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Physical Layer Scalability Demonstration of a WDM Packet Interconnection Network

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Introduction

One of the most critical performance parameters of interconnection networks is their scalability to efficiently route data packets among thousands of ports under heavy traffic conditions. But beyond the logical scalability of the architecture is the question of the physical layer scalability. This issue is of particular importance to WDM optical packet networks, where the signal propagation through multiple switching nodes in the physical layer may place the ultimate limit on the size of the switching fabric. The most widely used switching element in optical packet networks is the semiconductor optical amplifier (SOA) primarily due to its broad gain bandwidth, fast switching time, and compact integration. As such, the physical layer scalability of large switching fabrics depends largely on the successful propagation of optical packets through multiple cascaded SOA switching elements.

In this paper we report on experiments that demonstrate the successful cascading of SOA based optical packet switching gates. Optical packets with payloads containing multiple WDM channels are propagated through SOA nodes in a re-circulating loop test-bed. The SOA switch nodes are constructed in accordance with the Data Vortex network architecture [1]. Our experiments show that a bit error rate (BER) of 10^{-9} can be maintained with an 8-channel 10 Gb/s-per-channel payload spanning the C-band after 58 such node hops. Recent simulations of the Data Vortex have shown that 99.99% of the injected packets will propagate through fewer than 60 internal switching nodes for a heavily loaded 10k×10k port interconnection network [2].

Experimental Setup

The experimental test-bed is shown in Figure 1. Eight DFB lasers with polarization controllers are combined by an 8:1 planar coupler into a SOA booster for transmission loss compensation. The WDM channels are distributed across the C-band ranging from1530-1575 nm with a minimum spacing of 3 nm. The channels are simultaneously modulated with an NRZ pseudo-random bit sequence (PRBS) of length $2^9 - 1$ produced by PPG1 via a single $LiNbO_3$ modulator at 10 Gb/s and then de-correlated by 450 ps/nm using 25 km of SMF fiber. A 25.6 ns long packet is created using a separate SOA to gate the continuous data stream. A single packet is injected once every 60 roundtrips into a 64 ns long re-circulating loop. Two Data Vortex switching nodes are placed in the loop [2]. Packets ingress through node 1 and either propagate back into the loop or exit from node 2. Both nodes are controlled by a separately programmed signal generated in PPG2. The SOAs are commercial devices (Kamelian OPB-10-10-X-C-FA) specified with a noise figure of 7 dB, an unsaturated gain of 10 dB, and a saturation input power of about 0 dBm. In each node, the SOA gain compensates for approximately 4.5 dB of loss due to the couplers and connectors. The optical receiver follows a band pass filter that selects the WDM channel under measurement. To avoid the accumulation of noise in the loop, the SOA in node 1 is turned off while the packet is dropped out of the loop from node 2. Bit error rate measurements are performed on all eight WDM channels of the packet using a BER tester externally gated by a pulse generator that is synchronized with PPG2. To avoid phase drift between the received data and the clock signal, the latter is recovered from the continuous data stream before the gating SOA and selected for the appropriate WDM channel with a band pass filter.

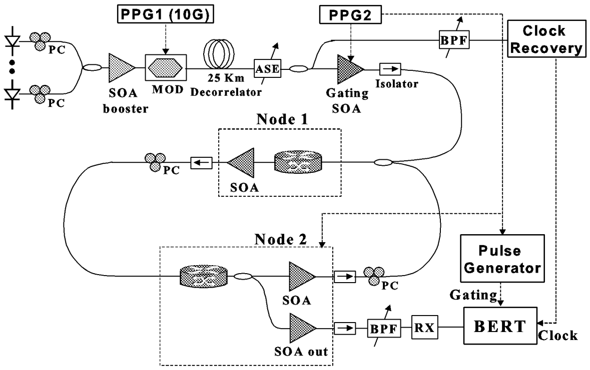

Figure 1: Experimental setup of re-circulating loop test-bed. PPG: programmable pattern generator; SOA: semiconductor optical amplifier; PC: polarization controller; MOD: $LiNbO_3$ modulator BPF: bandpass filter; solid line: optical signal; dashed line: electrical signal.

Results

The optical power spectrum of eight channels across the C-band from 1540 nm to 1560 nm in Figure 2 illustrates the input channels in gray and the output channels after 58 node hops in black. The input power is defined as the average power, taking into account the 1.67% duty cycle of the packet. The input power per channel is -15 dBm on average, for a total input power of less than -5 dBm. With lower input powers the optical signal to noise ratio is degraded by the beat noise between the amplified spontaneous emission (ASE) and signal. Higher input powers

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force the SOA to operate in saturation, leading to enhanced cross gain modulation between channels. After 58 hops, a 10 dB power slope across 10 nm for wavelengths shorter than 1550 nm and a 6 dB power slope across 8 nm for wavelengths longer than 1550 nm can be observed. Although the gain peak of the SOA is centered at 1465 nm, the parabolic peak at 1550 nm can be attributed to the passive elements in the loop test-bed.

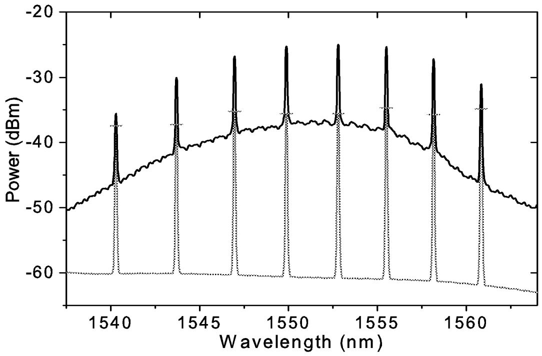

Figure 2: Eight channels across the C-band: input spectrum (gray); after 58 hops (black).

The number of cascaded SOA nodes versus the BER for each of the 8 channels is shown in Figure 3 where a dashed line is drawn at 10^{-9} BER. Shorter wavelength channels (Ch. 1, 2 3) are the first to limit maximum number of hops. For eight WDM channels spanning across a 24.2 nm band the maximum number of cascaded SOAs nodes achieved is 58.

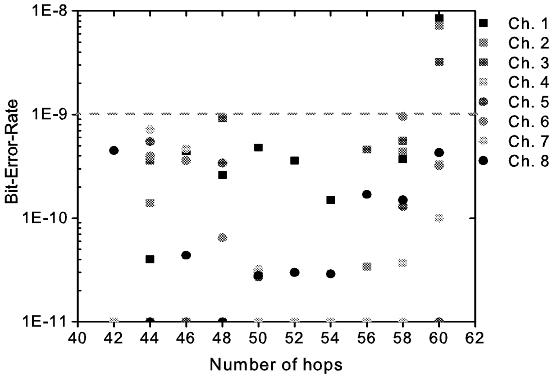

Figure 3: BER as a function of number of cascaded SOAs

In Figure 4, the shortest and the longest wavelengths are dynamically shifted to measure the widest usable bandwidth as a function of the number of hops with a BER below 10^{-9}. Two phenomena clearly determine the limits on the payload bandwidth: (1) channels at shorter wavelengths saturate the gain and experience gain compression; (2) longer channels experience less gain, which challenges the optical receiver sensitivity as the ASE based noise accumulates. Our measurement shows that the usable payload bandwidth can be increased from 24 nm to 44 nm by reducing the number of hops from 58 to 10.

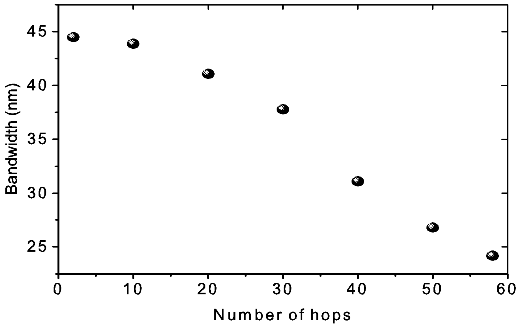

Figure 4: Multi-channels usable optical bandwidth.

Conclusion

The physical layer scalability of a WDM optical packet interconnection network is demonstrated in a re-circulating loop test-bed that mimics propagation through multiple cascaded SOA-based switching nodes. Optical packets carrying an 8-channel 10Gb/s-per-channel payload distributed across the C-band are shown to successfully propagate through 58 node hops while maintaining a BER of less than 10^{-9}. With the demonstrated physical diameter of 58 nodes, the Data Vortex network architecture could scale to interconnect nearly 10,000 ports.

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References

[1] Q. Wang, K. Bergman, *et al.*, "WDM packet routing for high-capacity data networks", *J. Lightwave Tech.*, **19** (10) 1420-1426 (Oct. 2001).

[2] W. Lu, O. Liboiron-Ladouceur, *et al.*, "Dynamic Switching Performance of Semiconductor Optical Amplifier in Data Vortex Packet Switching Network", *Elec. Lett.*, (To appear).

[3] Q. Wang and K. Bergman, "Performances of the Data Vortex Switch Architecture Under Nonuniform and Bursty Traffic", *J. Lightwave Tech.*, **20** (8) 1242-1247 (Aug. 2002).

[4] J. Yu and P. Jeppesen, "Improvement of Cascaded Semiconductor Optical Amplifier Gates by Using Holding Light Injection", *J. Lightwave Tech.*, **19** (5) 614-623 (May 2001).

[5] L. H. Spiekman, J. M. Wiesenfeld, *et al.*, "8 x 10 Gb/s DWDM Transmission over 240 km of Standard Fiber Using a Cascade of Semiconductor Optical Amplifiers", *Photon. Tech. Lett*, **12** (8) 1082-1084 (Aug. 2000).