Invited Paper

A 10G QoS-Enabled Optical Packet-Switching System: Technology and Experimentation

Steven S. W. Lee[a], Maria C. Yuang[b], Po-Lung Tien[c], Yu-Min Lin[a], Julin Shih[b], and Jason J. Chen[d]

[a]Information & Communications Research Labs, Industrial Technology Research Institute, Taiwan
[b]Department of Computer Science, National Chiao Tung University, Taiwan
[c]Department of Communication Engineering, National Chiao Tung University, Taiwan
[d]Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan

ABSTRACT

The paper presents the architecture and experimentation of a 10-Gb/s QoS-enabled almost-all-optical packet switching system (QOPS) for metro WDM networks. By applying cluster-based wavelength sharing and downsized single-staged optical buffers, QOPS is featured by its highly scalable and cost-effective design. In this paper, we first introduce the switch architecture, system operation, and the key techniques. We describe the in-band header/payload modulation and optical label swapping that is suitable for high-speed optical packet switching. We also present the design of the highly efficient Four-Wave Mixing wavelength converters for packet preemption. We then present an adaptive bifurcated routing (ABR) that directs same-connection packets to different switch clusters according to optimal bifurcation probabilities. Experimental and simulation results demonstrate that QOPS can achieve superior packet-loss performance, QoS differentiation, and minimize traffic blocking probability.

Keywords: Optical Packet Switching (OPS), Quality of Service (QoS), Optical Label Switching (OLS), Superimposed Amplitude Shift Keying (SASK), Four-Wave Mixing (FWM), Adaptive Bifurcating Routing (ABR).

1. INTRODUCTION

Current applications of WDM mostly follow the Optical Circuit Switching (OCS) paradigm for long-haul backbone networks. Metro WDM networks, on the other hand, which are geographically closer to users, exhibit a wide range of heterogeneous traffic with different time-varying bandwidth demand and Quality-of-Service (QoS) requirements. Such facts bring about the necessity of exploiting Optical Packet Switching (OPS) [1] that is capable of achieving high statistical multiplexing gains, superior packet loss performance, QoS differentiation, and minimizing traffic blocking probability.

In this work, we aim at the design and experimentation of a 10-Gb/s QoS-enabled almost-all-Optical Packet Switching System (QOPS) that is facilitated with four beneficial features to metro WDM networks. First, full wavelength sharing attains higher degrees of statistical multiplexing gains, however at the cost of requiring a large space switch size, and thus results in poor scalability. To circumvent the problem, QOPS employs cluster-based wavelength sharing where wavelengths are grouped into clusters and wavelength sharing is only allowed within the same cluster. Figure 1 displays the general architecture of a switch with w wavelengths and c wavelength clusters. A switch with k clusters is called a Class-k switch.

Second, QOPS adopts the use of FDL-based single-stage downsized optical buffers. The rational behind the design is based on the following observation shown in Fig.2. We discovered that applying few optical buffers yield immense decline in loss probability. The improvement, however, becomes insensitive and thus unbefitting under larger buffer sizes. For example, an increase of buffer size from 2 to 3 results in almost two order of magnitude of packet loss improvement. However, it needs a buffer increase from 11 to 16 to achieve similar performance. Thus, the packet loss can be maintained with only a small amount of buffers under adequate number of wavelengths in a cluster.

Third, QOPS provides QoS differentiation by means of optical packet preemption, with which a high-priority packet entering a fully occupied system can preempt a low-priority packet that is already in one of the optical buffers. As a

Network Architectures, Management, and Applications IV, edited by
Yong Hyub Won, Gee-Kung Chang, Ken-ichi Sato, Jian Wu, Proc. of SPIE
Vol. 6354, 635402, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.691224

result, QOPS achieves superior packet loss probability and effectual QoS differentiation under varying traffic loads. As will be shown how packet preemption is achieved by taking the advantage of multiple wavelength conversion of Four-Wave Mixing (FWM) wavelength converters.

Fourth, we have observed that, satisfying a given packet loss probability, high (low) switch classes attain distinctly greater (smaller) normalized per-wavelength capacities due to more (less) statistical multiplexing gains. Our goal is to determine optimal routing of QOPS networks taking cluster capacities into account. In this paper, we propose a new Adaptive Bifurcated Routing (ABR) method for OPS networks with switches possessing different clusters and capacities. Differing from existing routing methods, ABR directs packets of the same connection to different switch clusters in accordance with optimal bifurcation probabilities. As will be shown, ABR achieves superlative load balancing and thus drastic decrease in connection blocking probability compared to other adaptive routing methods without bifurcation.

The remainder of this paper is organized as follows. In Section 2, we describe the architecture of QOPS and key techniques used in the system. The experimentation and the simulation results of packet loss probability are then presented in Section 3. In Section 4, we introduce the ABR scheme. We provide the problem formulation and draw comparisons of traffic blocking probability. Finally, concluding remarks are made in Section 5.

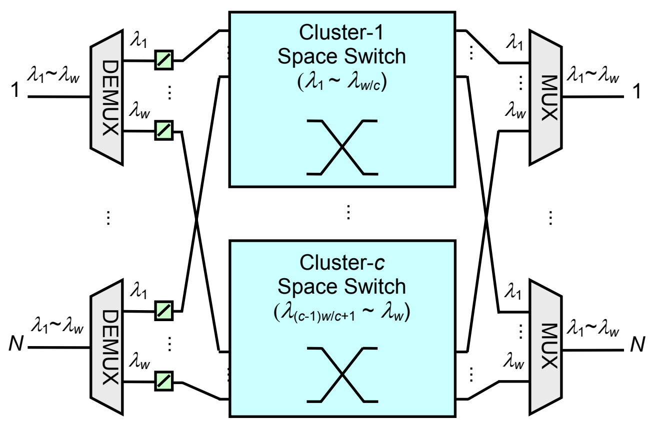


Figure 1. Architecture of a Class-c optical switch.

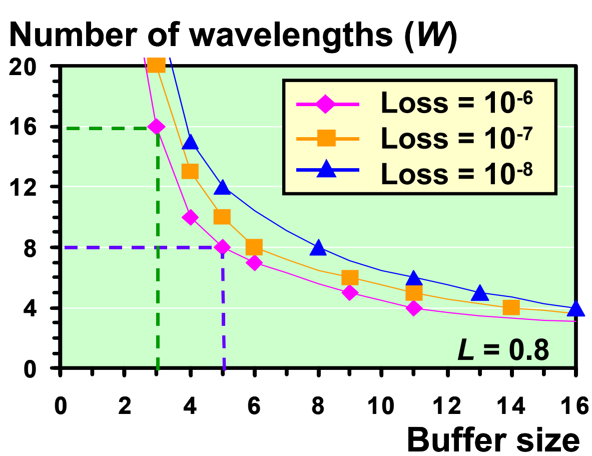


Figure 2. Packet loss probability under different size of buffers and number of wavelengths.

2. SYSTEM ARCHITECTURE AND KEY TECHNOLOGIES

QOPS is a synchronous switching system that supports fixed-size packets. It consists of two parts- the optical switch and the Central Switch Controller (CSC), as shown in Figure 3. While the header of each packet is electronically processed by CSC, the payload travels within the optical switch all-optically. The header that carries forwarding (i.e., label) and QoS (i.e., priority) information is modulated with its payload based on the Superimposed Amplitude Shift Keying (SASK) technique [2]. Upon packet arriving at QOPS, the label is SASK-based swapped [2] and the priority information is passed to the QoS Control module which determines the destined wavelength and delay to which the packet belongs. QOPS is specially featured by its QoS capability. A newly arrived high priority packet can preempt a low priority packet that has been in the system if the optical buffer is fully occupied. The preemption is achieved by the fast FWM-based wavelength converters [3] which are able to convert multiple wavelengths at the same time. We describe the detailed of system architecture, the SASK, and the FWM wavelength converter in the following sections.

2.1 System Architecture and Operation

The optical switch consists of four sections: input, Many-to-One Space Switch (MOSS), output buffer, and output sections. In the input section, there are N input/output fibers, each carrying n wavelengths. After DEMUX, each Tunable Optical Wavelength Converter (TOWC) converts the wavelength on which a packet is carried to an internal wavelength that is associated with the free space of the output buffer for the packet. For a Class c QOPS, in the MOSS section, there are c space switches corresponding to c clusters of wavelengths, respectively. Specifically, space switch C_k takes on n/c wavelengths, from $\lambda_{(k-1)n/c+1}$, $\lambda_{(k-1)n/c+2}, \ldots, \lambda_{kn/c}$, for each of N fibers. Thus, the size of each space switch is $N \cdot (n/c) \times N \cdot (n/c)$, where c is the number of clusters in the switch. Then, each packet will be switched to the outlet that corresponds to the destined wavelength and output fiber on which the packet is carried. Notice that by Many-to-One, multiples packets coming from different inlets can be switched to the same outlet using different wavelengths.

Followed by the MOSS, the output buffer section contains n sets of FDL-based shared optical buffers corresponding to n wavelengths, respectively. Each set of buffers is composed of a pair of Arrayed Waveguide Grating (AWG's) and a set of F optical FDL's connecting the AWG's. Such buffer set can accommodate B packets at once, where $B=(F-1) \cdot M$, and M is the number of internal wavelengths used within the switch. Notice that a packet entering the buffer at the ith input port of the first AWG will exit the buffer from the ith output port of the second AWG after receiving a specific delay determined by the QoS control module. Most significantly, more than one packet may be arranged to exit from the same output port of the second AWG. Nevertheless, only one packet with the highest priority can be passed (through the

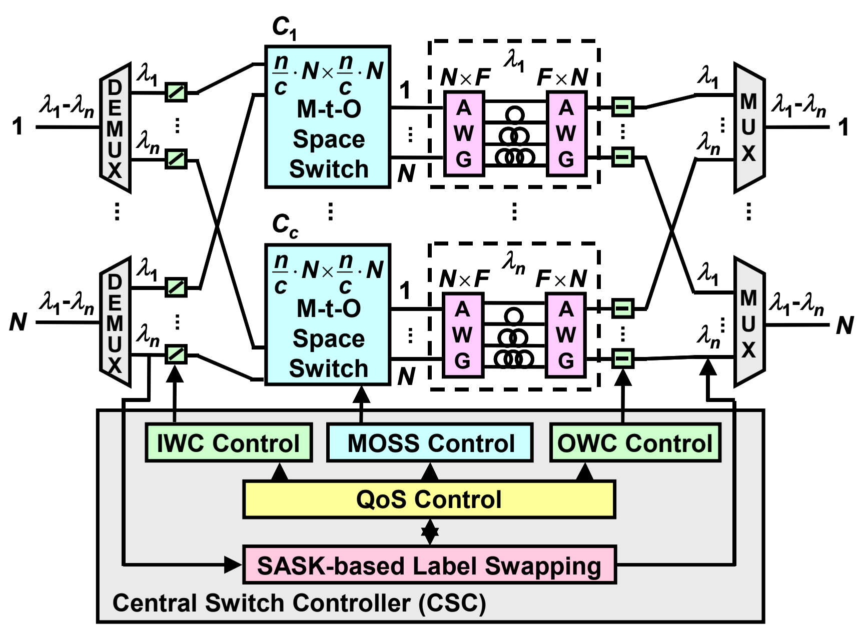


Figure 3. QOPS system architecture.

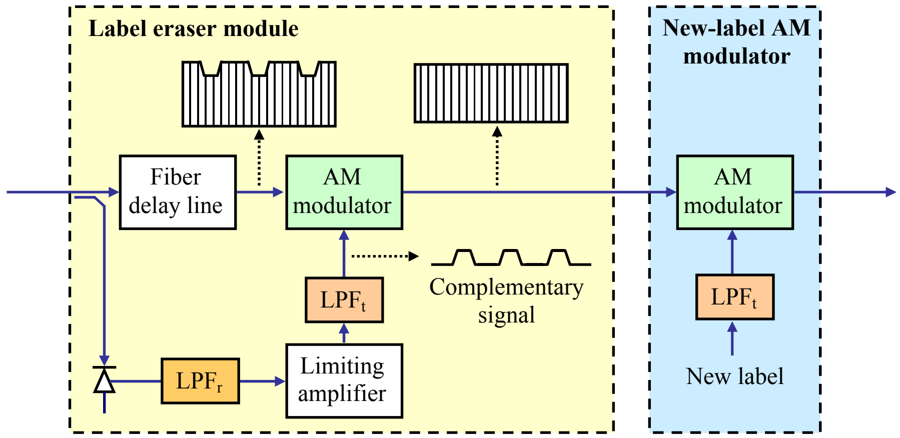


Figure 4. SASK label swapping subsystem.

optical filter) preempting other earlier arriving lower priority packets in the delay lines. Finally, wavelength selection is performed via MUX's in the output section.

The QoS control module performs packet scheduling as follows. Simultaneous arriving high- and low-priority packets are randomly scheduled and assigned from the wavelength with the smallest delay. If the system is full, a low-priority packet is dropped, and a high-priority packet can preempt the low-priority packet receiving the lease delay.

2.2 Superimposed Amplitude Shift Keying (SASK) Technique

QOPS is an Optical Label Switching (OLS) system that follows the operation of GMPLS protocols. A label which carries forwarding and QoS information is modulated with the payload based on the Superimposed Amplitude Shift Keying (SASK) technique. As shown in Figure 4, SASK superimposes a low-speed ASK label on top of a high-speed DC-balanced line-coded ASK payload. At any intermediate switching node, the old ASK label is erased by modulating the combined payload and label signal with the inverse of the received ASK label. It has been shown [2,8] that such technique requires only low-speed external modulators and low-speed optical receivers to perform label swapping. As a result, sophisticated phase modulation devices or optical components, such as MZI-SOA, can be eliminated.

The basic building blocks of an optical transmitter are two-stage intensity modulators. A continuous-wave light source is first modulated by a high-speed Non-Return-to-Zero (NRZ) payload with a large modulation depth. It is subsequently modulated by a low-speed NRZ label with a small modulation depth. A DC-balanced line-encoder was adopted to suppress the low frequency energy of the payload signal. An 8B/10B line code has been adopted due to high practicability and bandwidth efficiency. It is worth noticing that the determination of a proper modulation depth for a label signal is crucial to the system performance. On one hand, a label with a low modulation index cannot sustain multi-hop long-distance transmission due to payload interference and transmission noise. On the other hand, a label with a large modulation index may result in a decrease in payload signal power, and thus higher residual noise due to non-ideal label erasers.

At each intermediate switching node, label swapping is performed by an optical label swapping subsystem that is composed of a label eraser module and a new-label AM modulator. In the label eraser module, a portion of the input signal is detected through a passive optical tap and a photodiode. A Low Pass Filter (LPFr) at the receiver front end is used to remove the payload signal and out-of-band noise. A limiting amplifier and a Low Pass Filter (LPFt) are then used to provide a constant amplitude and to reshape the received label waveform, respectively. The LPFt in the switching node should have a frequency response as close to that of the transmitting-end LPFt in order to inversely compensate the superimposed old label. Should the received label have a low error-rate performance, it can be considered as an analog copy of the original label signal. We use this re-shaped label, called complementary signal, to reverse modulate the optical signal via the AM modulator. Notice that a fiber delay line is placed before the AM modulator to minimize the deterministic phase error between the incoming and complementary signals. Consequently, most of the incoming (old) label can be removed.

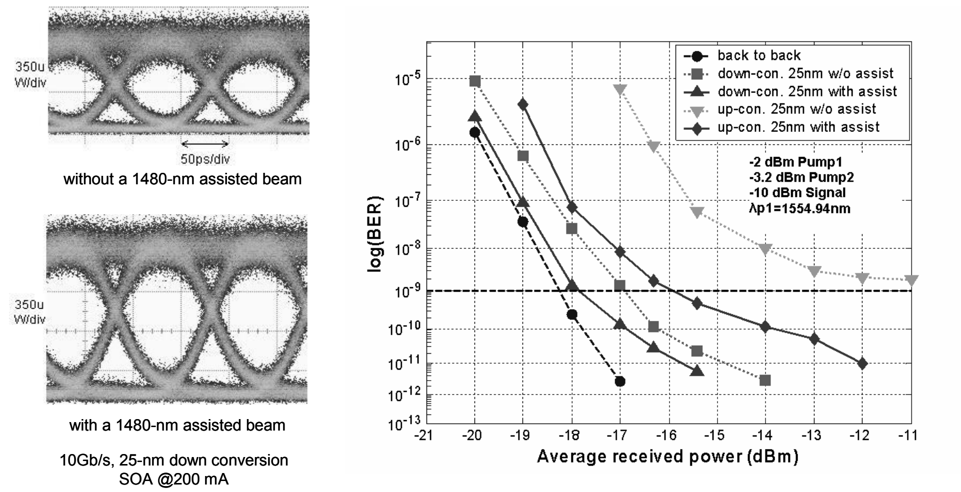


Figure 5. Performance of the FWM-based OWC.

The performance of the Label Eraser may be affected by the timing error during matching the path of the fiber delay line and that of the electrical signal (see Figure 4). In the absence of noise, since all components on both paths are analog and not clock driven, the timing difference is a static value. Thus, timing control can be carried out by a manually tunable optical delay line, which can compensate the delay difference within tens of picoseconds. In the presence of noise, the random timing jitter problem arises from the Limiting amplifier as a result of the amplitude noise, subject to the selections of modulation index, optical amplifier spacing, and received power. A detailed performance analysis in this case has been presented in paper [2]. In general, using a modulation index of 0.22 and an optical received power of -14dBm, the label signal integrity can be fully maintained in 10-hop links [2].

Notice that an important design parameter of SASK is the data rate for payload and label. To avoid payload's interference to the low-frequency label, not only the DC-null channel coding is used in payload signal, but also the label's data rate should be relatively low compared to the payload's data rate. The payload and label rates are 10G/b and 125 Mb/s in the experiments shown in Section 3.

2.3 High Efficient SOA-based Four-Wave Mixing Wavelength Converter

We use a FWM-based wavelength converter to be the outbound OWC in QOPS system. Four-wave mixing (FWM) is distinguished from other wavelength conversion techniques by its ability to simultaneously convert a number of input wavelength channels [4,5]. However, it generally suffers from poor conversion efficiency and narrow conversion range. Significant improvement on the signal-to-background-noise ratio (SBR) and the conversion wavelength range is required for practical applications in optical switching networks. We have developed a new FWM wavelength converter which has high conversion efficiency and wide conversion range by applying a 1480-nm assisted beam in the SOA [3].

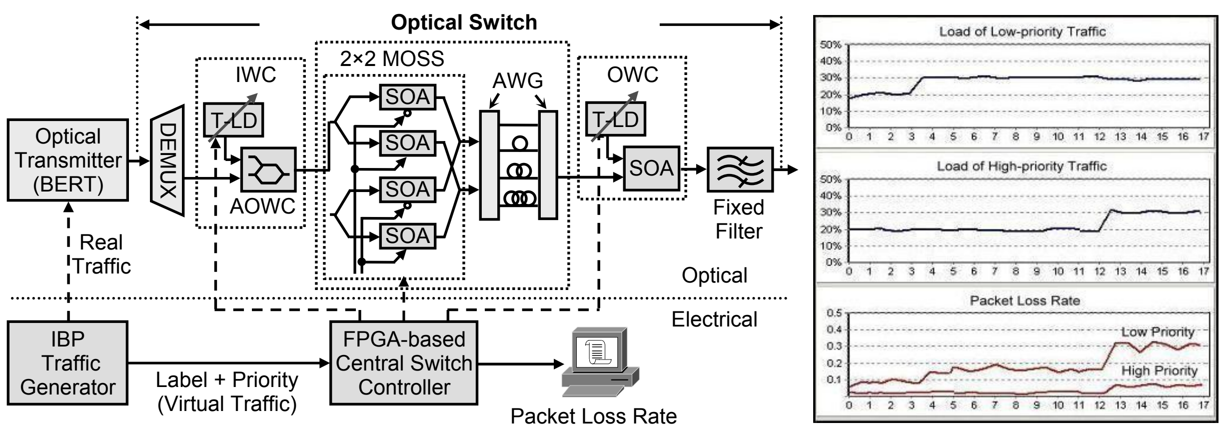
The wavelength converter combines the merits of using the two orthogonal polarized pumps (OPPs) scheme and an assisted beam [6]. The assisted beam allows obtaining high conversion efficiency by using a SOA with moderate gain and the OPP scheme provides wide conversion range. It is known that the maximum FWM efficiency is proportional to the unsaturated gain and square of the saturation power of an SOA. Therefore, increasing the gain and/or saturation power of a SOA is the key to improve the conversion efficiency and SBR. Since the fiber-to-fiber gain of a commercial SOA is typically around 20 dB, the maximal gain is usually limited by the amplified spontaneous emission (ASE) and the thermal effect. Instead, the saturation intensity and wavelength conversion efficiency of a single-pump SOA converter can be increased with a short-wavelength assisted beam [6].

Fig. 5 shows the performance improvement by using a 1480-nm assisted beam. The 1480-nm assisted beam increases the signal amplitude by > 3dB and enhances the eye opening. The power penalties at a BER of 10^{-10} for 25-nm down-conversion without and with the assisted beam are less than 1.2 dB and 0.8 dB, respectively. With the help of an assisted beam, the BER can be better than 10^{-10} with a power penalty of 2.7 dB for up-conversion. An assisted beam can reduce the power penalty because it improves not only the conversion efficiency but also the SBR. Further detailed results can be found in [3].

3. EXPERIMENTATION AND RESULTS

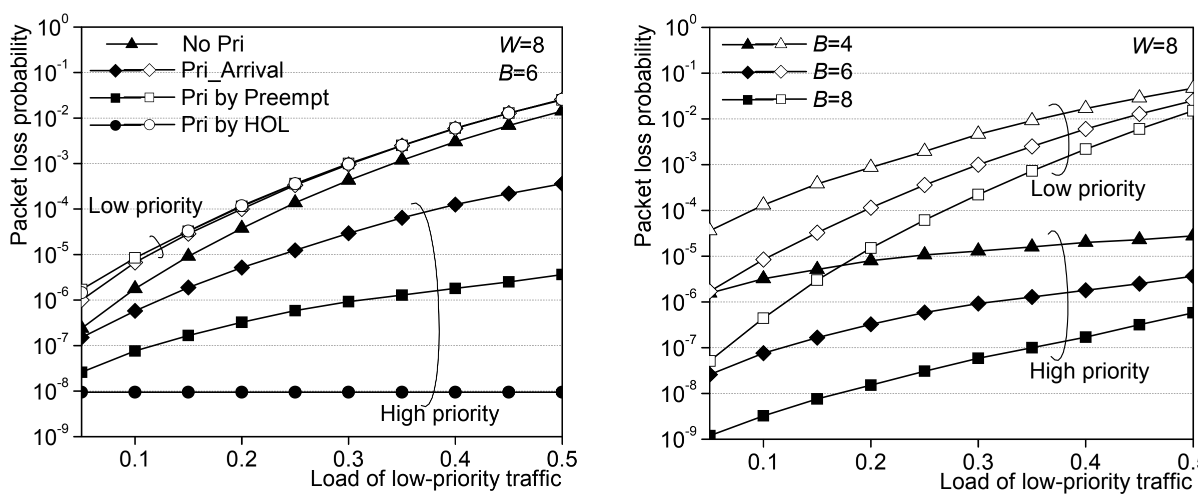
We set up an experimental testbed to demonstrate the feasibility and performance of QOPS, as shown in Figure 6(a). The testbed operated at a data rate of 10 Gb/s and was time-slotted with each slot being 0.64 μs or 800 bytes long. Without loss of generality, we only implemented one optical signal path. In the control plane, an FPGA-based traffic generator produced four traffic channels using two different labels (fibers 1 and 2) and two priorities (H and L), respectively. For each channel, the traffic arrivals were generated following an Interrupted Bernoulli Process [7] characterized by two parameters (α,β), where α (β) corresponds to the probability of the state change per slot from "ON" ("OFF") to "OFF"("ON"). While the first-channel traffic was used to trigger the 10 Gb/s data pattern generator to actually pump out data packets, the remaining three channel's information was passed to CSC to virtually emulate the environment with desired traffic and loads. The packet loss rate over time was monitored and displayed on a PC.

In the optical switch, based on cross-phase modulation (XPM), the Input Wavelength Converter (IWC) was implemented by a fast tunable laser and Mach-Zehnder interferometer with a transient time shorter than 200 ns. The input wavelength (1550.92 nm) that carried packets was first converted to one of four AWG wavelengths, 1544.13 nm, 1545.72 nm, 1550.52 nm, and 1552.12 nm, corresponding to 0- to 3-packet delays, respectively. The many-to-one switch consisted of fiber couplers and Semiconductors Optical Amplifiers (SOA's). While couplers were used to broadcast packets, SOA's functioned as on/off gates with a switching time less than 50 ns and an on/off extinction ratio greater than 30dB with a



(a) Experimental setup (b) Packet loss rate shown on PC

Figure 6. Experimentation and results.



(a) Compare with different scheme (b) Loss in different buffer size

Figure 7. Simulation results.

140mA switching current.

With the aim of converting multiple wavelengths at the same time, the Output Wavelength Converter (OWC) was implemented by means of the Four-Wave-Mixing (FWM) technique shown in Section 2. Followed by OWC, a fixed optical filter was used to extract the desired wavelength (1540.56nm) from the converted wavelengths.

Figure 6(b) displays snapshots of the packet loss rate over time. In the experiment, we first increased the low-priority-traffic load at time 3, followed by raising the high-priority-traffic load at time 12. Testbed results show that high-priority traffic experienced unaffected loss rate prior to time 12, and suffered higher loss only under an increasing traffic load of the same class.

We further draw comparisons of packet loss probability among four QoS schemes: priority-less (PL), priority upon arrivals (PA), PA with preemption (PA+P), and head-of-line priority (HOL). Notice that, PA+P is our approach described above. While in PA, priority takes effect only upon arrivals; HOL gives absolute priority to high-priority packets, which cannot be realized for switches with non-circulated FDL-based buffers. In simulations, there were 40 high-priority and 40 low priority channels, each given identical load and IBP arrivals with probabilities of switching from ON to OFF and OFF to ON being 0.225 and 0.225A/(1-A), respectively, where A is the mean arrival rate. Figure 7 displays packet loss probability under increased low-priority traffic load and a given high priority traffic load (0.4). We discover from Figure 7(a) that our scheme (PA+P) distinctly outperforms PL and PA and PL. Finally, as shown in Figure 3(b), QOPS achieves great QoS differentiation between high- and low-priority traffic by four orders of magnitude under aggregate loads 0.7 and above.

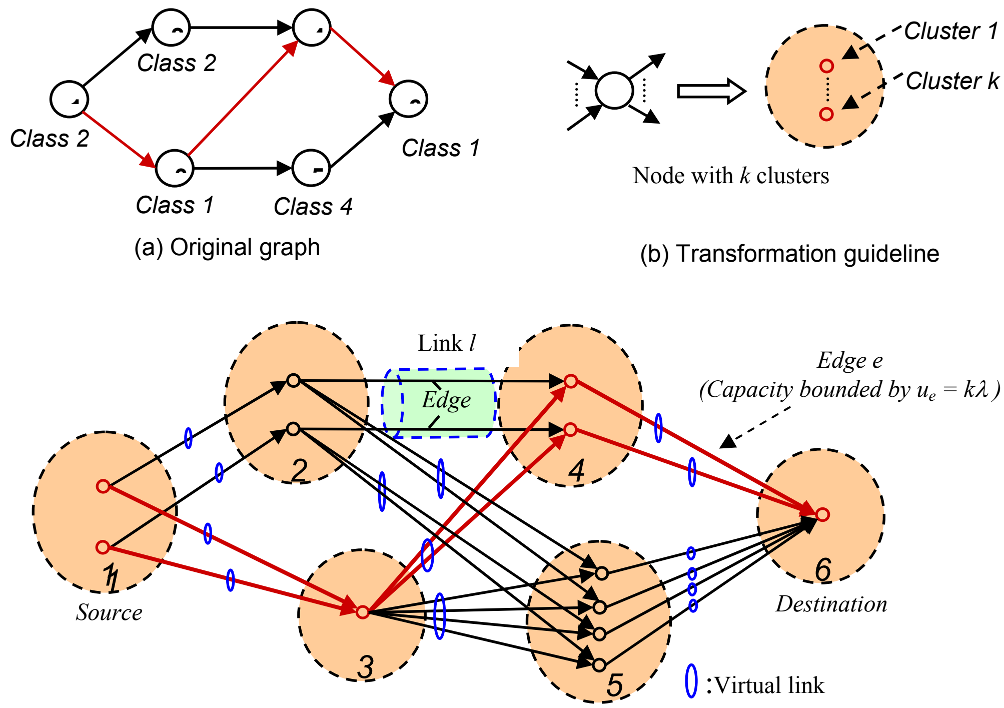
4. ADAPTIVE BIFURCATED ROUTING (ABR) IN CLUSTER BASED OPS NETWORKS

We have observed that in a cluster-based wavelength sharing switch, satisfying a given packet loss probability, high (low) switch classes attain distinctly greater (smaller) normalized per-wavelength capacities due to more (less) statistical multiplexing gains. Table 1 displays simulation results of the normalized capacity for various classes of switches (without optical buffer), satisfying 10^{-6} loss probability, under 2, 3, and 4 input ports each with four traffic-load ratios, and w=32. For example, a 2-port Class-1 switch offers normalized capacity 0.53 that is three times as high as that of a Class-4 switch (0.17). Saliently, the capacity gain is more insensitive to the number of multiplexed input port and traffic load ratio. Then, the cluster capacity becomes the per-wavelength capacity multiplied by the number of wavelengths in the cluster. Our goal is to determine optimal routing of OPS networks taking cluster capacities into account.

Due to the structure of cluster switch, a graph transformation is first required. For each node with k clusters, it is replaced by a subgraph with k artificial vertices. These artificial vertices are interconnected by corresponding artificial edges depending on their wavelengths relationship. Artificial edges that belong to the same cluster are grouped into a virtual link. An example of the transformation is shown in Figure 8.

Table 1 Per-wavelength capacity of different switch classes (w=32)

		1:1	1:2	1:4	1:8
Class-1	2 ports	0.530	0.534	0.565	0.603
Class-2		0.350	0.360	0.380	0.420
Class-4		0.170	0.175	0.190	0.210
Class-8		0.040	0.042	0.046	0.054
		1:1:1	1:2:4	1:4:16	1:8:64
Class-1	3 ports	0.490	0.510	0.550	0.593
Class-2		0.320	0.335	0.370	0.413
Class-4		0.150	0.156	0.177	0.204
Class-8		0.035	0.037	0.042	0.052
		1:1:1:1	1:2:4:8	1:4:16:64	1:8:64:512
Class-1	4 ports	0.480	0.492	0.537	0.593
Class-2		0.310	0.320	0.363	0.410
Class-4		0.140	0.148	0.175	0.202
Class-8		0.032	0.035	0.042	0.051



(a) Original graph

(b) Transformation guideline

(c) Transformed graph

Figure 8. Graph transformation.

4.1 Problem Formulation

The proposed adaptive bifurcated routing (ABR) directs same-connection packets to different switch clusters according to optimal bifurcation probabilities. Given a physical topology including cluster capacities of switches, a source (*src*) and destination (*dest*) node pair, and traffic demand *d*, the ABR problem is to determine a path and all bifurcation probabilities so as to optimize a given objective function. Based on the graph transformation shown in Figure 8, we formulate ABR as an Integer Linear Programming (ILP) problem as follows.

<u>Input values</u>:

N: denote the switch node set;

L: the physical optical link set;

M: the virtual link set;

(V,E): the artificial vertices and edges set, namely the cluster set on the transformed graph;

E_l: the artificial edge set inside physical link l;

E_m: the artificial edge set inside virtual link m;

V_n: the artificial vertices inside node n;

C_m: denote the capacity of virtual link m ;

t_e: the existing flow on artificial edge e;

$\varphi_{nl} = -1$, if link l exists from node n; =1, if link l enters node n; and =0, otherwise.

$\eta_{ve} = -1$, if edge e exits from vertex v; =1, if edge e enters vertex v; and =0, otherwise.

<u>Decision variables</u>:

x_l=1, if l is included in the final optimal path; and =0, otherwise.

y_e/d: the optimal bifurcation probability for edge e, where y_e represents the partial traffic demand flowing into edge e.

Thus, ABR is formulated as follows.

Problem (ILP):

$$\min \sum_{l\in L} w_l x_l$$

subject to:

$$\sum_{l\in L}\varphi_{nl}x_l = \begin{cases} -1, \text{if } n = src \\ 1, \text{if } n = dest \\ 0, \text{otherwise} \end{cases} \qquad \forall n \in N \qquad (1)$$

$$x_l = 0 \text{ or } 1 \qquad \forall l \in L \qquad (2)$$

$$\sum_{e\in E_l} y_e = dx_l \qquad \forall l \in L \qquad (3)$$

$$\sum_{e\in E}\eta_{ve}y_e = 0 \qquad \forall v \in V, v \notin V_{src} \bigcup V_{dest} \qquad (4)$$

$$y_e \le u_e \qquad \forall e \in E \qquad (5)$$

$$\sum_{e\in E_m} t_e + y_e \le C_m \qquad \forall m \in M \qquad (6)$$

Constraint (1) and (2) give path routing constraints. Constraint (3) requires that the traffic demand being carried on the edges inside the selected links. Constraint (4) states the flow conversation law for each vertex. Constraints (5) and (6) are the capacity constraints. In our work, we consider three ABR methods respectively satisfying three objective functions associated with three different weight assignments. They are (1) Shortest Feasible Path with Bifurcation (SFP+BF): w_l =1; (2) Weighted Feasible Path with Bifurcation (WFP+BF): $w_l = \sum_{e\in E_l} t_e \Big/ C_l$; and (3) Reciprocal of Residual Capacity with Bifurcation (RRC+BF): $w_l = 1\big/(C_l - \sum_{e\in E_l} t_e)$.

4.2 Simulations

We carried out simulations over two randomly generated networks with 14 and 20 nodes, respectively, as shown in Figure 9. In simulations, without loss of generality, all switches in the network were assumed to have 32 wavelengths. Switches were set to be of one of three classes (Class-1, Class-2, and Class-4). The source and destination pair was randomly selected with traffic demand being uniformly distributed between 0 and 1λ. The ILP ABR problem was solved directly through CPLEX package. We drew comparisons between three variants of ABR methods and three corresponding adaptive routing approaches without bifurcation, i.e., SFP, WFP, and RRC. We measured the Traffic Blocking Probability (TBP), defined to be the ratio of rejected connections' traffic demand to the total requested traffic demand, under different network loads in unit of Erlang (network call arrival rate × mean call holding time). Simulation results are plotted in Figure 10. Simulation results show that, the three ABR variants distinctly outperform the three corresponding routing mechanisms without bifurcation irrespective of network size and load.

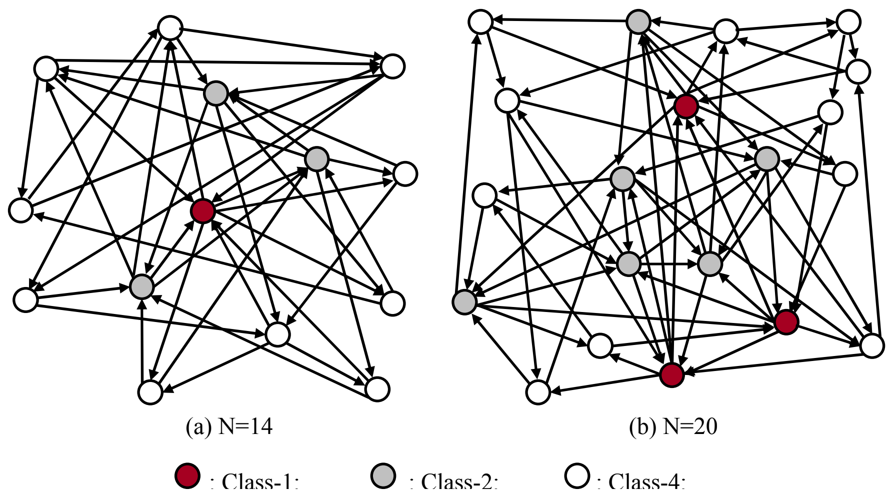
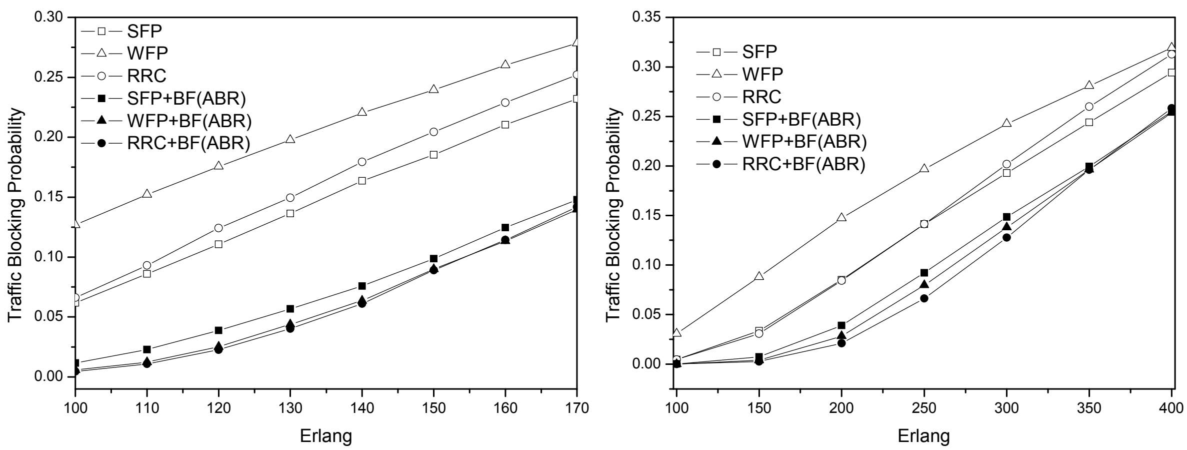


Figure 9. Network topology.



(a) Comparison under N14 network (b) Comparison under N20 network

Figure 10. ABR Simulation results.

5. CONCLUSION

In this paper, we have presented the architecture of QOPS, a 10-Gb/s QoS-enabled almost-all-optical packet switching system. QOPS is facilitated with scalable many-to-one space switch and downsized single-staged optical buffers. Those features make QOPS to be highly scalable and to achieve superior packet loss probability and QoS differentiation performance. The system performs efficient optical label swapping by the proposed SASK-based modulation of the header and optical payload. In addition, QoS differentiation is provided by means of packet preemption that is achieved by our high efficient FWM-based wavelength converters. To minimize the call blocking probability, the proposed ABR algorithm provides optimal bifurcated routing by taking cluster capacity into account. ABR achieves superlative load balancing and thus drastic decrease in connection blocking probability compared to other three adaptive routing methods without bifurcation.

REFERENCES

1. S. Yao, B. Mukherjee, and S. Dixit, “Advances in Photonic Packet Switching: An Overview,” IEEE Comm. Mag., vol. 38, pp. 84- 94 (2000).
2. Y. Lin, M. Yuang, S. Lee, and W. Way, “Using Superimposed ASK Label in a 10 Gbps Multi-Hop All-Optical Label Swapping System,” IEEE/OSA J. Lightwave Technol., vol. 22, pp. 351-361 (2004).
3. D. Hsu, S. Lee, P. Gong, Y. Lin, S. Lee, and M. Yuang, “High-Efficiency Wide-Band SOA-based Wavelength Converters by using Dual-Pumped Four-Wave Mixing and an Assist Beam,” IEEE Photon. Technol. Lett., vol. 16, pp. 1903-1905 (2004).
4. C. Politi, D. Klonidis, and M. J. O’Mahony, “Waveband Converters Based on Four-Wave Mixing in SOAs,” IEEE/OSA J. Lightwave Technol., vol. 24, pp. 1203-1217 (2006).
5. Maria C. Yuang, et al. “HOPSMAN: An Experimental Optical Packet-Switched Metro WDM Ring Network with High-Performance Medium Access Control,” ECOC’06.
6. S. Lee, P. Gong, and C. Yang, “Performance Enhancement on SOA-Based Four-Wave-Mixing Wavelength Conversion Using an Assisted Beam,” IEEE Photon. Technol. Lett., vol. 14, pp. 1713–1715 (2002).
7. M. Yuang, P. Tien, and J. Shih, “QoS Scheduler/Shaper for Optical Coarse Packet Switching IP-over-WDM Networks,” IEEE Journal on Selected Areas in communications, vol. 22, no. 9, pp. 1766-1780 (2004).
8. M. Yuang , S. Lee, P. Tien, Y. Lin, J. Shih, F. Tsai, and A. Chen, “Optical Coarse Packet-Switched IP-over-WDM Network (OPSINET): Technologies and Experiments,” IEEE Journal on Selected Areas in Communications, vol. 24, no. 8 (2006).