All-Optical Label Swapping

for the Future Internet

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All-optical label swapping (AOLS), an approach to transparently route IP packets all-optically, has potential application to the future Internet. AOLS uses optical encapsulation to route packets independent of their bit-rate, format or length. Photonic technologies like rapidly tunable all-optical wavelength converters play a key role in realizing AOLS. This article also covers semiconductor optical amplifier and nonlinear optical-fiber-based wavelength converter implementations. Results of an AOLS systems demonstration with 40-Gbps packets is shown.

Within today's Internet, data is transported between powerful electronic Internet protocol (IP) routers using optical-fiber transmission and wavelength-division-multiplexing (WDM) systems. Fiber-transmission systems today typically carry 32 wavelengths modulated at 2.5 **Gbps** to 10 **Gbps** (1 **Gbps** = 10^9 bits/sec.) per wavelength. At an IP router, multiple WDM fibers are terminated and signals are converted from optical to electronic at the input and electronic to optical at the output. Today's routers need to handle almost 0.5 Tbit/s (0.5 x 10^{12} bits/sec.) of data in order to redirect incoming Internet packets from fully loaded WDM fibers.

Things become very interesting when we consider that the capacity of optical fibers continues to double every 8-12 months. Today's state-of-the-art single fiber capacity exceeds 10 Tbps. Comparing this increase with that of electronic processor speeds which doubles every 18 months (Moore's Law) and comes at the expense of increased chip power dissipation, we start to see that there is a potential mismatch in bandwidth handling capability between fiber-transmission systems and electronic routers. The story is more complex when we consider that future routers will terminate potentially hundreds or thousands of optical wavelengths and the increase in bit-rate per wavelength will head out to 40 **Gbps** and potentially beyond to 160 **Gbps**. Additionally, electronic memory access speeds only increase at the rate of approximately 5% per year, an important data point since memory plays a key role in how packets are buffered and directed through the router. It is not difficult to see that the process of moving a massive number of packets per second (100 million packets/sec. and beyond the 1 billion packets/sec. mark) through the multiple layers of electronics in a router can lead to router congestion and exceed the performance of electronics and the ability to efficiently handle the dissipated power. Cost is also an important issue: The cost of performing conversion between optics and electronics can consume more than half the cost of a router.

In this article we review all-optical label swapping (AOLS), a technique intended to solve the potential mismatch between fiber capacity and router packet-forwarding capacity. AOLS imparts the functionality to direct packets through an optical network without the need to pass these packets through electronics whenever a routing decision is necessary.[1-6] Inherent to this approach is the ability to route packets independently of bit-rate, packet or coding format and packet length. For this reason, AOLS is not limited to IP packets, but can handle **ATM (AQ:1)** cells, bursts, data-file transfer and other data structures. We review research results obtained at the University of California at Santa Barbara in collaboration with Professors John Bowers' and Larry Coldren's groups at UCSB under the support of the DARPA NGI program, Cisco systems, Spirent Technologies, the DARPA-sponsored MOST Center and a State of California CORE grant sponsored by New Focus. An AOLS network is illustrated in Fig. 1(a). IP packets enter the network through an "ingress" node and are encapsulated with an optical label and then retransmitted on a new wavelength. The optical label and new wavelength are determined by reading the packet's IP header (called "IP layer 3" information) and using information stored in a pre-established local lookup table. Once inside the network, only the optical label is used to make routing decisions and the wavelength is used to dynamically redirect (forward) packets. Nodes inside the network have an increased functionality over their ingress node counterparts. At these internal nodes, labels are read and optically erased, then a new label is attached to the packet and the optically labeled packet is converted to a new wavelength using all-optical

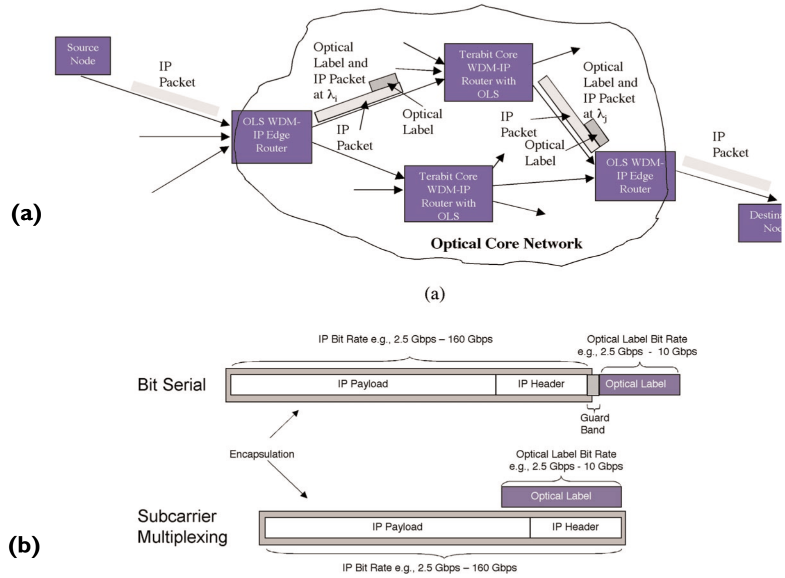

Figure 1. (a) All-optical label switched (AOLS) network. (b) Bit serial and subcarrier multiplexed optical label coding techniques.

Glossary of Terms

Semiconductor optical amplifier (SOA): A semiconductor optical waveguide with gain.

Cross-phase modulation (XPM): A nonlinear optical effect where the intensity modulation of one wavelength modulates the index of refraction in a material where another wavelength is propagating and therefore modulates its phase.

Wavelength-division multiplexing (WDM): The transmission of multiple independent data streams on a single fiber using a different optical frequency for each stream.

Internet protocol (IP): The addressing scheme for packets on the Internet.

Bibliography

IEEE Journal of Lightwave Technology, Special Issue on Photonic Packet Switching Architectures, Techniques and Technologies, Dec. (1998).

IEEE Journal on Selected Areas in Communications, Special Issue on Optical Networks, Sept. 1998.

Optical Networks: A Practical Perspective, Ramaswami and Sivarajan, Second Edition, Morgan Kaufmann Publishers, 2002.

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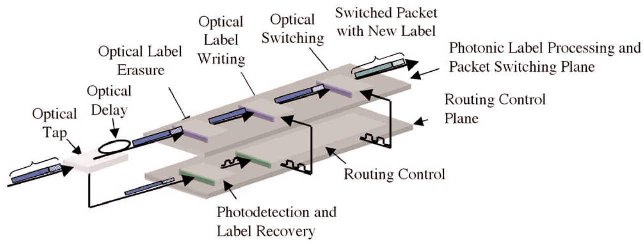

Figure 2. AOLS module functionality.

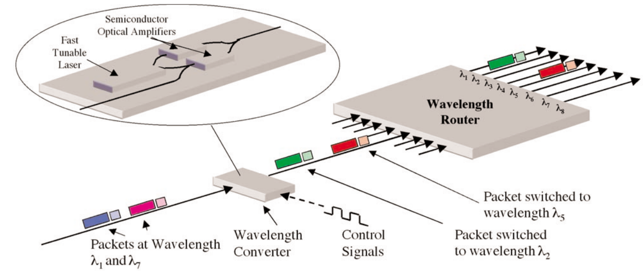

Figure 3. AOLS and packet routing using a fast tunable wavelength converter and wav length demultiplexer/router.

wavelength conversion. Throughout this process, the contents (e.g., the IP packet header and payload) are not passed through electronics and are kept intact until the packet exits the optical network through the "egress" node where the optical label is removed and the original packet is handed back to the electronic routing hardware.

A module that performs the label-swapping function is shown schematically in Fig. 2. As packets enter the module, a small percentage of light is redirected, using an optical tap, to a lower label-processing circuit where it is converted to an electronic signal and the new label and new wavelength are computed. While the new label and new wavelength computation are being performed, the labeled packet passes through a fixed fiber delay-line that matches the electronic-processing delay. The electronic circuit then sets up the new label and wavelength in the upper photonic processing circuit. The packet arrives at the first stage of the photonic processing circuit and the incoming label is optically erased. The packet is then converted to a new wavelength and a new optical label is reattached all-optically. Today we use electronics to process labels even though the packet is switched all-optically. This approach allows us to use more powerful table lookup and routing decisions than if current all-optical logic technology were used. As long as the label bit-rate is operated at a relatively fast rate and compatible with today's state-of-the-art electronics (for example 2.5 **Gbps** or 10 **Gbps**), and the number of bits in a label are held to a minimum, the routing decision can be computed relatively fast and not decrease the optical packet throughput. The label bit-rate is independent of the payload bit-rate and is chosen to be compatible with burst-mode electronics. For example both 40 Gbit/s and 10 Gbit/s packets can be routed using 2.5 Gbit/sec headers. In the future, optical logic and memory elements may prove feasible to replace the fixed delay line and electronic-processing circuit. In electronic routers, digital memory is used to hold packets for arbitrary amounts of time while a routing decision is made. However, it is difficult to get all-optical buffer technology that can hold packets with arbitrary delays to work with the arbitrary length inherent to IP packets, an issue that adds to the complexity of AOLS today **(AQ:2)**.

Switching technology to redirect packets at the output must be capable of doing so on the order of a nanosecond (10^{-9} sec.). Wavelength conversion using fast tunable lasers is a scalable switching technique that can meet the demands of optical-packet switching applications. Figure 3 illustrates how a rapidly tunable laser is used as a local source for a wavelength converter. When combined with a wavelength-demultiplexing device, such as a wavelength router,[6] packets can be spatially directed by selecting the correct wavelength at the tunable laser. Switching between any pair of 36 ITU channels in less than 5 ns has been reported[7] and is scalable to a larger number of wavelengths.

The choice of wavelength-converter technology tends to be strongly coupled to the label-coding technique. Two main approaches to optical label coding are bit-serial and subcarrier multiplexed,[6] as illustrated in Fig. 1(b). Here we focus on serial labels to illustrate the process of erasing and rewriting labels using wavelength converters. The serial label is placed at the head of the IP packet following an optical guard-band. This guard-band is used to facilitate label removal and reinsertion without static packet buffering and to accommodate finite switching times of optical switching and wavelength conversion. The bit-serial label is encoded on the same optical wavelength as the IP packet.

Two types of wavelength converter have been employed for AOLS, semiconductor-optical-amplifier (SOA) based and nonlinear-optical-fiber based converters. A popular converter configuration that performs most of the AOLS functions is the SOA interferometric wavelength converter (SOA-IWC). The SOA-IWC uses cross-phase modulation (XPM) in an SOA to realize an optically driven modulator and has been shown to operate to data rates exceeding 40 Gbit/s. Its operation is based on the well-known principle of constructive and destructive interference of optical waves. A tunable laser, located at one input of the SOA-IWC as shown in the inset of Fig. 3, is split to two optical waveguides. The original modulated wavelength drives an SOA in one of the interferometer arms, thereby modulating the local laser signal and transferring its data over to the new wavelength. The SOA-IWC can also be used as the output stage in a two-stage converter. One example is shown in Fig. 4, where a XGM converter is turned off as the serial label passes through and blocks the label bits. The XGM-SOA is then turned on as the packet bits arrive and converts the packet to an intermediate wavelength (λ_{int}). Meanwhile, the new serial label is premodulated onto the tunable laser that has been tuned to the new wavelength (λ_{out}). The label is transmitted to the SOA-IWC output ahead of the packet arrival at the second stage. The SOA-IWC converts the packet to the final wavelength while regenerating and reinverting the bits. An optical tap, photodetector and burst-mode receiver at the input are used to detect the label for selection of the new wavelength and label.

For operation at ultrahigh bit-rates (from over 40 **Gbps** up to 160 **Gbps**) a wavelength converter based on nonlinearities in an optical fiber has been demonstrated.[8] This converter employs XPM in a dispersion-shifted fiber to phase modulate continuous wave (cw) light from the local tunable laser using the intensity-modulated signal on the original wavelength as shown in Fig. 5. The resulting phase-modulated signal is converted to intensity modulation by optically filtering the converter output. The fiber XPM converter is capable of erasing and writing new labels. The high-speed packet bits are coded return to zero (RZ) and the lower-speed serial-label bits are coded non-return to zero (NRZ). XPM effectively converts the RZ bits and not the NRZ bits. Therefore the label is automatically erased. A new NRZ label is premodulated onto the local laser and passes straight through the converter on the final wavelength.

A systems experiment that demonstrated AOLS[8] using a fiber XPM wavelength converter with 40 **Gbps** packets is shown in Figure 6. The payload was 40 Gbit/s RZ and the serial label at 2.5 Gbit/s NRZ. In the lower left hand trace, the packets with labels at the input to the converter are compared to the output where the labels are erased. In the lower right hand scope traces are packets being switched between two output wavelengths.

In summary, we have described all-optical label swapping (AOLS) and its potential application to the future Internet. AOLS uses optical encapsulation to transparently route packets independent of bit-rate, format or length. The basic functions of AOLS are reviewed including label erasure, rewriting and all-optical wavelength conversion. Two types of wavelength converters to implement the AOLS and packet routing, one semiconductor optical amplifier based and the other nonlinear fiber-based were reviewed. This approach has been shown to operate at packet bit-rates out to 40 **Gbps**. **(Does this mean Gbit/s?)**

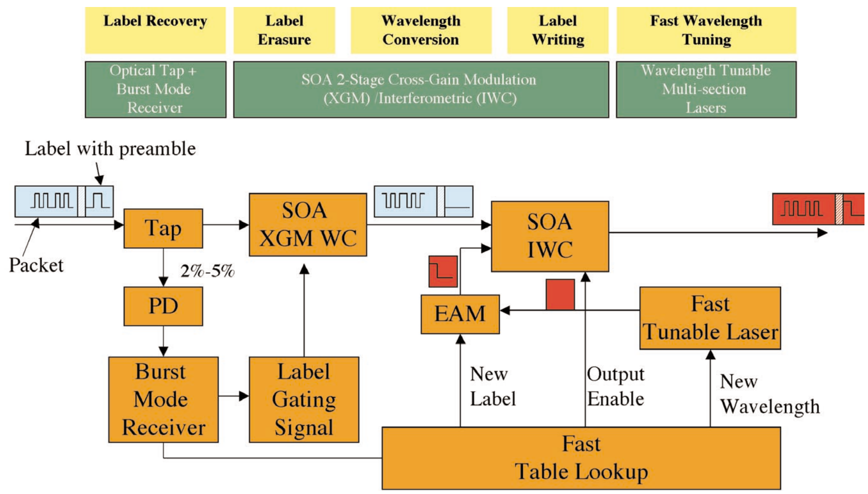

Figure 4. AOLS using a two-stage SOA-based wavelength converter.

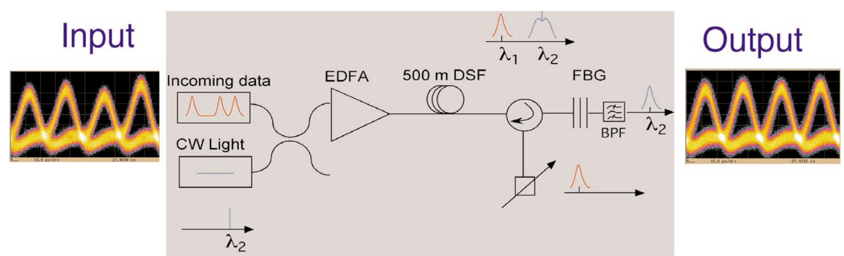

Figure 5. Nonlinear fiber cross-phase modulation (XPM) converter operating at 40 Gbps.

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References

1. D. J. Blumenthal, Scientific American, January (2001) **(AQ:4)**
2. D. J. Blumenthal, P. R. Prucnal, and J. R. Sauer, Proc. IEEE, **82** (11), 1650-67, November (1994).
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, **24** (6), CSELT, 1049-56, Dec. 1996.
4. 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 J. Lightwave Technol., Special Issue on Optical Networks, Dec. 2000 (Invited Paper).
5. Y. M. Lin, W. I. Way, and G. K. Chang, IEEE Photon. Technol. Lett. **12** (8), 1088-90, Aug. 2000.
6. A. Carena, M. D. Vaughn, R. Gaudino, M. Shell and D. J. Blumenthal IEEE J. Lightwave Technol., Special Issue on Photonic Packet Switching, **16** (12) 2135-45, Dec. (1998).
7. O. A. Lavrova, G. Rossi, and D. J. Blumenthal, "Rapid tunable transmitter with large number of ITU channels accessible in less than 5ns," Proc. 26th European Conference on Optical Communication (ECOC 00), Munich, Germany, Paper 6.3.5, 169-70, September 4-7 (2000).
8. 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 **2** 52-3, Nice, France, September 1999.

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