Demonstration of 8×40-Gb/s Wavelength-Striped Packet Switching in a Multi-Terabit Capacity Optical Network Test-Bed

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Abstract: **We report on the successful and error-free routing of 8×40-Gb/s wavelength-striped packets in a transparent optical network test-bed, supporting multi-terabit switching capacity. A 0.5-dB power penalty per switch hop is shown at 40 Gb/s.**

Introduction

As current networking and high-performance computing systems scale, a major challenge involves delivering high-bandwidth, broadband user traffic with the necessary low communication latencies required by next-generation routers and network elements. Future networking designs will necessitate leveraging emerging physical-layer technologies to meet the exploding user demand in bandwidth and wide variety of applications. Optical packet switching (OPS) has been proposed as a promising, scalable approach for the construction of high-performing switching fabrics for future routers in the Internet core [1] and access networks [2], as well as low-latency interconnection networks [3-5]. OPS networks can offer a programmable communications infrastructure for high-bandwidth, multi-wavelength optical messages by allowing for the transparent transmission of broadband wavelength-striped optical messages. In order to adequately address the increased growth in bandwidths in future optical routers, the optical switching fabric will need to support line-card rates at extremely high data rates. Thus, each payload wavelength-division-multiplexing (WDM) channel in the optical message may be required to be modulated at rates of 40 Gb/s and beyond. By supporting these high-speed network links, OPS networks can potentially achieve dynamic, intelligent, and programmable packet switching on the optical layer.

Here, we report on an 4×4 OPS fabric test-bed that can seamlessly support the error-free routing and transmission of wavelength-striped optical packets with 8×40-Gb/s payloads, providing an aggregate bandwidth of 320 Gb/s per network port. Thus, the test-bed supports over a terabit of total optical bandwidth. The test-bed is constructed in a multistage network architecture that utilizes semiconductor optical amplifier (SOA) gates. We experimentally verify that bit-error rates (BERs) less than 10^{-12} can be achieved on all eight of the 40-Gb/s payload wavelength channels, with an average power penalty of 0.5 dB per SOA hop, taken at 40 Gb/s and a BER of 10^{-9}. This demonstration illustrates the potential for achieving high-speed optical network lightpaths with error-free performance of wavelength-striped optical messages.

Optical Network Test-Bed

The optical switching fabric architecture (Fig. 1) is a multistage Banyan network design, comprised of broadband 2×2 photonic switching nodes [3]. It provides a means of achieving high-bandwidth transparent optical lightpaths and interconnections for next-generation Internet routers and switches. The electronic control logic is distributed among the switching nodes, realizing optical routing with programmable and reconfigurable logic. Optical messages are injected in the optical network with a wavelength-striped packet format. The supported WDM messages have control signals (such as frame, quality-of-service, and address) encoded on dedicated wavelengths using one bit per wavelength, and the payload information distributed over the rest of the available wavelength band. Each payload segment is modulated simultaneously at a high data rate (here, at 40 Gb/s per wavelength) to yield a high aggregate message bandwidth. The wavelength-striped optical packets are routed at each photonic node using four SOA switching elements, which offer message-granular routing, and data-rate and packet-format transparency. The SOAs are operated in the linear regime, and the characteristic wide gain spectrum allows for broadband, high-bandwidth optical switching. Previously, each payload channel was modulated at 10 Gb/s [3], [5]; here, due to the network's inherent broadband transparency, we can achieve data rates of 40 Gb/s per payload wavelength. This demonstration uses eight wavelengths each at 40 Gb/s; this does not approach the achievable limit. Synchronous transmission of fixed-length packets is shown here, though asynchronous transmission may also be supported [6].

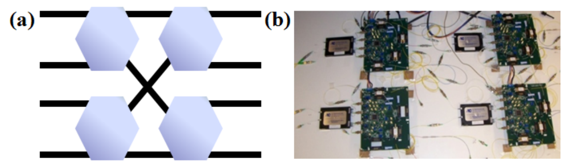

Fig. 1: (a) Block diagram of optical network architecture; (b) Photograph of implemented network test-bed.

Using optical receivers and fixed wavelength filters, the 2×2 photonic switching nodes filter and decode the packet's control information as the leading edge of the packet reaches each node. Based on the recovered two-bit control signals (frame and one address bit), simple electronic control logic gates turn on the appropriate SOAs, which then route the optical messages to their desired node port. Contentions within the nodes are resolved by fast message dropping during packet transmission. An optical-layer acknowledgement (ack) protocol can be realized, levering short optical pulses that inform the source of successful transmission. Input sources that do not receive acks can retransmit at a later time, minimizing the latency penalty.

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Experimental Demonstration and Results

The experimental optical network test-bed is implemented as a 4×4 topology using two stages of 2×2 photonic switching nodes, connecting four independent input and output ports (Fig. 1). Xilinx complex programmable logic devices (CPLDs) are used to realize the electronic control logic for packet routing. In addition to the CPLDs, the test-bed is composed of discrete, commercially-available components such as Kamelian SOAs, low-speed p-i-n photodiodes, passive optics, and electronic circuitry. The test-bed here supports 8×40-Gb/s wavelength-striped optical messages, with 40-Gb/s non-return-to-zero (NRZ) data encoded on eight payload wavelength channels.

The experimental setup uses eight distributed-feedback (DFB) lasers ranging from 1540.56 nm to 1560.61 nm that are combined using a wavelength-division-multiplexer. All channels are simultaneously modulated with a single 40-Gb/s $LiNbO_3$ modulator, encoding a 2^{15}-1 pseudo-random bit sequence (PRBS) on all eight payload channels. The 40-Gb/s RF signal is created using a pulse pattern generator (PPG) and electrical multiplexer. The control wavelengths are generated independently, using separate DFB lasers at specific wavelengths. The data and control information are gated into 64-ns long optical packets using SOAs driven by a data timing generator (DTG) and combined, resulting in wavelength-striped optical packets with three control bits multiplexed with eight payload wavelength channels.

The WDM optical packets are injected in the test-bed and switched using the SOA-based switching nodes. The SOAs provide sufficient amplification to compensate for the passive losses incurred by propagation through the photonic switching nodes. Correct routing of the 8×40-Gb/s packets through the network is verified. At the output of the network, the packet analysis system involves transmitting the egressing packets to an erbium-doped fiber amplifier (EDFA). A tunable filter then selects one 40-Gb/s payload channel, which is transmitted to an optical attenuator, and subsequently to a high-speed receiver composed of a p-i-n photodiode and transimpedance amplifier. The received electronic data signal is time-demultiplexed for evaluation by a BER tester (BERT). The DTG is also used to gate the BERT on the optical packets. A common clock synchronizes the DTG, PPG, BERT, and electrical multiplexer/demultiplexer.

We experimentally confirm that all egressing packets achieve error-free transmission, obtaining BERs less than 10^{-12} on all eight 40-Gb/s payload wavelength channels. Fig. 2a depicts the input and output optical packets with the encoded 40-Gb/s data, as well as the 40-Gb/s input and output eye diagrams corresponding to four of the eight payload channels (Fig. 2b-e). Sensitivity curves for one representative error-free channel (Fig. 3) show a power penalty of 1 dB for the two-stage network, taken at a BER of 10^{-9}. For this demonstrated transmission of wavelength-striped packets with 40-Gb/s data on each payload channel, the resulting average power penalty is 0.5 dB per SOA switch hop. The power penalty for 40-Gb/s data rates is higher than that at 10 Gb/s, which is a design factor for future network implementations.

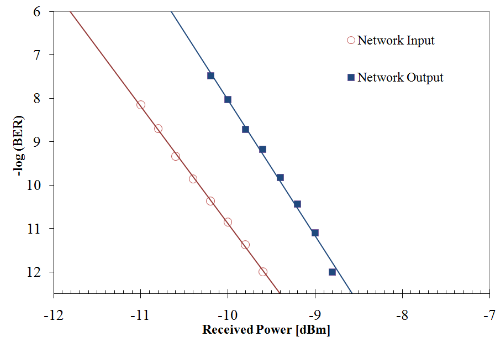

Fig. 3: BER curves for the demonstration (1550.92 nm).

Conclusions

Links in future optical networks and routers will be required to operate at very high data rates in order to accommodate the exploding demand in bandwidth. Here, we experimentally demonstrate an optical packet-switching fabric that successfully supports wavelength-striped messages with 40-Gb/s data encoded on multiple payload wavelengths. 8×40-Gb/s optical packets are shown correctly routed with error-free transmission of all payload channels, achieving an increased aggregate bandwidth of 320 Gb/s per network port. The implemented 4×4 fabric thus realizes over a terabit of optical switching capacity. This demonstration of high-speed optical packet routing and transmission constitutes a fundamental step in realizing the data rates required by future applications, specifically at 40 Gb/s and beyond.

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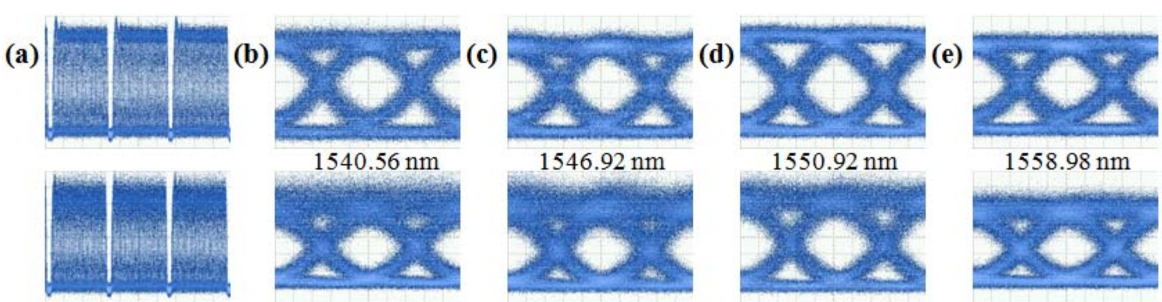

Fig. 2: Input (top) and output (bottom) of (a) the optical packets; (b)-(e) 40-Gb/s eye diagrams of a subset of payload wavelength channels.