A Data Rate- and Modulation Format-Independent Packet-Switched Optical Network Test-Bed

Daniel Brunina, *Student Member, IEEE*, Caroline P. Lai, *Member, IEEE*, and Keren Bergman, *Fellow, IEEE*

***Abstract*— Adopting high data rates and advanced modulation formats in optical interconnection networks will enable future computing systems to achieve greater performance and scalability. We experimentally demonstrate the data rate and modulation format independence of a 4 x 4 optical packet-switched network test-bed. Leveraging wavelength-division multiplexing, we show the transmission of multiwavelength 320-Gb/s optical packets, using 8 x 40-Gb/s wavelength-striped payloads. Both on–off keying (OOK) and differential-phase-shift-keying (DPSK) modulation formats are investigated. Optical packets are correctly routed through the network, and error-free operation is confirmed for all wavelengths with bit-error rates less than 10^{-12}. Best-case power penalties of 1 dB for OOK data and 0.52 dB for DPSK streams are obtained.**

***Index Terms*— Differential phase-shift keying (DPSK), optical communication, packet switching, photonic switching systems.**

I. Introduction

THE rapid growth in computational performance of microprocessors is vastly outpacing the development of high-performance network communication infrastructures [1]. The resulting communications bottleneck is a substantial design challenge for future high-performance computers (HPCs), and the limitations of electronic interconnects necessitate trade-offs between communication bandwidth, latency, and energy efficiency [2], [3]. Optical interconnects can alleviate this bottleneck by enabling the low-latency, energy-efficient communication necessary for next-generation HPCs through improved bandwidth density and bit-rate transparency [4 - 6]. However, these future HPCs must also leverage data rate- and modulation format-independent optical interconnection networks in order to optimize the electronic/optical interface while scaling to meet growing performance requirements.

Traditionally, the simplicity of non-return-to-zero on-off keying (NRZ-OOK) has made it a popular modulation format for optical communication links. However, phase-shift keying (PSK), specifically differential-binary-phase-shift-keying (DBPSK or DPSK), has long been known as a potential method for improving resilience to nonlinearities, with a 3-dB improved receiver sensitivity (with balanced detection) as compared to OOK. Such benefits of advanced modulation formats are becoming more significant as data rates now exceed 10 Gb/s and even 40 Gb/s, and the optical network elements are beginning to exceed the abilities of the driver and receiver electronic circuitry. At the computer scale, per-channel data rates can reach 25 Gb/s [7], and at such data rates, the power dissipation becomes a significant design challenge. Current microprocessors already dissipate up to half of their energy in the interconnect alone [8], and scaling up per-channel data rates without optimizing overall communication efficiency would result in an undesirable increase in energy dissipation. Therefore, next-generation computer systems must leverage optical interconnection networks that utilize not only high per-channel data rates, but also advanced modulation formats with improved resilience and spectral efficiency [9]. This need for networks to support both OOK and DPSK modulated data is the primary motivation for this letter.

In this letter, we experimentally demonstrate the transmission of 8×40-Gb/s wavelength-striped optical packets across a 4×4 optical interconnection network test-bed using both OOK and DPSK modulation formats. The optical interconnection network used here is a bit-rate transparent, multi-stage, 4×4 optical packing-switching fabric. Independent photonic switching nodes at each network stage enable distributed routing, with contention resolved by fast packet dropping. The aggregate 320-Gb/s payloads, resulting in over a terabit of bandwidth for the 4×4 network, are correctly routed through the optical test-bed and all eight wavelengths are verified error-free with bit-error rates (BERs) less than 10^{-12}.

We show a power penalty of 0.5 dB per 2×2 switch hop for the 40-Gb/s OOK data, and a power penalty of 0.26 dB per switch hop is measured for 40-Gb/s DPSK data. This demonstrates comparable power penalties for different bit rates and modulation formats with respect to photonic switching node traversals, presenting the opportunity to scale these networks in the future. The data-rate and modulation-format independence of the optical network thus enables improved network capabilities with higher data rates and advanced modulation formats.

II. Optical Interconnection Network

The 4×4 optical network test-bed (Fig. 1) is a multi-stage Omega network comprised of four 2×2 non-blocking

Manuscript received September 11, 2011; revised October 28, 2011; accepted December 7, 2011. Date of publication December 13, 2011; date of current version February 15, 2012. This work was supported in part by the National Science Foundation Engineering Research Council on Integrated Access Networks (subaward Y503160).

D. Brunina and K. Bergman are with the Department of Electrical Engineering, Columbia University, New York, NY 10027 USA (e-mail: daniel@ee.columbia.edu; bergman@ee.columbia.edu).

C. P. Lai is with Tyndall National Institute, Cork, Ireland (e-mail: caroline.lai@tyndall.ie).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2179642

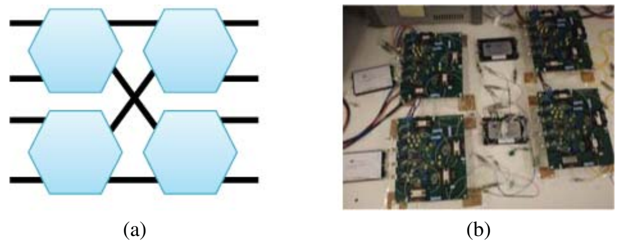

Fig. 1. (a) Block diagram of 4 × 4 optical interconnection network. (b) Photograph of implemented optical network test-bed.

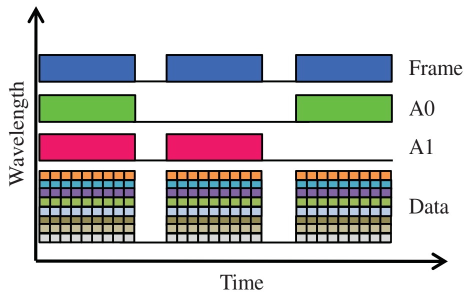

Fig. 2. Wavelength-striped optical packet.

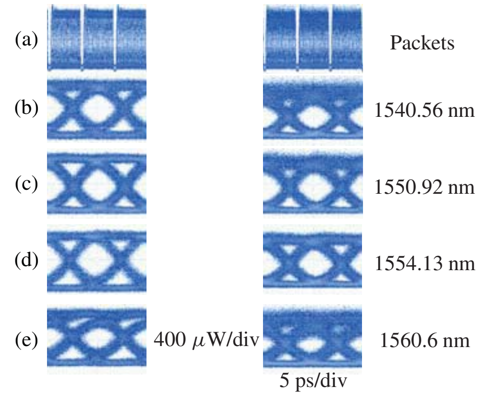

Fig. 3. Optical eyes at the input (left) and output (right) of the optical network showing (a) packets and (b)–(e) subset of 40-Gb/s OOK payload wavelengths.

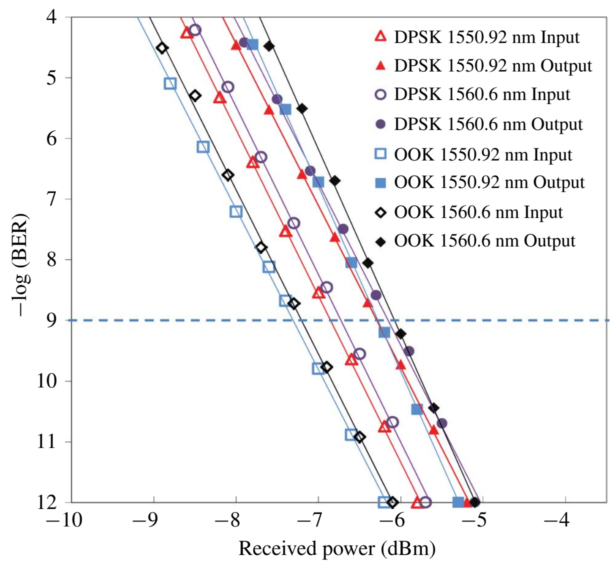

Fig. 4. BER curves for best case (1550.92 nm) and worst case (1560.6 nm) 40-Gb/s OOK and DPSK payload wavelengths. Input measurements are shown with open points, while output measurements are depicted with filled points. The power penalty spread from best- to worst-case is 0.1 dB for OOK and >0.1 dB for DPSK at 10^{-9} BER.

photonic switching nodes [10]. Four semiconductor optical amplifiers (SOAs) are used at each 2×2 switching node, gated either on or off, to transparently pass the wavelength-striped optical packets (Fig. 2) from a given input port to any output port. The use of SOAs enables broadband, data-rate transparent photonic switching nodes with nanosecond switching times. Each optical packet contains dedicated, low-speed header wavelengths to rapidly convey routing information to the complex programmable logic device (CPLD) at each switching node. This encoding scheme allows each switching node to sample the header wavelengths and process the address signals to route the optical packets with a nanosecond time-scale.

Here, the payloads consist of 8 wavelengths, each modulated at 40-Gb/s, combined into a single wavelength division multiplexed (WDM) transaction and modulated with either OOK or DPSK using a single modulator. Three control wavelengths (a frame and two address bits), are multiplexed together with the 40-Gb/s payloads using WDM to determine which output port is being addressed for each optical packet. These header wavelengths remain constant for the duration of each packet. The wavelength-striped packet format ensures that the optical network test-bed is transparent not to only data rate, but also to modulation format.

III. Experimental Demonstration

A. 40-Gb/s OOK Overview

The experimental setup, fully detailed in [10], is comprised of a 2-stage 4×4 optical network test-bed that routes optical packets from any input to any output port. The 4×4 optical network test-bed is comprised of commercially available components, including SOAs, 155-Mb/s photodetectors, passive optical components, and high-speed electronic circuitry. Each 64-ns optical packet is created using eight distributed feedback (DFB) lasers, which are passively combined and modulated with OOK data by a 40-Gb/s $LiNbO_3$ modulator. The 40-Gb/s OOK data is generated by a pulse pattern generator (PPG), using a 2^{15}-1 pseudo-random bit sequence (PRBS), and an electrical multiplexer. Each optical packet is combined with three, independently-generated network control signals, creating wavelength-striped optical packets that pass transparently through the optical test-bed.

B. 40-Gb/s OOK Results

We experimentally measure error-free transmission of all optical packets at the output of the network, with BERs less than 10^{-12} for all eight payload wavelengths. Fig. 3a shows the optical packets at the input and output of the network. Fig. 3b shows the optical eye diagrams for a subset of 40-Gb/s payload wavelengths. The sensitivity curves shown in Fig. 4 demonstrate a power penalty of 1 dB for the best-case payload

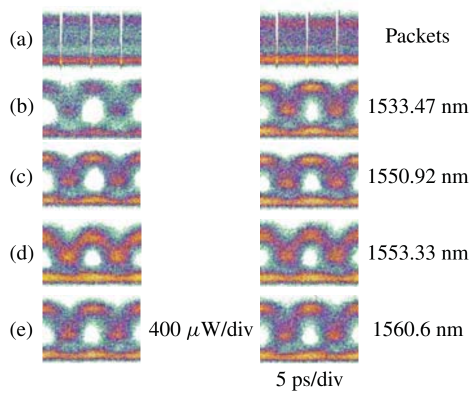

Fig. 5. Optical eyes at the input (left) and output (right) of the optical network showing (a) packets and (b)–(e) subset of 40-Gb/s DPSK payload wavelengths.

wavelength of 1550.92 nm (0.5 dB per SOA hop) and 1.1 dB for the worst-case payload wavelength of 1560.6 nm (0.55 dB per SOA hop). The small variation in power penalties is likely due to the slight gain curve of the EDFA used in BER testing.

C. 40-Gb/s DPSK Overview

Optical packets with 8×40-Gb/s DPSK data are then generated and transmitted through our test-bed. The second experimental setup consists of the above transparent, 2-stage 4×4 optical test-bed, again correctly routing 64-ns wavelength-striped optical packets. A 40-Gb/s PPG drives a single 40-Gb/s phase modulator (PM) to encode $2^{15}-1$ PRBS DPSK data onto eight payload wavelength channels, each with an average power of -14 dBm at the network input and with wavelengths ranging from 1533.47 nm to 1560.6 nm. Immediately after modulation, and before entering the network, the WDM data passes through a 2-km span of single mode fiber for decorrelation. The three separate header wavelengths (frame, address0, address1) are modulated at the packet rate using three external SOAs, which are controlled by an Agilent ParBERT.

In the experiment, the combined eight payload wavelengths are gated using a single SOA, controlled by the ParBERT, to create 64-ns optical packets. The resulting configuration is such that each optical packet consists of 8×40-Gb/s DPSK wavelength channels and 3 low-speed header wavelength channels. As before, all eleven wavelengths traverse the optical interconnection network concurrently as a single wavelength-striped packet. The amplification provided by the SOA-based switching nodes within the optical test-bed maintains this average power during propagation through the network and to the network output.

At the output, the eight payload wavelengths are sent to a tunable filter to select a single 40-Gb/s DPSK signal, which is amplified using an erbium-doped fiber amplifier (EDFA) and filtered again. The single wavelength is then sent to the constructive port of a delay interferometer (DI), a variable optical attenuator (VOA), and a 40-Gb/s photodiode with transimpedance and limiting amplifiers. This received electrical data is time-demultiplexed and verified using a bit error rate tester (BERT), which is gated for packetized data by the ParBERT. The 40-Gb/s optical signals are simultaneously inspected using a digital communications analyzer (DCA).

D. 40-Gb/s DPSK Results

We confirm error-free operation for all eight 40-Gb/s DPSK payload wavelengths with BERs less than 10^{-12} at the output of the optical network test-bed. The optical packets at the input and output are shown in Fig. 5a, and Fig. 5b shows the input and output 40-Gb/s optical eye diagrams for a subset of payload wavelengths at the output of the constructive port of the DI. A best-case power penalty of 0.52 dB was measured at a BER of 10^{-9} (Fig. 4) for the 2-stage network at 1550.92 nm. The worst-case power penalty of 0.56 dB was measured at 1560.6 nm. This demonstrates an average power penalty of 0.26 dB per SOA switch hop when transmitting 40-Gb/s DPSK data at 1550.92 nm, and a power penalty spread >0.1 dB for all eight wavelengths ranging from 1533.47 nm to 1560.6 nm.

IV. Conclusion

We experimentally demonstrate a data rate- and modulation format-transparent, multi-terabit optical interconnection network. Eight 40-Gb/s payload wavelengths are modulated with either OOK or DPSK and correctly routed through the network achieving BERs less than 10^{-12}. Further, we show a comparable power penalty for 40-Gb/s DPSK data (0.26 dB per SOA switch) versus 40-Gb/s OOK (0.5 dB per SOA switch). This work demonstrates the ability to not only scale per-channel data rates, but also to adopt advanced modulation formats within optically-interconnected computing systems that can further improve spectral efficiency and overall network scalability.

References

[1] K. Bergman, *et al. Exascale Computing Study: Technology Challenges in Achieving Exascale Systems* [Online]. Available: http://www.notur.no/news/inthenews/files/exascale_final_report_100208.pdf
[2] R. Ho, W. Mai, and M. A. Horowitz, "The future of wires," *Proc. IEEE*, vol. 89, no. 4, pp. 490–504, Apr. 2001.
[3] International Technology Roadmap for Semiconductors. (2009). *The ITRS Technology Working Groups*, London, U.K. [Online]. Available: http://www.itrs.net
[4] A. F. Benner, *et al.*, "Optics for high-performance servers and supercomputers," in *Proc. OFC 2010*, San Diego, CA, Mar., pp. 1–3, paper OTuH1.
[5] B. J. Offrein and P. Pepeljugoski, "Optics in supercomputers," in *Proc. ECOC 2009*, Vienna, Austria, Sep., pp. 1–2, paper 3.1.3.
[6] R. Luijten, W. E. Denzel, R. R. Grzybowski, and R. Hemenway, "Optical interconnection networks: The OSMOSIS project," in *Proc. 17th LEOS 2004*, Nov., pp. 563–564, paper WM1.
[7] *IEEE P802.3ba Specification* [Online]. Available: http://ieee802.org/3/ba/public/jan09/ghiasi_01_0109.pdf
[8] N. Magen, A. Kolodny, U. Weiser, and N. Shamir, "Interconnect-power dissipation in a microprocessor," in *Proc. SLIP '04*, pp. 7–13.
[9] P. J. Winzer and R.-J. Essiambre, "Advanced modulation formats for high-capacity optical transport networks," *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4711–4728, Dec. 2006.
[10] C. P. Lai, D. Brunina, and K. Bergman, "Demonstration of 8×40-Gb/s wavelength-striped packet switching in a multi-terabit capacity optical network test-bed," in *Proc. 23rd Annu. Meet. IEEE Photon. Soc.*, Denver, CO, Nov. 2010, pp. 688–689, paper ThQ-2.