optical components other than C-band is considerable. This exhibits the potential benefits of our MB-OXC in terms of maximizing the use of well-established C-band technologies on network costs. When comparing two S+C+L-band solutions and a 3-fiber one, although the conventional S+C+L-band solution provides cost-per-bit benefits only when fiber cost is high, the proposed S+C+L-band solution can attain the best results even when fiber cost is low. For instance, assuming that γ is about 0.3 for 5-year fiber leasing (according to the discussion in [5] and dark fiber pricing in US [11]), our proposed solution can achieve cost-per-bit reduction by more than 10% compared to a 3-fiber solution if AO-WC cost is comparable to TR cost. Note that this reduction amount can be larger when the assumed operation period is longer, enabling cost-effective capacity scaling.

4. Conclusions

We conducted a techno-economic analysis in which S+C+L-band networks employing different MB-OXCs and a multi-fiber C-band network are compared. Numerical results elucidated that our band-switchable MB-OXC enables S+C+L-band networks to achieve exceptional cost-per-bit performance compared to a 3-fiber network even when fiber cost is low. This proves the potential of MB networks for further cost-effective capacity scaling.

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