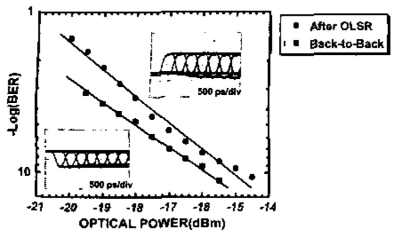


WO2 **Fig. 3.** Packet by packet bit-error-rates measured for back-to-back operation and for time domain contention resolution case.

length conversion would not solve the contention content but time buffering could. The T-WC at $(2,1)_{in}$ changes from its default value 1545.8 nm (Fig. 2(f)) to 1552.2 nm (Fig. 2 (g)) to achieve the relative time delay by 835 nsec (approximately 167 meter delay line) and both P_1 and P_2 packets come out of $(1,1)_{out}$ without any contention (Fig. 2 (h)), thus achieving contention resolution in the time domain. Lastly, the third scenario involves the same input packet diagram P_1 and P_2 (Fig. 2(i)) as in the second scenario, except that now all wavelengths in the desired output port and in the fiber delay lines are occupied so that wavelength domain and space domain contention resolutions are not available. Then the later arriving packet, P_2 seeks contention resolution by space deflection in the process of FPGA instructing the tunable laser to tune from the default wavelength value 1545.8 nm (Fig. 2 (f)) to 1563.6 nm (Fig. 2 (k)). The output packet measured at $(1,1)_{out}$ and $(2,1)_{out}$ showing successful contention resolution (Fig. 2 (l)) by space deflection without adding relative packet latency. The logic inversion is again due to the cross-gain wavelength conversion of the semiconductor optical amplifier at the input.

Error free operations are achieved in the contention resolution schemes. Fig. 3 shows (packet by packet) bit-error-rates measured for back-to-back operation and for time domain contention resolution case (scenario 2). Approximately 1 dB penalty was obtained, which is mainly due to extinction ratio degradation by cross-gain modulation SOA wavelength conversion.

3. Summary

We report optical-label switched optical packet routing with wavelength, time, and space domain contention resolution. Testing of the packet routing system under three contention scenarios demonstrated the successful contention resolution in the three domains and error free performance.

This work was partially funded by the Defense Advanced Research Projects Agency (DARPA) and Air Force Research Laboratory under agreement number F30602-00-2-0543, by the National Science Foundation under grant number ANI-998665, and by the support of OIDA.

References

1. Shun Yao, S.J.B. Yoo, and Biswanath Mukherjee, "A comparison study between slotted and unslotted all-optical packet-switched network with priority-based routing," Technical Digest, *Optical Fiber Communication Conference*, Anaheim, California, paper TuK2 (2001).
2. S.J.B. Yoo, G.K. Chang, 'Optical-Label Switching', U.S. Patent Application (1997).
3. D.J. Blumenthal, A. Carena, L. Rau, V. Curri, S. Humphries, vol. 11, p. 1497–1499, *IEEE Photon. Tech. Lett.* (1999).
4. Hyuek Jae Lee, S.J.B. Yoo, Vincent K. Tsui, and S.K.H. Fong, "A simple all-optical label detection and swapping technique incorporating a fiber Bragg grating filter", *IEEE Photonic Technology letters*, vol 13, p. 635–637 (2001).

WO3 **(Invited)** **2:00 pm**

Photonic Packet and All-Optical Label Switching Technologies and Techniques

Daniel J. Blumenthal, *Optical Communications and Photonic Networks Group, Dept. of ECE, University of California, Santa Barbara, CA 93106, Email: danb@ece.ucsb.edu*

1. Introduction

Research in photonic packet switching[1–4] is aimed at developing techniques and technologies to route packets without passing the packets directly through an electronic layer. Optoelectronic conversion at every switching point can become costly and difficult to perform as the number of wavelengths, the packet bit rates and the aggregate number of packets per second increases. The prospect of creating a photonic packet switched network rests on overcoming multiple technological hurdles, some of which require advances in optical technologies and their integration. In this talk we will review all-optical label swapping architectures, the associated packet coding techniques and label swapping technologies. Research results from a DARPA NGI program at UCSB will be described as well as results from other AOLS research programs.

2. All-Optical Label Swapping

All-Optical Label Swapping (AOLS) is a promising approach to packet switching without opto-electronic conversion.[5–8] Individual IP packets or groups of packets are encapsulated with an optical label as they enter the optical packet network as shown in Figure 1. The optical label is erased and rewritten at each photonic packet switch while the IP packet is kept intact in the optical domain. Labels are electronically processed at each routing point in order to figure out which output port to send the packet to, which wavelength to convert the packet to and what is the new outgoing label. At each packet switch input, a small percentage of light is removed and the label recovered. The label is used to compute switch settings and a new wavelength/label pair for the outgoing packet. The label data rate is independent of the payload bit rate and is chosen to be compatible with burst mode electronics. For example both 40 Gbit/sec and 10 Gbit/sec packets can be routed using 2.5 Gbit/sec headers and electronic circuits.[9]

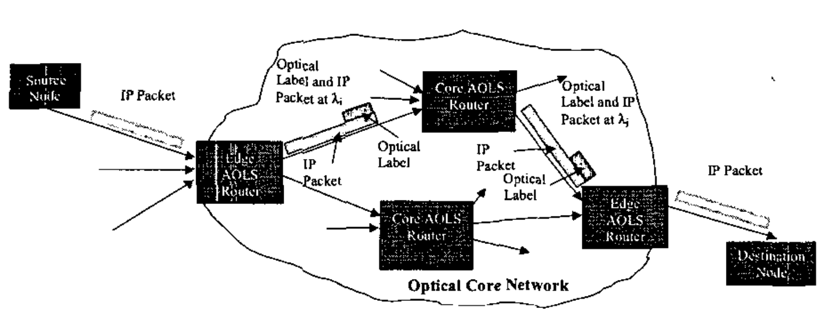
In electronic routers, digital memory is used to hold packets for arbitrary amounts of time while a routing decision is made. However, all-optical buffer technologies that hold packets with arbitrary delays are difficult to realize with the arbitrary length inherent to IP packets. With AOLS, the optical label is converted to an electronic signal in an electronic processing plane where label and switching information is computed. The optical packet continues through an optical fiber delay set equal to the time it takes the electronic circuitry to make a routing decision. During the routing computation process, the optical packet passes through a combination of devices that erase the label, write a new label and switch the packet to a new wavelength and switch port optically. The optical switching technology must operate on the order of a nanosecond (10^{-9} sec) or less. Wavelength conversion using fast tunable lasers is a scalable switching technique that can meet the demands of optical packet switching applications. This approach is supported by a recent demonstration of switching between any pair of 36 ITU channels in less than 5 ns.[10]

3. Label Coding

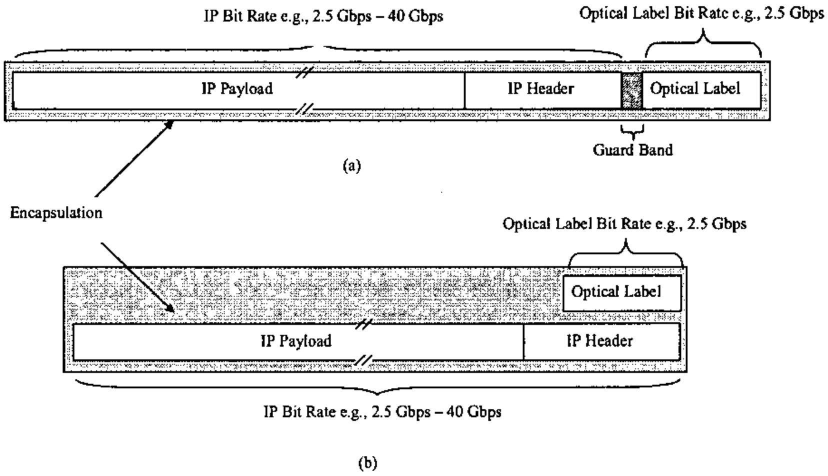
Two main approaches to optical label coding are bit-serial and optical subcarrier multiplexing.[5] Bit-serial labels (illustrated in Figure 2a) are placed at the head of the IP packet, buffered by an optical guard-band that facilitates label removal and reinsertion. With optical subcarrier multiplexed labels (Figure 2b) the optical label is first modulated onto a RF subcarrier and then onto the same wavelength as the IP packet. In both cases, the optical label bit-rate is chosen to balance the requirements for low cost label processing electronics and the duration of the label relative to the optical IP packet length. Encapsulation of IP packets using optical labels has advantages in that the contents of the original IP packet are not modified and the label is coded at the same wavelength as the IP packet.

4. AOLS Technologies

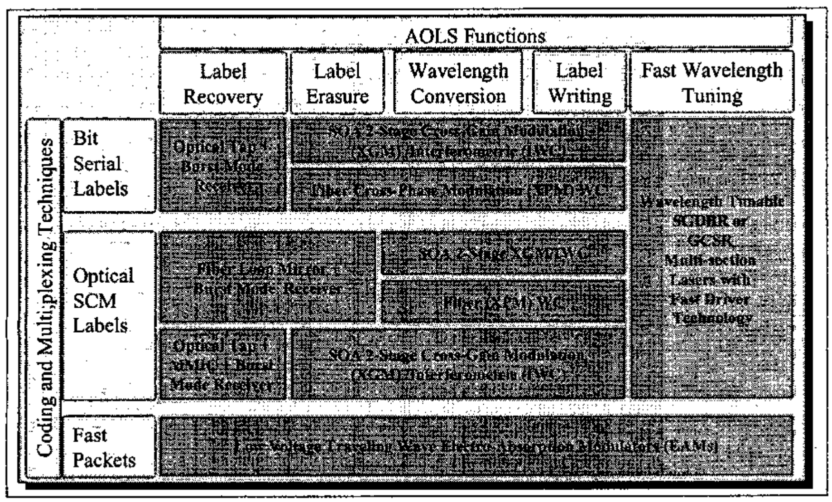
Various technologies have been used to implement AOLS functions including wavelength converters, fiber loop mirrors, wavelength agile sources, optical demultiplexers and packet trans-



WO3 **Fig. 1.** Encapsulation of IP packets in a core network with AOLS.



WO3 Fig. 2. AOLS (a) bit-serial and (b) OSCM Packet Coding Techniques.



WO3 Fig. 3. Summary of AOLS functions, coding and multiplexing techniques and implementation technologies.

mitters. A summary of AOLS technologies demonstrated at UCSB is shown in Figure 3 and will be described in more detail in the talk as will approaches from other institutions. The horizontal axis depicts the basic AOLS functions including label recovery, label erasure, wavelength conversion, label writing and fast wavelength tuning. The vertical axis summarizes the bit serial and optical SCM label coding techniques as well as ultrafast multiplexing. Each AOLS function, for a given label coding technique, can be realized using a combination of technologies shown in the green boxes.

AOLS Packet Wavelength Converters

An AOLS packet wavelength converter can perform all or a subset of the functions of optical label erasure, packet rate wavelength conversion, IP packet regeneration and optical label rewriting. Depending on the combination of label coding technique and wavelength converter technology, the label tap may or may not handle the label erasure function. A tap that handles the function of erasure and label recovery is described in the next section on fiber loop mirrors. An important feature of AOLS wavelength converters is that they can simultaneously erase and rewrite labels during the conversion process. Two wavelength converters that will be discussed are semiconductor optical amplifier wavelength convereters (SOA-WCs) and fiber cross phase modulation (XPM) converters. SOA based AOLS converters allow an intensity-modulated signal to be transferred from wavelength to another wavelength. SOA interferometric wavelength converters (SOA-IWCs) have been shown to operate to data rates beyond 40 Gbit/sec and are built using photonic integrated circuit (PIC) technology. In order to allow operation at ultra-high bit-rates (greater than 40 Gbps) fiber XPM wavelength converters may be used for AOLS.[11–13]

Wavelength Agile Sources

Packet wavelength conversion depends on the switching speed and stability of the tunable laser used as the local source. New multi-element widely tunable lasers with the capability of tuning over hundreds of channels represent the current state of the art in semiconductor laser development. Two promising candidates are the Sampled Grating DBR (SGDBR) and the Grating assisted co-directional Coupler with Sampled Reflector (GCSR). Rapid tuning over a large number of channels (>35) using GCSR lasers has been demonstrated.[10]

References

1. IEEE Journal of Lightwave Technology, Special Issue on Photonic Packet Switching Architectures, Techniques and Technologies, Dec. 1998.
2. D.J. Blumenthal, P.R. Prucnal, and J.R. Sauer, "Photonic Packet Switches: Architectures and Experimental Implementations," Proceedings of the IEEE, 82(11), 1650–1667, November (1994). (Invited Paper).
3. B. Bostica, A. Cappellari, M. Burzio, B. Vercellone, C. Guillemot, A. Gravey, P. Gravey, F. Masetti, M. Sotom, M. Renaud, "A Novel Packet Switching network Adopting Transparent Optical Packets," CSELT Technical Reports, Vol. 24, No. 6, CSELT, pp. 1049–56, Dec. 1996.
4. D.J. Blumenthal, "Packets over Light," Scientific American, Jan. 2001.
5. D.J. Blumenthal, B-.E. Olsson, G. Rossi, T. Dimmick, L. Rau, M. Masanovic, O. Lavrova, R. Doshi, O. Jerphagnon, J.E. Bowers, V. Kaman, L.A. Coldren and J. Barton, "All-Optical Label Swapping Networks and Technologies," IEEE Journal of Lightwave Technology, Special Issue on Optical Networks, Dec. 2000.
6. Y.M. Lin, W.I. Way, and G.K. Chang, "A Novel Optical Label Swapping Techniques using Erasable Optical Single0Sideband Subcarrier Label," IEEE Photonic Technology Letters, Vol. 12, No. 8, pp. 1088–90, Aug. 2000.
7. D.J. Blumenthal, A. Carena, L. Rau, V. Curri, and S. Humphries, "All-Optical Label Swapping with Wavelength Conversion for WDM-IP Networks with Subcarrier Multiplexed Addressing," IEEE Photonics Technology Letters, Vol. 11, No. 11, pp. 1497–99, Nov. 1999.
8. A. Carena, M.D. Vaughn, R. Gaudino, M. Shell and D.J. Blumenthal, "OPERA: An Optical Packet Experimental Routing Architecture with Label Swapping Capability," IEEE Journal of Lightwave Technology, Special Issue on Photonic Packet Switching, Vol. 16, No. 12, pp. 2135–45, Dec. (1998).
9. B.E. Olsson, P. Ohlen, L. Rau, and D.J. Blumenthal, "A Simple and Robust 40 Gbit/s Wavelength Converter using Fiber Cross-Phase Modulation and Optical Filtering," *IEEE Photonic Technology Letters*, July, 2000.
10. O.A. Lavrova, G. Rossi, and D.J. Blumenthal, "Rapid tunable Transmitter with over 36 ITU Channels Accessible in less than 5 ns," ECOC 2000.
11. P. Ohlen, B.E. Olsson, and D.J. Blumenthal, "Wavelength Dependence and Power Requirements of a Wavelength Converter Based on XPM in a Dispersion-shifted Optical Fiber," *IEEE Photonic Technology Letters*, May 2000.
12. P. Ohlen, B.E. Olsson, and D.J. Blumenthal, "All-optical Header Erasure and Penalty-free Rewriting in a Fiber-based high-speed Wavelength Converter," *IEEE Photonic Technology Letters*, July 2000.

13. B.E. Olsson, P. Ohlen, L. Rau, G. Rossi, O. Jerphagnon, R. Doshi, D.S. Hunphries, D.J. Blumenthal, V. Kaman and J.E. Bowers, "Wavelength Routing of 40 Gbit/s Packets with 2.5 Gbit/s Header Erasure/Rewriting using an All-Fiber Wavelength Converter," Postdeadline Paper, ECOC, Vol. 2, p. 52–53, Nice, France, September 1999.

WO4 **2:30 pm**

An All-Optical Packet Header Recognition Scheme for Self-Routing Packet Networks

Kit Chan, Frank Tong, Chun K. Chan, Lian K. Chen, Wai Hung, *Dept of Information Engineering, The Chinese University of Hong Kong, Hong Kong, SAR, China, Email: kchan0@ie.cuhk.edu.hk*

Introduction

In future ultrahigh-speed self-routing optical packet networks, the packet header has to be examined at each packet node to retrieve the destination information, which is essential for making routing decision. As the data rate (several tens of Gbit/s) of the packet stream is far beyond the processing capability of the common electronics, several all-optical signal processing techniques have been proposed to perform ultrafast packet header recognition.[1,2] However, these approaches have limitations in terms of complexity and scalability.

With optical serial-to-parallel conversion of the packet header, header recognition and control signal generation for self-routing will be much simpler as a result of relaxed speed requirement.[3] Therefore, an array of common electronics can be adapted to process individual packet header bits. For a self-routing network node, the recovered parallel header bit sequence can be used to control the routing switch at different stage in a switching matrix, as shown in block diagram Fig. 1.

In this paper, we propose an all-optical ultrafast packet header recognition scheme for self-routing switch based on all-optical serial-to-parallel conversion. Each bit in the packet header is converted to a distinct wavelength, which is then separated by a 1 × N wavelength demultiplexer. Thus, a parallel header bit sequence, each at a lower bit rate, can be obtained and it will be used to perform packet routing.

Proposed Scheme

Fig. 2 shows the schematic of the proposed scheme. As an incoming packet enters the network routing node, a single pulse (sync pulse) is generated to mark the start of the optical packet, which can be performed either by cross-correlation technique[4] or by power differentiation. The generated sync pulse is amplified and injected into a segment of super-continuum fiber (SCF). The output pulse with broadened spectrum is then spectrum-sliced with a pair of array waveguide gratings (AWG) in which fiber delays are inserted between different wavelength channel with time delay of $0, \tau, 2\tau \ldots n\tau$, where τ is the bit duration of the packet header and n corresponds to the total number of bits in the packet header. As a result, wavelength interleaved pulse stream is produced at output of the pair of AWG.

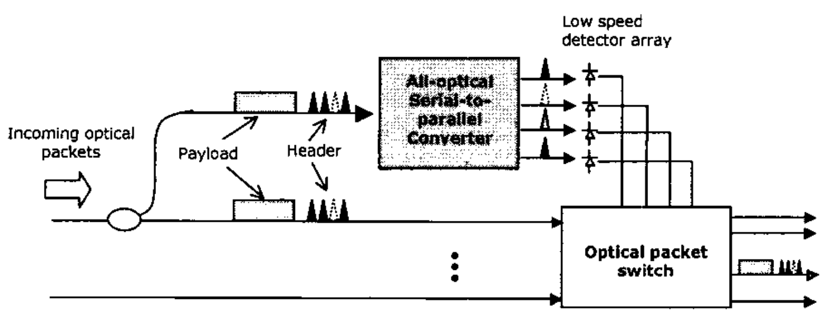
The multi-wavelength pulse stream is then launched into a wavelength converter with ultrafast nonlinear interferometer (UNI) configuration, which consists of a semiconductor optical amplifier (SOA) and some polarization-controlling components. A portion of the incoming packet is tapped off and injected into the UNI as the control signal. The relative time delay between the multi-wavelength pulse stream and the control signal is properly adjusted in such a way that each bit in the packet header is converted to a distinct wavelength at the output of UNI. The wavelength converted signal is then demultiplexed with an AWG. With fine adjustment of the fiber delay, different bits in the packet header can be detected by the low-speed photodetector array simultaneously. The retrieved packet header parallel bit sequence is fed into the switch control unit to trigger the $N \times N$ optical packet switch so as to route the high-speed optical packet to the destined output port.

Experiment

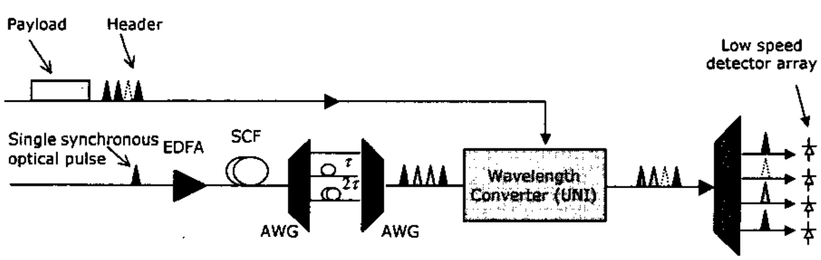
In our experiment, a three-bit packet header with bit pattern "110" was generated. It was then followed by a payload of 40 ns. Both packet header and payload were at a bit rate of 10-Gbit/s in return-to-zero (RZ) format. The generated sync pulse was injected into the SC-fiber with a launch power of 19 dBm. The generated SC spectrum with spectral width more than 10 nm was then spectrum-sliced with an AWG with 100 GHz spacing. Three wavelengths, 1554.1 nm (λ_1), 1554.9 nm (λ_2), and 1555.7 nm (λ_3), were selected respectively. At the second AWG, those three spectrum-sliced optical pulses with different wavelengths were combined with a temporal delay of 100-ps introduced between adjacent wavelengths. Fig 3(a) shows the resultant wavelength interleaved pulse stream. It was then input to the wavelength converter as probe signal.

With proper adjustment of time delay between the probe signal and the incoming optical packet, only the packet header was wavelength converted by feeding both signals into the UNI device and the output signal was shown in Fig 3(b). The slightly reduced magnitude of second bit (λ_2) was due to the pattern effect of the SOA in the wavelength converter (UNI); this could be improved by using holding light injection.[5] As each bit in the packet header was mapped to different wavelengths, serial-to-parallel operation could be easily achieved by using a wavelength demultiplexer. Fig 4 shows the output waveform at different output ports of the serial-to-parallel converter.

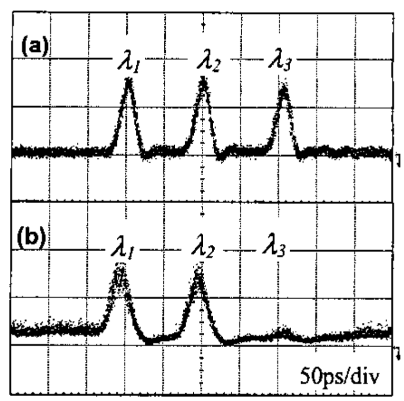
With this serial-to-parallel conversion for packet header processing, low speed photodetector array can be used for parallel optical signal detection. For header recognition, CMOS based electronic logic gate can be used. For self-routing network, the parallel-generated signal can be di-



WO4 Fig. 1. All-optical serial-to-parallel converter enabled self-routing node.



WO4 Fig. 2. Our proposed all-optical serial-to-parallel converter.



WO4 Fig. 3. (a) Wavelength interleaved pulse from spectrum-slicing of SC generation. The three wavelengths are 1554.1 nm, 1554.9 nm, and 1555.7 nm respectively. (b) Wavelength converted packet header "110". (50 ps/div).