A Cyclic MUX–DMUX Photonic Cross-Connect Architecture for Transparent Waveband Optical Networks

Volkan Kaman, *Member, IEEE*, Xuezhe Zheng, *Senior Member, IEEE*, Olivier Jerphagnon, *Member, IEEE*,
Chandrasekhar Pusarla, Roger J. Helkey, *Senior Member, IEEE*, and John E. Bowers, *Fellow, IEEE*

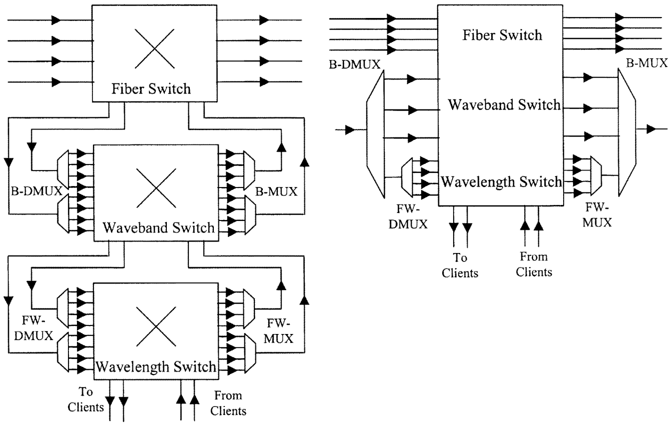
***Abstract*—A novel photonic cross-connect (PXC) configuration with cyclic multiplexers and demultiplexers (DMUXs) is proposed for realizing dynamic switching and transparent add–drop in waveband dense wavelength-division-multiplexed networks. The PXC architecture allows for a flexible operation while maintaining low optical losses for express wavebands and add–drop wavelengths. The drop functionality of this architecture is demonstrated using an integrated cyclic optical DMUX and four 10-Gb/s PIN receivers with an average receiver sensitivity of −34 dBm as a compact and cost-effective solution.**

***Index Terms*—Integrated optoelectronics, optical crosstalk, photonic switching systems, wavelength-division multiplexing.**

I. INTRODUCTION

GROUPING of adjacent wavelengths into wavebands has recently attracted a lot of interest in realizing optically transparent dense wavelength-division-multiplexed (DWDM) networks that employ photonic cross-connects (PXC) [1]–[7]. The main physical characteristics of waveband nodes are a low port count PXC with band-level optical multiplexers (MUXs) and demultiplexers (DMUXs) as well as limited filtering for wavelength-granular add–drop, regeneration, and switching [5], [6]. At the expense of a loss of wavelength in the guard bandwidth between wavebands and a reduced dynamic wavelength-granular network characteristic, express wavelengths in waveband DWDM networks experience low insertion losses and channel passband narrowing, which improve the optical signal-to-noise ratio (OSNR) and, therefore, allow for longer optical transparency distances [4].

The waveband PXC system configuration with its switching and add–drop functionalities strongly depends on the architecture of the waveband DWDM network. The network can be configured such that each waveband strictly consists of a group of wavelengths that share the same add–drop nodes where wavelength granularity is required, which effectively simulates a time-division-multiplexed signal of the same capacity [3]. The network can also be realized by additionally grouping wavelengths that share a common intermediate path within the network without having to share the same add–drop nodes [5]. In comparison to the point-to-point waveband architecture, this architecture requires a limited amount of wavelength switching at specific express sites, which necessitates a multigranular or hierarchical PXC configuration.



(a) (b)

Fig. 1. Multigranular PXC configurations with (a) three switching stages (Architecture I) [5], and (b) a single switching stage (Architecture II) [6]. B: band. FW: fixed wavelength.

Multigranular PXCs have been proposed and realized by using three separate space switches for fiber, waveband, and wavelength switching [1], [5], while more recently a single PXC system with concurrent fiber, waveband, and wavelength switching was proposed [6]. However, both PXC configurations are based on fixed wavelength-selective MUX–DMUXs. In this letter, we present a novel PXC configuration using cyclic (or transparent) MUX–DMUXs for wavelength switching and add–drop functionalities, which increases the flexibility, dynamics, and upgradability of the PXC. We also demonstrate the use of an integrated cyclic optical DMUX with four 10-Gb/s PIN receivers as the drop element of this PXC in waveband DWDM networks.

II. TRANSPARENT WAVEBAND ADD–DROP AND DYNAMIC SWITCHING

Fig. 1(a) shows the multilevel PXC configuration with three separate space switches for fiber, waveband, and wavelength switching (Architecture I) [5], and Fig. 1(b) shows the multigranular PXC configuration with a single switching system (Architecture II) [6]. In terms of optical transport, while the former multilevel configuration requires three switch transitions for wavelength switching (ignoring the fiber switching stage), the latter single-switch configuration has the advantage

---

Manuscript received August 6, 2003; revised October 10, 2003.

The authors are with Calient Networks, Goleta, CA 93117 USA (e-mail: vkaman@calient.net).

Digital Object Identifier 10.1109/LPT.2003.821244

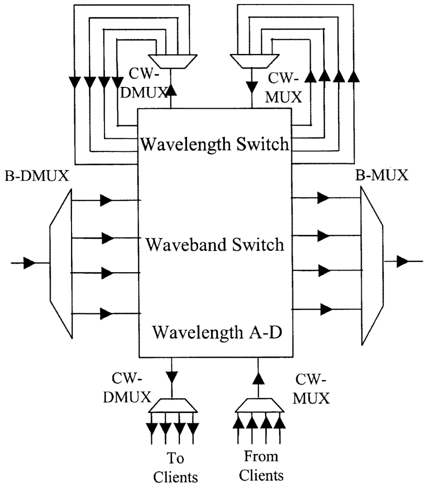


Fig. 2. Proposed waveband PXC configuration using cyclic MUX–DMUX and a single switching stage for add–drop and switching of wavelengths (Architecture III). Fiber switching is not shown as it can be implemented in either Architecture I or II formats. CW: cyclic wavelength.

of reduced optical losses for both switched and add–dropped wavelengths, as the signals need to traverse the optical switch only once. However, Architecture II requires prior knowledge of the wavelengths that need to be switched and add–dropped by placing fixed wavelength-selective filters in conjunction with the band filters. Hence, the flexibility and dynamics of this PXC node is limited as future network demands change, such as routing and wavelength assignment (RWA) processes, leading to potential service interruption to accommodate additional wavelength switching and drop upgrades. On the other hand, this issue is resolved in the multilevel switch configuration as additional wavelength MUX–DMUXs can be added without affecting the current service. However, the use of fixed wavelength-selective filters in both of these systems still limits the dynamics and flexibility of the PXC.

Fig. 2 shows the proposed PXC configuration based on a single switch and cyclic wavelength MUX and DMUXs placed at the add–drop sides of the PXC (Architecture III). A cyclic DMUX is an interleaver that has a periodic passband for each output port, which allows for the demultiplexing of any waveband into individual wavelengths using the same DMUX. In the proposed PXC node, incoming DWDM channels are separated into wavebands by using a band DMUX whose outputs are directly fed into the switch. In the case of the point-to-point waveband network architecture, any of the wavebands can be dropped by traversing the switch only once, and then demultiplexed into wavelengths using the cyclic DMUX. Table I compares the three waveband PXC architectures from a functionality perspective. Since a cyclic DMUX can accommodate any of the wavebands transparently over a broad optical bandwidth, such as an array waveguide grating (AWG)-based DMUX for both the C- and L-bands, at any given time for changing traffic requests and RWA processes, the proposed Architecture III provides dynamic add–drop using a minimum number of wavelength DMUX stages. In comparison, Architectures I and II need to provide each wavelength MUX–DMUX per waveband, even if unused, to be able to provide the same dynamic functionality. Architecture II is also limited to accommodating either the waveband express or its wavelength tributaries at a time, but not concurrently. In contrast, Architectures I and III both allow for the rapid provisioning of wavebands from express wavebands to wavelength-granular add–drops (and vice versa) assuming the necessary wavelength filters are present, although Architecture III provides this capability at a lower initial cost. Furthermore, upgrading an active express waveband to wavelength drop can easily be implemented without disrupting the traffic only in Architectures I and III. On the add port, a similar dynamic and flexible functionality is also achieved using tunable lasers with cyclic MUXs. If the network architecture additionally requires express wavelength switching at the PXC node, cyclic MUX–DMUXs that are routed back to different input–output PXC ports can be added to allow for the transparent wavelength switching of any waveband by crossing the PXC three times, as shown in Fig. 2.

TABLE I
COMPARISON OF THE MAIN FUNCTIONALITIES AND CHARACTERISTICS OF THE THREE WAVEBAND PXC ARCHITECTURES

Functionality and Characteristics	**Architecture I**	**Architecture II**	**Architecture III**
Wavelength-MUX/DMUX Type	Fixed	Fixed	Cyclic
RWA Process Flexibility (e.g. band-to-wavelength-to-band switching)	Flexible	Fixed	Flexible
Upgrade a Band Express to Wavelength-Granular Add/Drop	Non-disruptive	Disruptive	Non-disruptive
Wavelength Add/Drop Loss	High	Low	Low
Integration of Band MUX/DMUX with Optical Switch	Yes	No	Yes
Integration of Wavelength MUX (DMUX) with Transmitters (Receivers)	No	No	Yes

TABLE II
COMPARISON OF THE OPTICAL SIGNAL PATH LOSSES FOR THE DIFFERENT PXC ARCHITECTURES. OPTICAL LOSS OF 3 dB FOR THE SPACE SWITCH, 4 dB FOR THE WAVELENGTH MUX–DMUX, AND 5 dB FOR THE BAND MUX–DMUX ARE USED

Optical Path in PXC	**Architecture I**	**Architecture II**	**Architecture III**
Waveband Switch/Express	13 dB	13 dB	13 dB
Wavelength Add/Drop	15 dB	12 dB	12 dB
Wavelength Switch	27 dB	21 dB	27 dB

III. OPTICAL TRANSPORT CHARACTERISTICS

It is essential from an OSNR perspective that the proposed cyclic MUX–DMUX waveband PXC architecture does not introduce excess loss. Table II compares the optical path losses for waveband express–switching, wavelength add–drop, and switching for the three architectures. The proposed Architecture III maintains the same optical loss for the waveband express–switching paths, and the wavelength add–drop losses are favorably low as in Architecture II while still maintaining the flexibility of Architecture I. As in Architecture I, the wavelength switching paths, which occur less frequently, require optical amplification to overcome the optical loss.

By integrating the band MUX–DMUX with the optical switch, Architectures I and III have the potential to reduce the optical losses as well as providing a compact switching

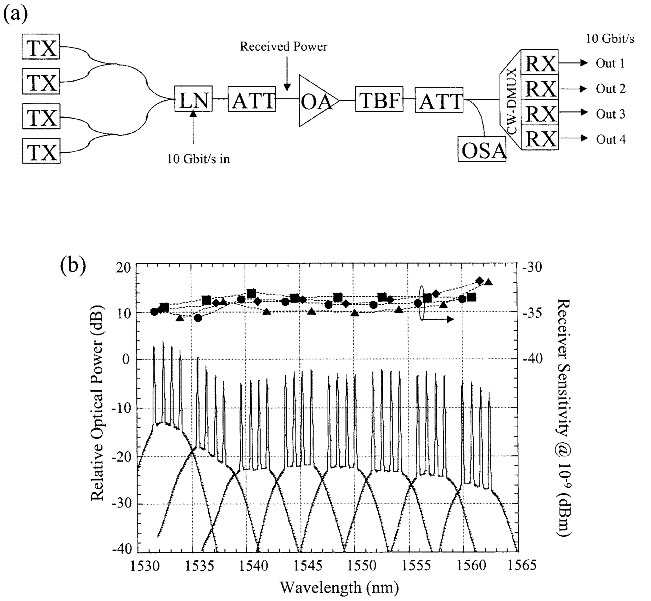


Fig. 3. (a) Experimental setup for testing the integrated cyclic DMUX receiver. TX: tunable laser. LN: modulator. OA: optical amplifier. TBF: tunable band filter. ATT: optical attenuator. RX: integrated DMUX and PIN receiver. OSA: optical spectrum analyzer. (b) Optical spectra (measured after the preamplifier EDFA) and receiver sensitivities at a BER of 10^{-9} for all wavebands in the C-band.

stage. The optical losses for the add–drop wavelengths can be further reduced in Architecture III since the wavelength MUX–DMUX placement allows for a compact and cost-effective monolithic integration with the transmitters and receivers, respectively. This integrated drop concept of the proposed PXC node was demonstrated using a commercially available cyclic AWG-based DMUX integrated with four 10-Gb/s PIN receivers on a single chip (multiwavelength receiver from ASIP, Inc.) [8]. This experimental demonstration not only characterizes the performance of the integrated cyclic DMUX receiver for our proposed architecture, but also simulates a static four-channel add–drop scenario. The 1.5-dB optical bandwidth of the DMUX is 22 GHz with channel spacing of 100 GHz and a crosstalk suppression of better than 20 dB while the typical responsivity of the receivers is about 0.8 A/W. The experimental setup [Fig. 3(a)] consists of four tunable lasers that are combined using 3-dB couplers into a $LiNbO_3$ modulator, which is then modulated by a 10-Gb/s $2^{31} - 1$ pseudorandom binary sequence electrical signal. The four-channel optical signal is then optically preamplified with an erbium-doped fiber amplifier (EDFA) before it is inserted into a 4-nm-wide tunable optical filter followed by a 3-dB optical attenuator. The optical filter and the attenuator simulate the 4-skip-1 band DMUX followed by a free-space optic switch with a 3-dB maximum loss and no other significant optical impairments (for example, see [9]). The waveband is then demultiplexed to four wavelengths and optical-to-electrical converted using the integrated receivers for bit-error-rate (BER) measurements. Fig. 3(b) shows the optical spectra when the signal was intentionally attenuated to produce a BER of approximately 10^{-9} for each waveband before the integrated receiver. The uneven relative power of the wavebands is due to the gain spectrum of the preamplifier EDFA. An average receiver sensitivity of -34 dBm corresponding to a BER of 10^{-9} is achieved for all wavebands [Fig. 3(b)]. Fig. 4 shows the BER measurements and the four eye diagrams corresponding to the individual channels of the first waveband. No error floor is observed and all channels exhibit clear eye openings.

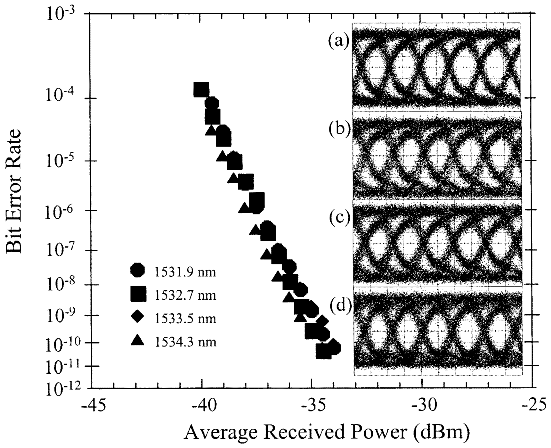


Fig. 4. BER measurements for the first waveband of the C-band. Inset: Eye diagrams of the four channels.

IV. CONCLUSION

A novel PXC node configuration with cyclic MUX–DMUXs was presented for waveband DWDM networks. The use of cyclic MUX–DMUXs gives the PXC dynamic transparency and flexibility for varying traffic requests and future upgrades. An integrated DMUX with four PIN receivers and an average receiver sensitivity of -34 dBm was also demonstrated as a compact and cost-effective drop element especially suited for this PXC architecture.

REFERENCES

[1] A. A. M. Saleh and J. M. Simmons, "Architectural principles of optical regional and metropolitan access networks," *J. Lightwave Technol.*, vol. 17, pp. 2431–2448, Dec. 1999.

[2] K. Harada, K. Shimizu, T. Kudou, and T. Ozeki, "Hierarchical optical path cross-connect systems for large scale WDM networks," *Tech. Dig. Optical Fiber Communications (OFC) '99*, pp. 356–358, 1999.

[3] E. Ciaramella, "Introducing wavelength granularity to reduce the complexity of optical cross connects," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 699–701, June 2000.

[4] O. Gerstel, R. Ramaswami, and W.-K Wang, "Making use of a two stage multiplexing scheme in a WDM network," *Tech. Dig. Optical Fiber Communications (OFC) 2000*, pp. 44–46.

[5] L. Noirie, M. Vigoureux, and E. Dotaro, "Impact of intermediate traffic grouping on the dimensioning of multi-granularity optical networks," *Tech. Dig. Optical Fiber Communications (OFC) 2001*, 2001.

[6] R. Lingampalli and P. Vengalam, "Effect of wavelength and waveband grooming on all-optical networks with single layer photonic switching," *Tech. Dig. Optical Fiber Communications (OFC) 2002*, pp. 501–502, 2002.

[7] R. Izmailov, S. Ganguly, T. Wang, Y. Suemura, Y. Maeno, and S. Araki, "Hybrid hierarchical optical networks," *IEEE Commun. Mag.*, vol. 40, pp. 88–94, Nov. 2002.

[8] C. A. M. Steenbergen, C. van Dam, A. Looijen, C. G. P. Herben, M. de Kok, M. K. Smit, J. W. Pedersen, I. Moerman, R. G. F. Baets, and B. H. Verbeek, "Compact low loss 8 × 10 GHz polarization independent WDM receiver," *Tech. Dig. Eur. Conf. Optical Communications (ECOC) '96*, pp. 129–132, 1996.

[9] X. Zheng, V. Kaman, S. Yuan, Y. Xu, O. Jerphagnon, A. Keating, R. C. Anderson, H. N. Poulsen, B. Liu, J. R. Sechrist, C. Pusarla, R. Helkey, D. Blumenthal, and J. E. Bowers, "Three-dimensional MEMS photonic cross-connect switch design and performance," *IEEE J. Select. Topics Quantum Electron.*, vol. 9, pp. 571–578, Mar./Apr. 2003.