Dynamic Power Considerations in a Complete 12 × 12 Optical Packet Switching Network

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***Abstract*—The dynamic optical power characteristics of an implemented 12-port optical packet switching network are measured for multiple-wavelength packets with 16 payload wavelengths and five routing header wavelengths. The system demonstrates an average dynamic optical power range of approximately 6.7 dB at the 10^{-12} bit-error-rate (BER) threshold, and 8.2 dB at 10^{-9} BER. These measurements which investigate how the system affects the encoded optical packets are discussed as metrics for network scalability and robustness.**

***Index Terms*—Interconnection networks, packet switching, photonic switching systems, wavelength-division multiplexing.**

I. Introduction

High-performance computing systems require interconnection networks with extremely high throughput and low latency in order to route messages between thousands of processor and memory elements [1]. Optical packet switching (OPS) fabrics offer a potentially viable solution to this requirement, owing to the ability of fiber-optic components and systems to carry many terabits/second of encoded optical data while maintaining near speed-of-light limited transit latencies [2]–[5]. The realization of a complete 12-port OPS interconnection network, which contains 36 discrete switching nodes and is based upon the data vortex topology, was recently reported [6].

The implemented architecture takes full advantage of the optical bandwidth of conventional fiber-optic components by utilizing a multiple-wavelength packet format. Two semiconductor optical amplifier (SOA) switching elements facilitate 1 × 2 switching at each of the 36 nodes [7]. Because SOAs also exhibit optically wide-band gain, the multiple-wavelength packets are routed through the network in an almost perfectly transparent manner.

The necessary topological features of the implemented 12 × 12 switching fabric have been demonstrated. Successful routing to all output ports has been confirmed, as has been the internal deflection scheme inherent to the data vortex topology. Furthermore, the average routing latency of the system has been measured to be approximately 100 ns for 20-ns packets [6].

Here, the effects of the system on the encoded optical data are presented. The receiver power penalty for the network, the optical signal-to-noise ratio (OSNR) degradation, and the dynamic optical power range for packets with 16 10-Gb/s payload wavelengths and five routing header wavelengths are measured.

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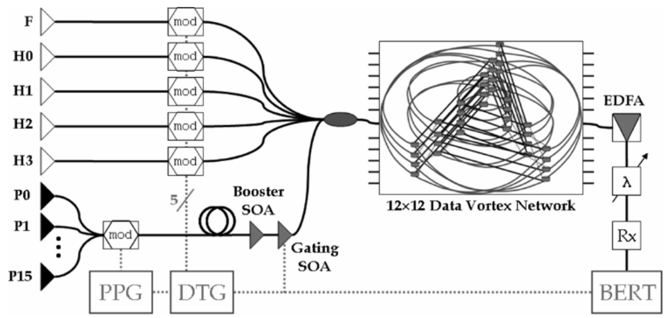

Fig. 1. Schematic of experimental setup with the appropriate packet generation and detection subsystems, with $LiNbO_3$ modulators (mod), pulse pattern generator (PPG), data timing generator (DTG), BER tester (BERT), EDFA amplifier, tunable filter (λ), and high-speed dc-coupled postamplified receiver (Rx).

This study of dynamic optical power considerations for the implemented OPS network provides a better understanding of the physical scalability and robustness of the system.

The implemented data vortex architecture is comprised of individual discrete switching nodes which conserve optical power by utilizing SOA switching elements [6], [7]. These switching elements are also capable of amplifying wavelengths that span a significant part of the ITU C-band. Therefore, a multiple-wavelength packet structure can be utilized quite effectively by the architecture. Particular wavelengths are designated for simple ON–OFF header encoding, and others are used for a wavelength-parallel payload structure. The whole multiple-wavelength packet propagates through the system simultaneously in time and in space and is routed as a whole unit by the switching nodes.

II. Experimental Setup

In order to generate packets of the correct format for the implemented 12 × 12 data vortex architecture, five routing header wavelengths are required, in addition to the wavelength-parallel optical payload which itself contains 16 wavelengths. These 10-Gb/s nonreturn-to-zero payload wavelengths are modulated together and then decorrelated by approximately 450 ps/nm with 25 km of fiber. The wavelengths used for both the payload and header are channels designated by the ITU wavelength-division-multiplexing grid, and some adjacent channels with a spacing of just 0.8 nm (100 GHz) are included. The 16-wavelength payload is then amplified by a high-gain booster SOA and gated into packets by a second SOA. This multiple-wavelength packet payload is then combined with the appropriate wavelength-parallel routing headers, and the whole packet is injected into one of the 12 input ports of the data vortex network (Fig. 1).

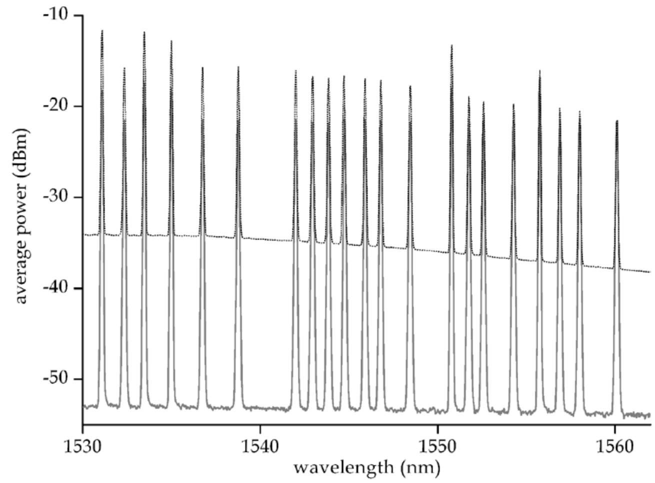

Fig. 2. Plot of input packet optical power spectrum (-) and output packet optical power spectrum (–), with the five routing header wavelengths higher than the 16 payload wavelengths.

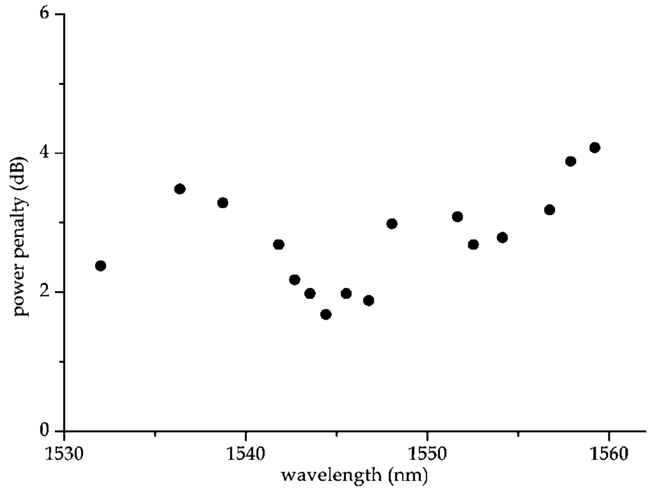

Fig. 3. Plot of receiver power penalty of each of the 16 payload wavelengths for the five-node path.

The packet traffic pattern which is encoded on the multiple-wavelength routing headers contains a packet with address [1111] which traverses five nodes within the network beginning at network input #4 [6]. This packet is extracted from the appropriate output node and then amplified with an erbium-doped fiber amplifier (EDFA) and filtered for bit-error-rate (BER) testing on one payload wavelength at a time. The BER tester is gated and synchronized to enable error testing only on the packet payload.

For many of the experimental results discussed below, the power of the optical payload wavelengths was varied. This is accomplished by adjusting the gain of the booster SOA and gating SOA, resulting in all wavelengths being amplified together. Thus, single payload wavelengths are not isolated out for amplification, but instead the whole bulk of the packet payload is amplified, increasing the total packet power.

III. Results

A. Gain Mismatch

All of the elemental switching nodes within the implemented network are intended to be as optically transparent as possible. That is, the outgoing signal power should be matched to the incoming signal power. Because the switching node contains a few couplers and filters in order to extract the routing header wavelengths, the gain of the subsequent SOAs must be set to compensate for these losses [7]. Due to the small wavelength dependence of passive optical components and of the SOAs, each successive switching node introduces a small amount of wavelength-dependent gain mismatch to the multiple-wavelength packet.

For each node in the implemented system, the gain mismatch is kept below 1.0 dB across the wavelengths of interest (about 1530–1560 nm). For the five-node path, the net gain mismatch is less than 4.9 dB (Fig. 2).

Future revisions of the OPS node design will contain a custom-designed gain-flattening filter in order to further compensate for this gain imbalance.

B. OSNR and Power Penalty

Each successive switching node introduces a small amount of noise to the optical packets. This effect can be quantified as the OSNR degradation, which is measured to be 2.7 dB per node on average. The OSNR degradation is primarily due to the amplified spontaneous emission (ASE) noise generated by the SOA switching elements. This noise amounts to approximately −20.5 dBm of total optical power, distributed across a large span (roughly 1450–1600 nm), so that the noise floor in the middle of the C-band increases by about 3.5 dB (0.1-nm resolution bandwidth) on average through each of the cascaded switching nodes. The SOA in each switching node adds ASE, and also, because the net gain of the nodes is not exactly zero for all wavelengths, further noise accumulation can result. Although the noise floor is not expected to increase linearly for large numbers of node passes, the precise scaling is difficult to quantify concisely [8].

The total receiver power penalty [9] of the whole five-node path is found to be between 1.7 and 4.1 dB at a BER of 10^{-9}, depending upon which of the 16 payload wavelengths is measured; the average power penalty is 2.6 dB (Fig. 3). This power penalty is slightly higher than what would be expected from the 0.2-dB penalty previously measured for a single switching node [7]. The discrepancy is due to signal degradation from the successively increasing optical noise floor through the cascaded switching nodes.

C. Dynamic Range

The dynamic power range indicates the range of optical power levels over which the OPS network remains functional. When signal power levels are too low, they are quickly overwhelmed by the optical noise floor, yielding poor error-rate performance. In the other extreme, when signal power levels are too high, the SOA switching elements may become saturated, degrading signal quality while also possibly corrupting the routing header wavelengths, which can ultimately lead to incorrect packet routing.

By carefully adjusting the gain of the booster SOA and the gating SOA, the optical power of the multiple-wavelength

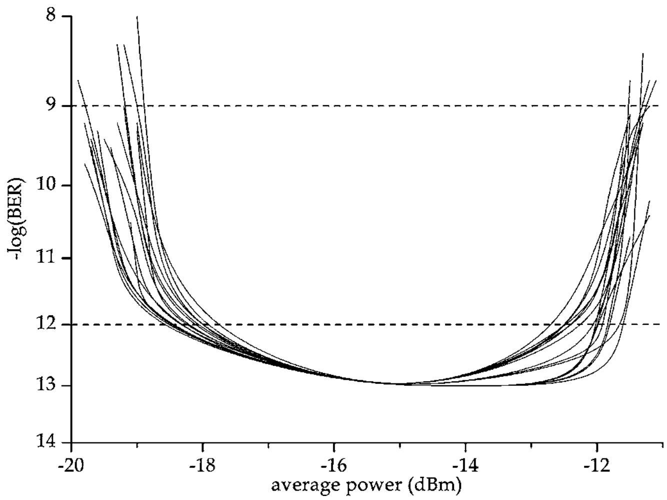

Fig. 4. Plot of the BER "bathtub curve" of the dynamic power range for the 16 payload wavelengths.

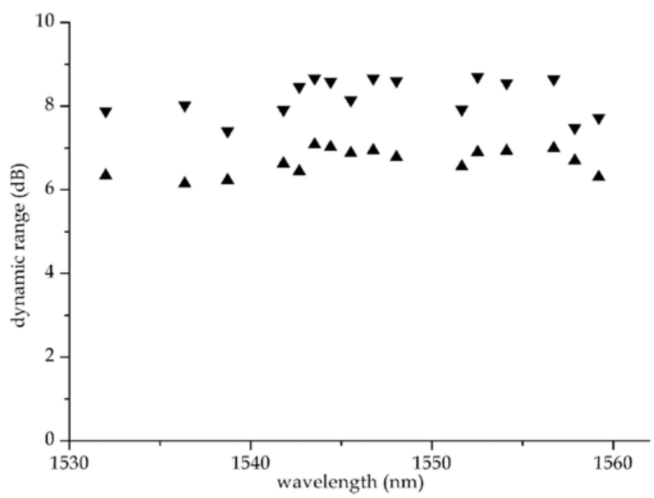

Fig. 5. Plot of the dynamic range of the 16 payload wavelengths at the 10^{-12} (▲) and 10^{-9} (▼) BER thresholds.

packet can be varied over a wide range of values. These varying optical packet power levels result in differing BER characteristics (Fig. 4). For the 16 payload wavelengths, the dynamic optical power range at a 10^{-12} BER threshold is found to be 6.7 $\pm$ 0.3 dB, depending upon wavelength. Similarly, the range at a 10^{-9} BER is 8.2 $\pm$ 0.5 dB (Fig. 5).

The optimal signal power for each payload wavelength is approximately -15 dBm. For 16 wavelengths, the total packet payload power is then -3 dBm, and with five routing header wavelengths of about -13 dBm each, the total packet power is almost -1 dBm. At these packet power levels, total power incident on the input of the SOA switching elements is approximately -7 dBm, due to the $\sim$6 dB of losses in the filters and couplers at the beginning of the switching nodes [7]. This input power value is just below the SOAs' input saturation power of -5 dBm. Thus, payload powers above -13 dBm for each wavelength begin to approach device saturation, yielding poor BER performance.

These large dynamic power ranges indicate the flexibility and robustness of this OPS network architecture. Due to the nearly transparent switching elements, very few distortions are imposed on the optical signals, resulting in a wide range of optical power levels over which they maintain nearly error-free integrity. As demonstrated previously in testbeds, these results from a real OPS system confirm that even more payload wavelengths could be added to the optical packets in order to increase system throughput, although there may be a tradeoff between network size and number of payload wavelengths [10], [11].

IV. Conclusion

The receiver power penalty results seem to indicate minimal penalty at wavelengths in the range near 1545 nm. Wavelengths with the largest dynamic power ranges are found to be in that wavelength range as well. These trends suggest that wavelengths in this region of the C-band are best suited for the implemented switching nodes, as corroborated by [10]. This result is owing to the design of the passive optical components and SOAs, which are generally designed for optimal operation in the 1545$\sim$1555 nm range [9]. The effects are then made even more noticeable by the quantity of components that have been cascaded in this OPS system.

Overall, the scalability and robustness of the implemented 12×12 data vortex-based OPS network are demonstrated by measurements of the receiver power penalty, noise floor characteristics, dynamic optical power range, and other considerations. These metrics illustrate the effectiveness of the utilized multiple-wavelength transparent switching node design and its applications to OPS.

References

[1] W. J. Dally and B. Towles, *Principles and Practices of Interconnection Networks*. San Francisco, CA: Morgan Kaufmann, 2004.

[2] R. S. Tucker and W. D. Zhong, "Photonic packet switching: an overview," *IEICE Trans. Electron.*, vol. E82-C, pp. 202–212, Feb. 1999.

[3] G. I. Papadimitriou, C. Papazoglou, and A. S. Pomportsis, "Design alternatives for optical-packet-interconnection network architectures," *J. Opt. Netw.*, vol. 3, pp. 810–825, Nov. 2004.

[4] R. Hemenway, R. R. Grzybowski, C. Minkenberg, and R. Luijten, "Optical-packet-switched interconnect for supercomputer applications," *J. Opt. Netw.*, vol. 3, pp. 900–913, Dec. 2004.

[5] T. Lin, K. A. Williams, R. V. Penty, I. H. White, M. Glick, and D. McAuley, "Self-configuring intelligent control for short reach 100 Gb/s optical packet routing," in *Proc. Optical Fiber Commun. Conf. (OFC)*, Anaheim, CA, Mar. 2005, Paper OWK5.

[6] B. A. Small, O. Liboiron-Ladouceur, A. Shacham, J. P. Mack, and K. Bergman, "Demonstration of a complete 12-port terabit capacity optical packet switching fabric," in *Proc. Optical Fiber Commun. Conf. (OFC)*, Anaheim, CA, Mar. 2005, Paper OWK1.

[7] B. A. Small, A. Shacham, and K. Bergman, "Ultra-low latency optical packet switching node," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1564–1566, Jul. 2005.

[8] H. A. Haus, "Optimum noise performance of optical amplifiers," *IEEE J. Quantum Electron.*, vol. 27, no. 6, pp. 813–823, Jun. 2001.

[9] G. P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed. New York: Wiley, 2002.

[10] O. Liboiron-Ladouceur, W. Lu, B. A. Small, and K. Bergman, "Physical layer scalability demonstration of a WDM packet interconnection network," in *Proc. 17th Annu. Meeting LEOS*, Nov. 2004, Paper WM3, pp. 567–568.

[11] W. Lu, O. Liboiron-Ladouceur, B. A. Small, and K. Bergman, "Cascading switching nodes in data vortex optical packet interconnection network," *Electron. Lett.*, vol. 40, pp. 895–896, July 2004.