Future Directions in Optical Networking Technology Development
-Optical Fast Circuit Switching and Multilevel Optical Routing-

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Abstract: The inefficiencies of current IP technologies will soon become pressing problems. Extension of optical layer technologies and coordination with new transport protocols will be critical to resolve these problems. Recent technical advances in several fields are highlighted.

Keywords: optical networking technology, waveband, optical fast circuit switching, wavelength routing

1. Introduction

The advances in electrical processing, which includes TDM multiplexing and electrical router/cross-connect/server throughput, now significantly lag the traffic growth rate; the advances were following Moore's law until the early 2000's. To fill this gap, we have been developing and introducing photonic network technologies; DWDM (Dense WDM) transmission with more than a tera bit per second capacity and wavelength routing using reconfigurable optical add/drop multiplexers (ROADMs) have been widely introduced. After 2005, the yearly traffic increase rate fell to 40-50% but router throughput per rack basically saturated due to the high IP-related processing burden and the power consumption constraint. The traffic growth rate of 40% a year is still huge and results in traffic that is 30(/160) times the present traffic in 10(/15) years. Given the emergence of new video centric bandwidth-hungry services, which will include the broadcasting/multicasting and streaming of IP-TV, high-quality videos using high definition (1k x 2k pixels), super-high definition (2k x 4k pixels), and ultra-high definition (4k x 8k pixels) videos, the traffic volume will explode. Super-high definition video, which requires about 6 Gb/s for uncompressed real time transmission, is now utilized in digital cinema [1]. Experimental broadcasting of ultra-high definition TV [2], which requires at most 72 Gb/s (12 bit coding) for uncompressed real time transmission, is expected in 2015 over satellite systems in Japan. To cope with this expected burst in traffic volume, further advances in network performance and cost reductions must be attained. Another important attribute for the future networks is agile reconfigurability. Unlike POTS (Plain Old Telephone Service), the Internet demonstrates unpredictable changes in bandwidth and geographical traffic patterns. New broad bandwidth on-demand provisioning services such as Optical Mesh Service by AT&T [3], JiT (Just in Time) service by Verizon [4], and optical VPN services have become possible with networks that offer agile reconfigurability. Optical layer path protection/restoration requires optical level network reconfigurability. The requirement for adaptability or reconfigurability of networks will become more and more critical and, therefore, the enabling network architecture must be developed. The important technologies are discussed in this paper.

2. Waveband and optical circuit/flow switching

Routing functions in the optical domain with optical paths were first put into commercial use by utilizing ROADMs. OXCs have been used for creating nation-wide testbed networks [5]. The OXCs will be deployed soon to interconnect multiple ROADM rings or to create mesh-based networks. One of the salient features of optical paths is that switch complexity does not depend on the bit rate carried by the optical paths. With electrical technologies, switching becomes more difficult and consumes more electrical power as the bit rate increases. Thus, the wide deployment of optical path technologies will be driven by the traffic increase and the limits created by power consumption and throughput, both of which are inherent in electrical switching. With regard to node throughput enhancement, different directions have been explored as shown in Figure 1 [6]; the introduction of higher-order optical paths (wavebands) and the introduction of optical circuit switching. It will take longer for the latter to yield practical applications than the former.

Against the background of the bottlenecks of present IP network technologies, and the requirements for the future optical networks, we propose the introduction of connection-oriented optical transport capability –fast optical circuit switching. Please note that optical circuit switching networks will overlay the Internet, and the Internet will continue to be utilized for a long time although it will evolve with the introduction of new technologies such as IPv6 and MPLS-TP [7]. Optical fast circuit switching will be suitable for transporting broadband data streams such as nation-wide video content distribution, VoD, and IP-TV. Video-oriented traffic is expected to be dominant in future networks as mentioned before. Regarding optical circuit switching, clarification on the terminology as used in this paper is given below. Connection establishment/tear-down can be done by either external control or be traffic driven; we call the former optical circuit switching and the latter optical flow switching. Optical circuits/flows in optical circuit switching utilize optical paths. In this paper, optical circuit, path, and flow switching will be used interchangeably and are not distinguished.

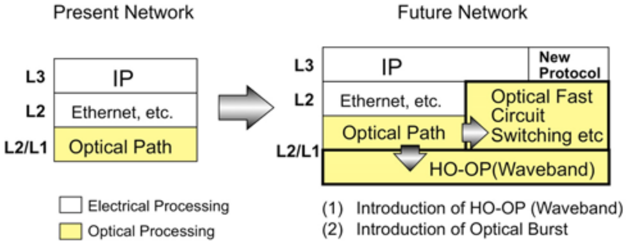
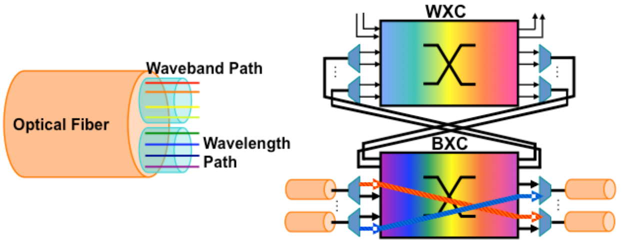


Figure 1 Directions to node throughput enhancement

3. Role of wavebands

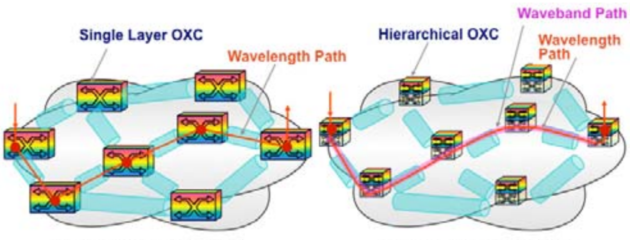
Many publications have discussed optical circuit switching performance, in particular blocking probability and the network resources necessary for establishing optical connections. However, few papers have discussed the network architecture, an omission that is rectified herein. We clarify the role of wavebands in realizing efficient optical circuit switching networks. Figure 2 depicts (a) a wavelength path and a waveband path, and (b) the hierarchical optical path cross-connect configuration [8]. Figure 3 depicts optical path establishment in a single optical path layer network and that in a multilayer optical path network. In a single layer optical path network, optical path establishment/tear-down requires node (optical cross-connect) by node optical switch setting. On the other hand, in a multilayer optical path network, optical path establishment can be done utilizing one (direct) or multiple wavebands. This means that in the connection establishment/release phase, the number of nodes involved is greatly reduced and the connection set-up/release delay minimized. Wavebands are usually established semi-permanently. This scheme requires bandwidth reservation for wavebands even when the optical paths/circuits that can be accommodated within the waveband are not used, which results in reduced resource utilization. The relationship between the optical wavelength path cross-connect and the waveband cross-connect corresponds to that between the electrical switching system and the cross-connect system in POTS networks. In regard to connection establishment and signaling, centralized and distributed control schemes can be applied as demanded by service requirements.



WXC: Wavelength path cross-connect
BXC: Waveband path cross-connect

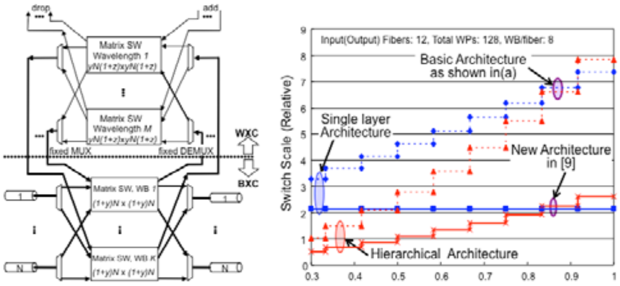
(a) Waveband and wavelength paths (b) Hierarchical optical path cross-connect configuration

Figure 2 Wavelength path and waveband path, and hierarchical optical cross-connect configuration



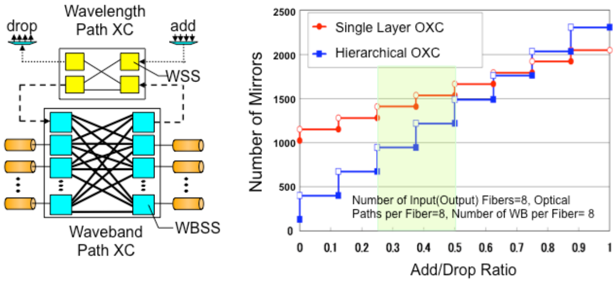
(a) Single Layer Optical Path Network (b) Hierarchical Optical Path Network

Figure 3 Comparison of single layer optical path network and hierarchical optical path network



(a) Hierarchical optical path cross-connect switch architecture based on matrix switches (b) Comparison of switch scales for single layer and hierarchical optical path cross-connect switches

Figure 4 Comparison of single layer and hierarchical optical path cross-connect switch scale



(a) Hierarchical optical path cross-connect switch architecture based on WBSS and WSS (b) Comparison of switch scales for single layer and hierarchical optical path cross-connect switches

Figure 5 Comparison of single and hierarchical optical path cross-switch scale

Compared with single layer optical path networks, the introduction of wavebands can greatly reduce network cost except when traffic volume is very small [8]. One of the fundamental benefits of wavebands is that they can reduce the switch scale needed to realize a specific throughput. This is critical in creating bandwidth-abundant future networks. Figure 4 (a) shows a basic hierarchical optical cross-connect switch architecture using matrix-type switches; (b) shows the switch scale reduction available compared to the corresponding single layer optical cross-connect switch [9]. Here the switch scale is measured by the number of basic 2x2 switches needed to construct the matrix switches. The conventional optical path add/drop ratio for each transit node ranges from 0.25 to 0.5, and the ratios yield switch scale reductions of more than 50% with the addition of waveband technologies. The other important switch architecture is the one that utilizes the WSS (Wavelength Selective Switch) and the WBSS (Waveband Selective Switch). Figure 5 (a) shows a basic hierarchical optical cross-connect switch architecture that uses WBSS and WSS to create waveband cross-connects and wavelength path cross-connects. Figure 5 (b) shows the switch scale reduction possible compared to the corresponding single layer WSS based optical cross-connect switch [10]. Here, for simplicity, switch scale is measured by the number of elemental 3D MEMS mirrors needed to construct WSS and WBSS. For the optical path add/drop ratios of 0.25-0.5, switch scale reduction of 21-48% is possible by introducing waveband technologies. In the hierarchical optical path cross-connect architecture depicted in Fig. 5 (a), the input side or the output side WSS and WBSS can be replaced by optical couplers. The switch scale reduction shown in Figure 5 (a) is not altered by this use of optical couplers.

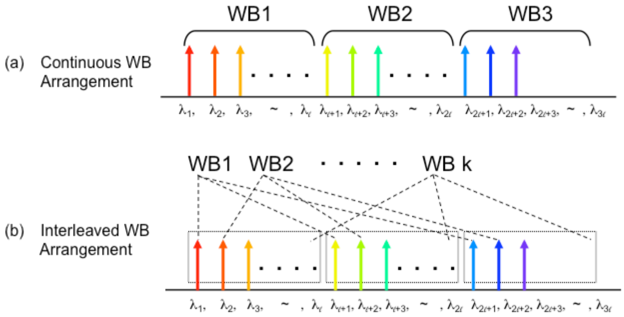


Figure 6 Different waveband arrangements

4. Optical cross-connect switch

Different arrangements are possible for defining wavebands as shown in Fig. 6 [11]. One integrates wavelength paths in a sequential manner whereas the other integrates them in a periodic manner. The waveband arrangement used has virtually no impact in terms of network provisioning and OA&M (Operation, Administration and Maintenance).

The key to the hierarchical optical path networks is the hierarchical optical cross-connect system or switching system. To realize the multi-layer optical path cross-connect, WBSS, an extension of WSS, is essential. Some of the recent advances in WBSS system development are presented below.

Figure 7 depicts a recently developed 5x5 WBXC architecture [12] that consists of five 1x5 WBSS and five 1x5 optical couplers (OC). At the input side of the WBXC, we use OCs instead of WBSSs, since the number of input/output ports is small (OCs have relatively small loss and are very cost effective). The architecture also allows optical multicasting, which will be useful for video distribution. The WBXC is designed to accommodate five input fibers. Each fiber carries forty wavelengths (191.7 + 0.1xn [THz]; n=0-39) in five wavebands; each waveband holds eight wavelengths.

The component WBSS is shown in Fig. 7 [13]. An interleaved channel allocation allows us to use cyclic AWGs for WB MUX/DEMUX in the WBSS, and to use wide channel bandwidth AWGs as MUX/DEMUX in the WXC part (in WSSs), which allows us to utilize cost-effective athermal AWGs. Here, cyclic means that the free spectral range (FSR) of the 1 x M AWG corresponds to the width that covers M consecutive channels. The developed 1x5 WBSS consists of six 1x5 cyclic AWGs and five 1x5 optical switches (Fig. 7). The cyclic AWG has periodic transmission response whose period equals the FSR [14], 500 GHz. This enables the 1st AWG to demultiplex the input signal into the interleaved WBs. Any WB output from the 1st AWG can be selectively routed to output AWGs (2nd AWGs) through the 1x5 switches. Finally, the 2nd AWGs multiplex the WBs and output them. The WBSS is realized monolithically on a chip utilizing PLC technologies; the chip has dimensions of 34 x 64 mm^2 as shown in Fig. 7, and includes six AWGs and five 1x5 switches [13]. In order to compensate the loss variations of the cyclic AWG output ports (waveband), a special connection arrangement between input and output AWGs is applied [13]. The implemented ultra-compact WBXC switch module was fabricated using five WBSS chips as shown in Fig. 7. The module size is 12.5 x 21 x 5 cm^3. The total throughput is 2 Tbit/s (10 Gbps x 40λs x 5 fibers). The average insertion loss was 15.2 dB, but it can be reduced by 2 dB when we use a 1x5 OC instead of the 1x8 OC used by this module. It was confirmed that after traversing 5 modules, the power penalty was about 0.2 dB [12]. Combining two of the modules, with channel grid frequencies offset by 50 GHz, and using 50-100 GHz interleavers, the system throughput is easily upgraded to 4 Tbit/s. Its small size, adjustment-free nature, and good performance further strengthen the advantages of the multi-layer optical path cross-connect.

5. Conclusion

IP convergence is now ongoing, however, we should be prepared for future evolution by identifying the best approach, since the IP bottleneck is becoming more and more tangible and will prevent the network expansion needed; the energy bottleneck and throughput bottleneck must be overcome. It is very difficult to predict future services, but video is expected to be the dominant bit rate demanding media. High-quality video technologies are steadily advancing. The future networks must be extremely efficient at transporting video data streams. To create future networks, the hierarchical optical path network and node technologies, and network architectures that fully harness the power of optical transmission are of great importance. Fast optical circuit/path switching will play a key role in creating cost effective and bandwidth abundant video-centric future networks.

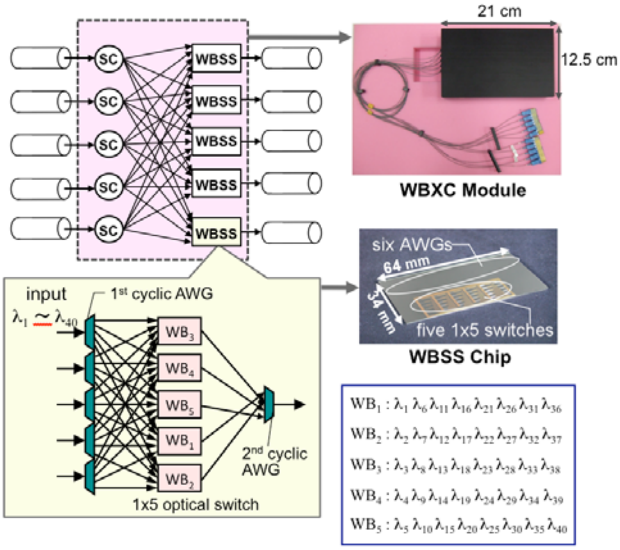


Figure 7 WBXC architecture and developed WBSS chip and ultra-compact WBXC module

6. Acknowledgment

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