4 Wavelength Routing / Optical Burst Switching / Optical Access Network

4-1 Experimental Study of a Burst-Switched WDM Network Testbed

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Optical burst switching is considered an attractive switching technology for building the next-generation optical Internet. To investigate its feasibility, evaluate its performance and explore its future direction, we designed and implemented an overlay-mode optical burst-switched network testbed. In this report, we present the node architecture, control algorithm, and performance evaluation of the testbed. A flexible "transceiver + forwarding" node architecture is proposed to perform both electronic burst assembly/disassembly and optical burst forwarding. It is designed to provide class of service and wavelength selection for locally generated bursts, and transparency to cut-through bursts. A scheduling mechanism, which efficiently combines two different contention resolutions in space and wavelength domains, is discussed in detail. Performances of the burst-switched network testbed, including end-to-end delay, burst blocking probability and TCP throughput, are evaluated; and online video services are demonstrated. Furthermore, key determinants of the network performance and future directions are also discussed.

Keywords
Optical burst switching, Burst assembly, Wavelength selection, Burst scheduling, Contention resolution

1 Introduction

The advances of wavelength division multiplexing (WDM) technology and rapid growth of Internet traffic have generated a serious mismatch between huge transmission capacity of optical fibers and routing/forwarding capability of electronic routers, which has triggered many research activities on optical switching technologies. Among various switching technologies, optical burst switching (OBS)[1][2] is considered an attractive switching paradigm because it is more efficient than optical circuit switching in terms of wavelength utilization efficiency and has less stringent requirements for optical devices than optical packet switching.

A data burst and its control signal, in burst-switched optical networks, are transmitted on separate channels and respectively switched in optical and electronic domains. Burst is an aggregation of multiple client data with the same egress node address; it is sent out following its control signal with a short delay called "offset time" without having to wait for reservation acknowledgement (one-way reservation paradigm). The offset time allows intermediate nodes to complete control signal processing and optical switch configuration ahead of the burst arriving; thus no optical buffers are necessary at intermediate nodes.

Since many key issues with OBS, such as burst assembly, signaling, scheduling and contention resolution, have been extensively studied[3]-[8], it is necessary and important to develop a network testbed for evaluating OBS technology. Up to now, several burst-switched node prototypes and testbeds have been developed and demonstrated[9]-[14]. However, most of them mainly focused on some key unit technologies, such as optical switches and signaling protocols, and can not provide a network-wide experimental platform with comprehensive OBS functions. To investigate the feasibility of OBS, evaluate OBS protocols and algorithms, and study the future direction, we have designed and implemented a general-purpose and flexible OBS network testbed. In this report, node architecture, control algorithm, and performance evaluation of the testbed are discussed. A flexible "transceiver + forwarding" node architecture is presented first, which can perform transparent optical burst switching and electronic burst assembly with support for class of service (CoS) and wavelength selection. Then we discuss the design of a scheduling scheme mechanism, which efficiently combines two different contention resolutions in space and wavelength domain. Through a series of experiments, performances of the OBS network testbed are evaluated and discussed finally.

2 Design principles of the OBS network testbed

An ideal testbed is expected to emulate real OBS networks to the maximum, provide a flexible network-wide experimental platform for new ideas and novel technologies, and contribute a viable evolution solution to the next-generation optical Internet. The following key functional requirements especially need to be fulfilled: burst assembly and disassembly, network protocols (e.g., routing and signaling), control algorithms (e.g., scheduling and contention resolution), scale and resources (e.g., sufficient nodes, WDM links, and wavelengths), and compatibility with legacy networks (e.g., interconnection with the Internet). To meet such challenging requirements, a general-purpose and flexible OBS testbed was designed. Detailed principles that we considered in the design are as follows:

(1) ***Compatibility and interoperability with IP networks***

Considering the popularity of IP networks, a testbed ideally needs to be designed to perform asynchronous variable-sized burst switching to match the natural characteristics of IP traffic. Furthermore, an overlay-mode needs to be adopted. This means the testbed can provide OBS functions for IP networks without any changes to them, promising good compatibility and interoperability with existing IP networks and the benefits of network evolution to the next-generation optical Internet.

(2) ***Generality, modularity, and expandability***

To provide an open evaluation environment, a testbed needs to be designed so that it is general-purpose, which is achieved with a transparent data plane and a reprogrammable control plane. It can support various traffic, protocols, and algorithms, e.g. flow/label/wavelength switching for IP or other traffic, just-enough-time (JET)[2] and just-in-time (JIT)[15] protocols. An OBS node needs to be divided into multiple functional modules. Each of these, such as the switch matrix, needs to be integrated into an individual circuit board. Higher performance devices, e.g. faster optical switches, can be employed by simply replacing the corresponding board. In addition, a reconfigurable topology and sufficient resources are also important factors in enhancing the generality of the testbed.

Guided by the principles above, we implemented a general-purpose OBS network testbed[16] with flexible node architecture, efficient JET signaling protocol, and novel scheduling mechanism. The testbed consists of one core node and three edge nodes. The IP network is connected to the OBS network through edge nodes. At the ingress edge node, multiple IP packets with the same egress edge node address are assembled into one burst. Then, the burst is routed and forwarded through the OBS network. Finally, it is disassembled back into IP packets at the egress edge node. OBS nodes transmit and switch bursts in the data plane, and exchange and process control signals in the control plane. Since the core node is a simplification of the edge node, we will mainly discuss the edge node hereafter.

3 “Transceiver + forwarding” node architecture

In many previous works, edge nodes only perform burst assembly/disassembly at the boundary of OBS networks. To support various network topologies and more intelligence, however, we propose a flexible “transceiver + forwarding” architecture for edge nodes to forward cut-through bursts, as well as perform burst assembly/disassembly with support for CoS and wavelength selection. As depicted in Fig. 1, an edge node consists of an optical switching unit, a burst transceiver unit, and a control unit. The optical switching unit performs all-optical burst switching. It is composed of couplers, mux/demuxes, an optical switch matrix, power equalizers, and amplifiers. The burst transceiver unit performs burst assembly/disassembly. The control unit processes control signals, configures the optical switch matrix, and controls the burst transceiver unit.

An edge node supports two remote WDM links and four local links as shown in Fig. 1. For simplicity, we use the term *remote link* to denote a WDM link between two OBS nodes, which carries four DWDM burst channels (wavelengths) and one shared control channel (wavelength). Similarly, the term *local link* denotes a link between an OBS node and its client IP network, which carries only one

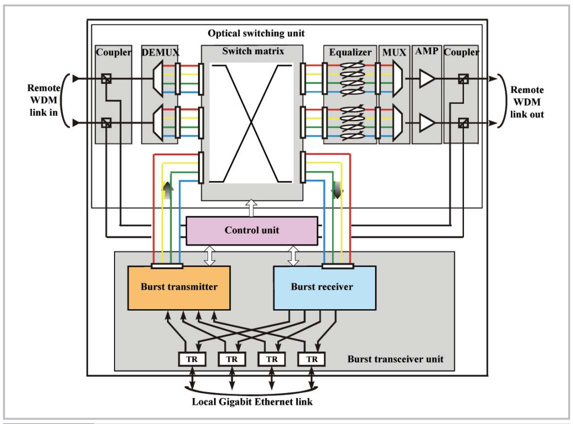

Fig. 1 *Node architecture.*

packet channel without employing WDM technology. For remote links, the control signals are extracted from bursts by couplers and processed in the control unit, while de-multiplexed bursts are sent to the switch matrix. After equalization, multiplexing, and amplification, bursts and control signals are multiplexed into links by couplers. For local links, multiple Ethernet frames are first assembled into bursts at the burst transmitter. Then the optical bursts are sent to the switch matrix. These two types of bursts, referred to as *remote* and *local*, respectively, cut through the switch matrix to their next hop nodes or local burst receiver according to the routing information contained in their control signals. Upon receiving a burst through the local switch matrix, the burst receiver disassembles it into multiple packets, which are forwarded to the legacy IP networks in a conventional way.

3.1 Key issues in the optical switching unit

The key point of designing the optical switching unit is how to implement a high-performance transparent optical path with considerations of optical device limitations and physical-layer constraints. This goal is achieved by commercial high-performance optical devices incorporating carefully designed control circuits. Among them, optical switch and power imbalance are two crucial concerns.

There are various optical switches applicable nowadays[17]. However, considering speed, scale, and reliability, commercial PLC switches were adopted to construct the *16×16* non-blocking switch matrix. The switching speed is less than *3 ms* and the insertion loss is less than *8 dB*.

In OBS networks, power imbalance occurs not only between different links and wavelengths but also within each wavelength because the bursts within a wavelength maybe come from different sources and go through different nodes and paths. Such rapid power fluctuations lead to instability and failure in serious cases. To solve this problem, we designed a dynamic channel-level power equalization scheme. By using a magneto-optical variable optical attenuator (VOA) array and a carefully designed feedforward control circuit, power equalization could be completed within *3 ms*, which includes the response time of the VOA and feedforward processing time.

3.2 Burst transceiver supporting CoS and wavelength selection

Considering the importance of CoS and the wavelength assignment issue in OBS networks, we focused our attention on how to efficiently and flexibly support CoS and wavelength selection in the design of the burst transceiver unit. As shown in Fig. 2, a new “3-level FIFOs + 2-level switch” burst transmitter architecture is proposed and implemented with an Altera high-end FPGA. The three-level first-in first-out buffers (FIFOs) are used for routing, burst assembly, and scheduling. The first-level switch classifies burst queues by destination and CoS, while the second-level switch executes wavelength selection. All the wavelengths can be shared for any burst, which makes the edge node flexible in supporting various wavelength assignment algorithms, e.g. random and priority-based assignment[18]. To simplify implementation, a burst is designed to be a simple aggregation of multiple Gigabit Ethernet frames with the same egress node address, which could further be classified by CoS. Asynchronous variable-sized bursts are generated to match the natural characteristics of IP traffic. Furthermore, asynchrony simplifies implementation by eliminating synchronization and burst alignment. More precisely, the burst transmitter works as follows:

(1) Gigabit Ethernet frames are buffered in the first-level FIFOs and then switched to the second-level FIFOs according to their egress node addresses and CoS attributes.

(2) Multiple frames buffered in the same second-level FIFO are assembled into one burst according to a time-size-based assembly mechanism[3]. Precisely, a burst is generated when either the assembly time threshold or the burst size threshold is reached.

(3) After channel scheduling, the output wavelength channel and sending time are determined. The generated burst is buffered in the third-level FIFOs and transmitted at the scheduled time.

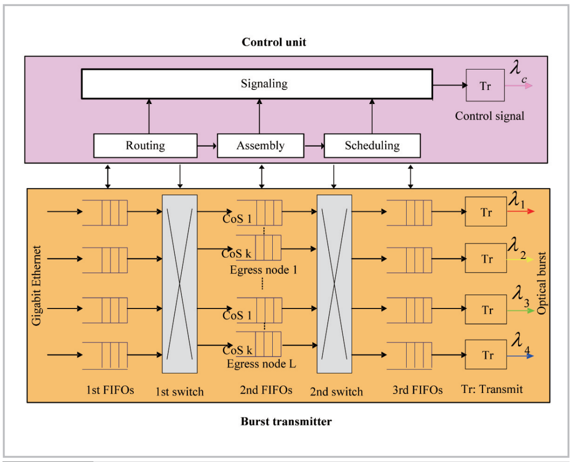

Fig.2 *Burst transmitter and control unit.*

4 Contention resolution and burst scheduling

Since burst transport is in the one-way connectionless manner and optical RAM is not yet available, contention resolution and burst scheduling are more challenging in OBS networks. Although fiber delay line and wavelength conversion have been proposed as contention resolutions, the immaturity of the technologies and the absence of a full configuration for OBS networks have necessitated the study of other approaches. A simple deflection routing protocol[19] and a smart wavelength assignment algorithm, called priority-based wavelength assignment (PWA)[18] have been proposed to efficiently decrease contentions and reduce burst blocking probability. As shown in Fig. 3, the deflection routing approach provides a detour path for a contending burst. With PWA, each edge node maintains a dynamically updated wavelength priority database where every wavelength is prioritized for each destination by learning from its utilization history. More specifically, when a node receives an ACK, which indicates a successful burst delivery, it increases the priority of the corresponding wavelength. Otherwise, on receiving a NACK, which indicates a burst loss, it decreases the priority of the corresponding wavelength. By prioritizing wavelengths, nodes tend to assign different wavelengths to bursts sharing the same links of the network, therefore proactively avoiding collisions as much as possible.

The two approaches above are efficiently combined in a carefully designed burst scheduling algorithm in our OBS testbed. Using the burst status information carried in control signal to indicate the deflection status and failure reason for each burst, wavelength priority could be properly updated while exploiting deflection routing functionality. By comprehensively managing the wavelength priority database, scheduling information tables, and forwarding procedure, the burst blocking probability is decreased and bandwidth utilization is improved. Details on the burst scheduling procedure are described below.

Scheduling information is saved in multiple scheduling tables. For an edge node with M output links and every link carrying N channels, there are $M \times N$ scheduling tables denoted $CST(m, n)$, where $1 \le m \le M$ and $1 \le n \le N$. Each $CST(m, n)$ contains scheduling information in a period of time, TT, including the start and end times of each scheduled burst. A scheduler manages $CST(m, n)$ and keeps track of the unscheduled time.

Figure 4 shows the burst scheduling procedure. For a local burst, the procedure can be divided into the following steps:

(1) When a burst is generated, its output link L is obtained. The scheduler looks up $CST(L, n)$ ($1 \le n \le N$) and finds an available outgoing channel, which is operated in order of channel priority. If one such channel, C, exists, go to Step 3; otherwise go to Step 2.

(2) The scheduler looks for an available outgoing channel in the near future within TT. If it succeeds, go to Step 3; otherwise the burst is discarded.

(3) Output channel C is assigned and scheduling table $CST(L, C)$ is updated.

(4) The burst is buffered and sent at the scheduled time.

For a remote burst, its output link L, and channel C are obtained by interpreting its control signal. Thus, the scheduler looks up

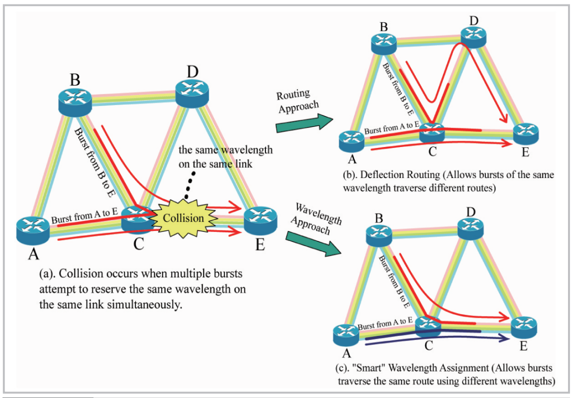

Fig.3 Concepts of deflection routing and PWA.

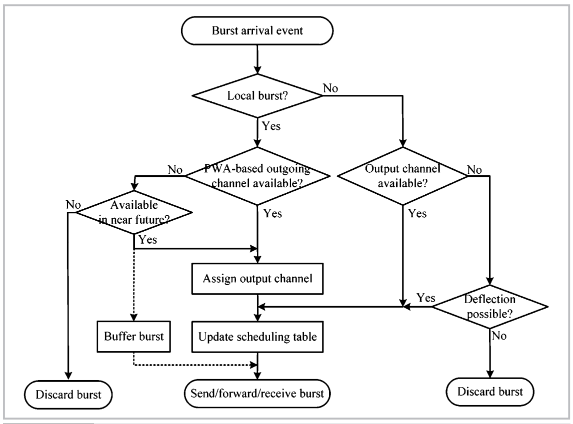

Fig.4 Scheduling procedure.

$CST(L, C)$ and tries to find whether it is available. If successful, $CST(L, C)$ is updated and the burst is forwarded or received; otherwise the burst is deflected or discarded.

This scheduling mechanism needs $O(EN)$ and $O(MN)$ memories to record the channel priority and scheduling information, respectively, where E is the number of edge nodes. It also takes $O(logN)$ time to maintain a ranked priority list, and $O(N)$ time to search a suitable wavelength. The required memory capacity is sensitive to the scale of the network. However, a large-capacity memory is no longer expensive and is easily available. The time for maintaining the priority list and searching the wavelength only depends on the number of wavelengths regardless of the number of nodes.

5 Evaluation and discussion

We built an optical burst-switched network testbed with self-developed OBS nodes; its main specifications are listed in Table 1.

Table 1 Specifications of the OBS testbed

Items		Specifications
Edge node	OBS WDM links	2
	Local Ethernet Links	4
	Power loss	< 0 dB
Core node	OBS WDM links	4
	Power loss	< 0 dB
OBS WDM link	Control channel	1510 nm, 100 Mb/s
	Burst channels	1551.72, 1553.33, 1554.92, and 1556.55 nm, 1.25 Gb/s
Switch matrix (PLC)	Ports	16×16
	Switching time	3 ms
	Insertion loss	< 8 dB
Equalizer (VOA)	Max. attenuation	15 dB
	Resolution	1 dB
	Response time	1 ms
Amplifier (EDFA)	Output power	> -2 dBm
	Gain flatness	< 1dB
Burst transmitter (FPGA)	Assembly time	0 ~ 32 s
	Assembly length	72~15000 bytes

On this OBS network testbed, important performance metrics, including end-to-end delay, burst blocking probability and TCP throughput, were evaluated and discussed. Furthermore, online video services were also demonstrated. Figure 5 outlines the experimental configuration of the OBS network. Three edge nodes were connected with 20 km fibers to form a ring network, where bursts were transferred in a clockwise direction. In experiments of delay and blocking probability, three clients were emulated with an Agilent Router Tester.

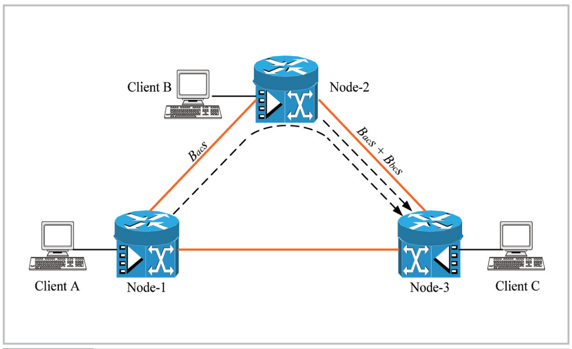

Fig.5 Configuration of the experimental network.

5.1 End-to-end delay

We define end-to-end delay, D, as the average time taken by IP packets from entering an OBS network to exiting it. More specifically, it is composed of four parts:

D_{in}: delay introduced at the ingress node;
TO: offset time between a burst and its control signal;
D_t: propagation delay;
D_e: delay introduced at the egress node.

As a distinct feature of OBS, offset time is an important factor of the end-to-end delay. Therefore we discuss it first. Considering the node architecture and characteristics of optical devices aforementioned, we introduce a guard time in one-way signaling procedure to compensate for the response time of the optical switch and power equalizer. In other words, bandwidth reservation starts ahead of burst arrival with the guard time. In our OBS testbed, the measured guard time was *10 ms*. To leave a margin for control signal processing and to make the transmission more reliable, the offset time *TO* was set to *13 ms* in our experiments.

Burst assembly has a great effect on the end-to-end delay. Hence, we measured the end-to-end delay between clients A and C as a function of burst assembly time, which was plotted in Fig. 6. Due to D_t =*0.2 ms* and D_e < *1 ms* in this experiment, the delay introduced by the ingress node was also approximately plotted in the same figure. We noted that D_{in} was shorter than the burst assembly time. This phenomenon is due to the fact that only the first packet must wait for the duration time of the whole assembly procedure for each burst, while the other packets wait for a shorter time. We also observed that the end-to-end delay is mainly contributed from the ingress node and guard time. The former mainly results from burst assembly and scheduling while the latter mainly results from the performance of the optical switch matrix.

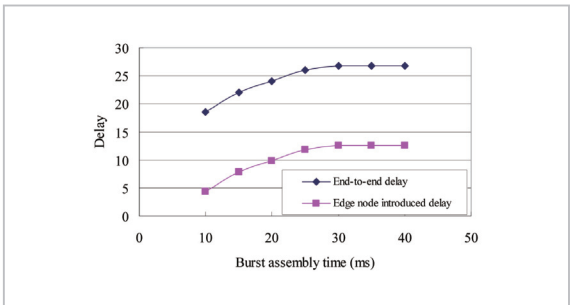

Fig.6 Delay vs. burst assembly time.

5.2 Burst blocking probability

Burst blocking probability is usually used to evaluate the effectiveness of contention resolution. In this experiment, burst blocking probability was measured in three cases: no contention resolution, PWA only, and deflection only. Each client sent IP packets to another two clients. Generated bursts were transferred in a clockwise direction. While in the case of deflection routing, contending bursts were deflected in a counterclockwise direction. Due to the short distance between nodes, the second collision between two bursts occurred at the destination node is not considered.

Experimental results are plotted in Fig. 7, where the network traffic was measured in terms of bursts generated by all nodes and was expressed as an average number of bits per second. By adopting PWA and deflection routing separately, the burst blocking probability was reduced from that of no contention resolution, especially when the network traffic is not high. We note that deflection routing had a more remarkable effect than PWA. This is because the deflection routes have lower traffic load than the default routes. Therefore, most deflected bursts can be delivered to their destinations.

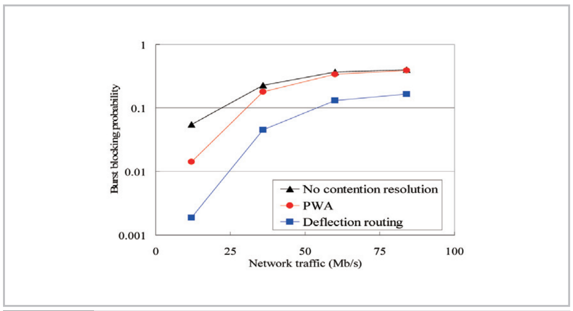

Fig.7 Burst blocking probability vs. network traffic.

5.3 TCP throughput

It is important to study the performance of TCP in OBS networks since TCP traffic is and may remain to be the most popular traffic type in the future Internet. TCP provides a reliable transport layer over an unreliable network layer mainly by using slow start, congestion avoidance and retransmission mechanisms. In OBS networks, these mechanisms will be affected by burst assembly algorithm, burst loss rate, and burst loss pattern as described in[20][21]. In brief, higher delay, loss rate and retransmission introduced by OBS networks will degrade TCP throughput. On the other hand, the fact that one burst contains multiple packets enables TCP to reach a larger sending window, and accordingly increases TCP throughput.

We experimentally studied the relationship between TCP throughput and burst assembly time. Figure 8 shows the theoretical throughput and available TCP throughput for a single wavelength between client A and C. It indicates the degradation of TCP performance over an OBS network. Another observation is the existence of an optimal assembly time. This phenomenon can be explained as follows. A shorter assembly time leads to more burst loss within edge node due to the long guard time, while a longer assembly time introduces larger delay. Both of two cases decrease TCP throughput compared with the case of optimal assembly time.

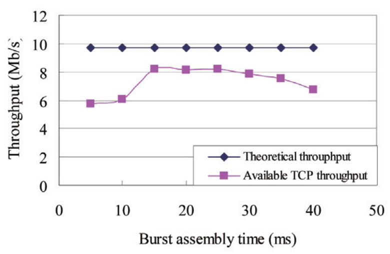

Fig.8 Throughput vs. burst assembly time.

5.4 Application demonstration

As shown in Fig. 9, online real-time transmission of video stream data was demonstrated on the OBS testbed. In this demonstration three clients were three personal computers and node 2 was connected with the Internet. Two real-time video stream services were successfully demonstrated simultaneously. The first was a TCP-based video on demand service between A and B. The second was a UDP-based live video chat service between A and C using Windows Messenger through the Internet. Dynamical switching of these two video streams could be monitored at node-2. Interoperability with IP networks and the possibility of providing TCP/UDP-based latency-sensitive video services over the OBS testbed were verified.

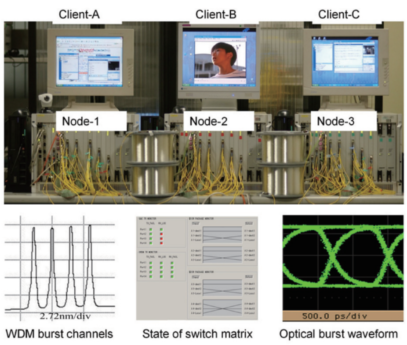

Fig.9 Application demonstration on the OBS testbed.

5.5 Discussion

Experimental results above reveal that the burst assembly, optical switching, and contention resolution are key determinants of OBS network performance. End-to-end delay increases slowly with the number of intermediate nodes because of one-way signaling and cut-through burst switching. This greatly benefits scalability. In addition, faster optical switches and optimized burst processing procedures are expected to effectively shorten the delay. These two approaches can also improve bandwidth efficiency, another significant performance metric. Bandwidth efficiency is defined as the ratio of burst size (in time domain) to the sum of burst size and guard time. In the current implementation, burst size, which is limited by the memory capacity available within the FPGA, is small compared with the long guard time. This leads to low bandwidth efficiency. However, by employing a specific high capacity memory and adopting high speed switches, bandwidth efficiency can be dramatically improved. Due to the modular design of OBS nodes, the discussed improvements in performance can be implemented by replacing the burst transceiver and switch boards. Furthermore, to achieve lower blocking probability, sparse wavelength converters, optical buffers and other new ideas should be considered.

6 Conclusion

In this report, the design, implementation, and experiments of a general-purpose OBS testbed were presented. This testbed supports various types of traffic and protocols, and enables simple system update with advanced devices. In addition, important design parameters (e.g., assembly time threshold) can easily be adjusted for various experimental studies. On this testbed, performances were evaluated and discussed, and online video services were demonstrated. To the best of our knowledge, this is the first implementation and demonstration of a network-wide testbed with comprehensive OBS functions. By improving its performance further, we can expect to provide a viable solution to the future optical Internet.

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References

1 J. S. Turner, “Terabit Burst Switching”, J. High Speed Networks, Vol. 8, No. 1, pp. 3-16, Jan.1999.

2 C. Qiao and M. Yoo, “Optical Burst Switching (OBS) - A New Paradigm for an Optical Internet”, J. High Speed Networks, Vol. 8, No. 1, pp. 69-84, Jan. 1999.

3 Y. Xiong, M. Vandenhoute, and H. Cankaya, “Control Architecture in Optical Burst-Switched WDM Networks”, IEEE JSAC, Vol. 18, No. 10, pp. 1838-1851, Oct. 2000.

4 L. Xu, H. G. Perros, and G. N. Rouskas, “Techniques for Optical Packet Switching and Optical Burst Switching”, IEEE Commun. Mag., Vol. 39, No. 1, pp. 136-142, Jan. 2001.

5 V. M. Vokkarane, J. P. Jue, and S. Sitaraman, “Burst Segmentation: An Approach for Reducing Packet Loss in Optical Burst Switched Networks”, Proc. ICC 2002, New York, NY, Apr. 2002.

6 S. Ovadia, C. Maciocco, M. Paniccia, and R. Rajaduray, “Photonics Burst Switching (PBS) Architecture for Hop and Span–Constrained Optical Networks”, IEEE Commun. Mag., Vol. 41, No.11, pp. s24-s32, Nov. 2003.

7 J. Li, C. Qiao, and Y. Chen, “Recent Progress in the Scheduling Algorithms in Optical-Burst-Switched Networks”, J. Optical Networking, Vol. 3, No.4, pp. 229-241, Apr. 2004.

8 Y. Chen, C. Qiao and X. Yu, “Optical Burst Switching: A New Area in Optical Networking Research”, IEEE Network, Vol. 18, No.3, pp. 16-23, May/Jun. 2004.

9 F. Masetti et al., “Design and Implementation of a Multi-Terabit Optical Burst/Packet Router Prototype”, Proc. OFC 2002, pp. FD1-1-FD1-3, Anaheim, CA, Mar. 2002.

10 I. Baldine, M. Cassada, A. Bragg, G. Karmous-Edwards, and D. Stevenson, “Just-in-Time Optical Burst Switching Implementation in the ATDnet All-Optical Networking Testbed”, Proc. Globecom 2003, pp. 2777-2781, San Francisco, CA, Dec. 2003.

11 A. Sahara et al., “Demonstration of Optical Burst Switching Network Utilizing PLC and MEMS Switches with GMPLS Control”, Proc. ECOC 2004, pp. 896-897, Stockholm, Sweden, Sep. 2004.

12 K. Kitayama, M. Koga, H. Morikawa, S. Hara, and M. Kawai, “Optical Burst Switching Network Testbed in Japan”, Proc. OFC2005, OWC3, Anaheim, USA, Mar. 2005.

13 H. Guo et al., “A Testbed for Optical Burst Switching Network”, OFC2005, OFA6, Anaheim, USA, Mar. 2005.

14 H. Yoo et al., “Microsecond Optical Burst Add-Drop Multiplexing for WDM Ring Networks”, Proc. COIN2005, pp. 78-80, Chongqing, China, May-Jun. 2005.

15 I. Baldine, G. Rouskas, H. Perros, and D. Stevenson, “JumpStart: a Just-in-Time Signaling Architecture for WDM Burst-Switched Networks”, IEEE Commun. Mag., Vol.40, No.2, pp. 82-89, Feb. 2002.

16 Y. Sun, T. Hashiguchi, V. Minh, X. Wang, H. Morikawa, and T. Aoyama: "Design and Implementation of an Optical Burst-Switched Network Testbed", IEEE Commun. Mag., Vol. 43, No. 11, pp. s48-s55, Nov. 2005.
17 X. Ma and G. S. Kuo, "Optical Switching Technology Comparison: Optical MEMS vs. Other Technologies", IEEE Commun. Mag., Vol.41, No.11, pp. s16- s23, Nov. 2003.
18 X. Wang, H. Morikawa, and T. Aoyama, "Priority-based Wavelength Assignment Algorithm for Burst Switched WDM Optical Networks", IEICE Trans. Commun., Vol.E86-B, No.5, pp. 1508-1514, May 2003.
19 X. Wang, H. Morikawa, and T. Aoyama, "Burst Optical Deflection Routing Protocol for Wavelength Routing WDM Networks", Opt. Net. Mag., Vol. 3, No. 6, pp. 12-19, Nov./ Dec. 2002.
20 A. Detti and M. Listanti, "Impact of Segments Aggregation on TCP Reno Flows in Optical Burst Switching Networks", Proc INFOCOM, Vol. 3, pp. 1803–1812, 2002.
21 X. Yu, J. Li, X. Cao, Y. Chen, and C. Qiao, "Traffic Statistics and Performance Evaluation in Optical Burst Switched Networks", J. Lightwave Technology, Vol. 22, No. 12, pp. 2722-2738, Dec. 2004.

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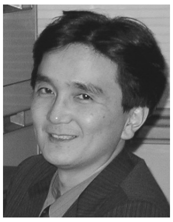

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