Flexibility of Optical Packet Format in a Complete 12×12 Data Vortex Network

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***Abstract*—Packets with variable-sized payloads between 48 and 384 bytes, depending upon the number of payload wavelengths and their duration, are simultaneously routed in an implemented 12×12 optical packet switching network with bit-error rates better than 10^{-12}. Payloads with varying offsets within the 25.6-ns timeslot are routed successfully as well, illustrating the flexibility and transparency of the data vortex architecture to multiple packet formats.**

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

I. Introduction

HIGH-BANDWIDTH low-latency interconnection networks are useful in a variety of applications, including high-performance computing (HPC), large-scale data storage and retrieval systems, and telecommunications core routers, all of which necessitate the high-speed transmission of enormous volumes of data [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 per second of encoded optical data while maintaining near speed-of-light limited transit latencies [2]. The realization of a complete 12×12 OPS interconnection network, which contains 36 discrete switching nodes and is based upon the data vortex topology, was recently reported [3], [4].

Detailed studies of this implementation have recently been published as well [5]–[7]. These investigations focus on the physical-layer properties of the network. However, data-layer transparency and flexibility are also important features for deployable interconnection networks. The current letter focuses on the robustness of the network against optical packets with variable payload data capacities and formats, and extends beyond the wavelength-based flexibility experiments first reported in [8].

The packets used in the data vortex architectures follow a wavelength-division-multiplexed (WDM) structure. A few of the wavelengths are designated for constant-value wavelength-parallel header encoding. The remaining wavelengths are modulated at a high data rate and comprise the packet payload. All of these wavelengths are routed together and traverse the network as a cohesive structure [3], [4], [9] (Fig. 1). Employing multiple-wavelength packet structures allows optical networks to more fully leverage the bandwidth available to photonic components [9]–[12].

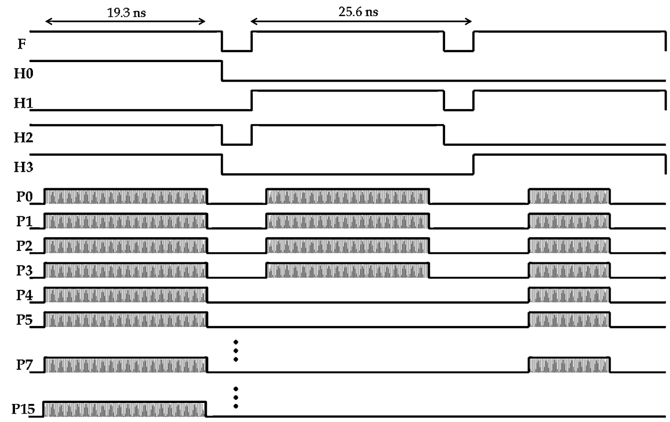

Fig. 1. Illustration of different possible payload formats for the multiple-wavelength packet. The first contains all 16 payload wavelengths with a duration of 19.3 ns; the second, four wavelengths and 19.3 ns; the third, eight wavelengths and 9.6-ns offset to the center of the timeslot.

Two experiments supporting the flexibility of the data vortex OPS network paradigm are presented. The first confirms that the system can simultaneously route packets that contain variable payload sizes, which are accomplished by altering the number of payload wavelengths. For the second experiment, the duration of the packet payloads is varied by an integer multiple so that some payloads are twice as long as others, and the position relative to the packet slot is varied as well. These demonstrations of data-layer flexibility address situations that are common within OPS switching networks used for a variety of applications, ranging from HPC systems to local area networks [13]–[17].

Specifically, packets with payloads comprised of 4, 8, 12, or 16 wavelengths, and durations of 9.6 and 19.3 ns, are routed error-free through the implemented network simultaneously. The modulation rate for all payload wavelengths is 10 Gb/s. For packets of the maximum length (19.3 ns), the capacities available are 96, 192, 288, and 384 bytes, respectively, for the 4-, 8-, 12-, and 16-wavelength payloads. For the shorter packets (9.6 ns), the data capacities are 48, 96, 144, and 192 bytes, respectively. Therefore, in a single 25.6-ns timeslot, the data capacity can range from 48 to 384 bytes, corresponding to net bandwidth in the range 15–120 Gb/s.

II. Applications

High-bandwidth interconnection networks are especially useful in systems which require large volumes of data to be transmitted between various client terminals. The traffic on the network depends upon the specific application, and can change

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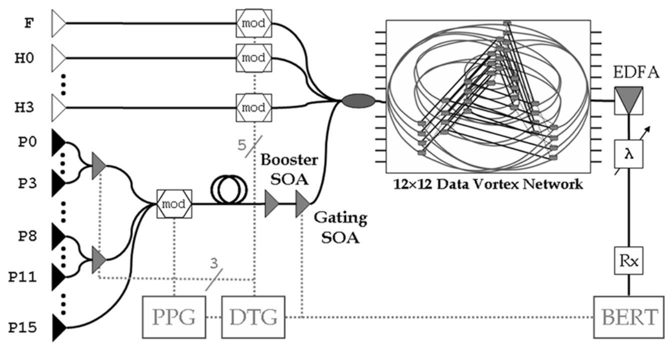

Fig. 2. Schematic of experimental setup with the appropriate packet generation and detection subsystems, with $LiNbO_3$ modulators (mod), pulse pattern generator (PPG), data timing generator (DTG), BER tester (BERT), EDFA amplifier, tunable filter (λ), and high-speed receiver (Rx). The payloads are grouped into four sets of four in order to produce packets with a variable number of wavelengths.

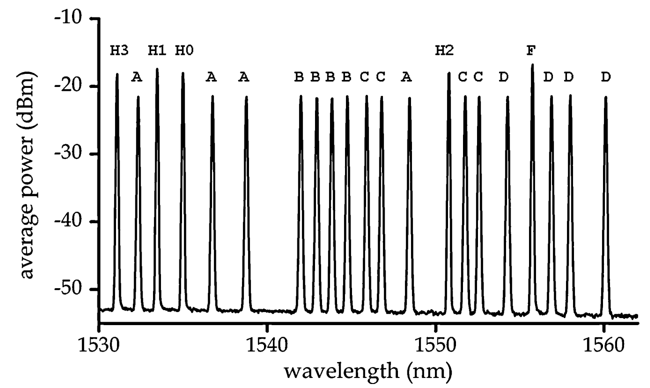

Fig. 3. Plot of packet optical power spectrum, with the five routing header wavelengths higher than the 16 payload wavelengths, which are divided into four groups (A, B, C, D).

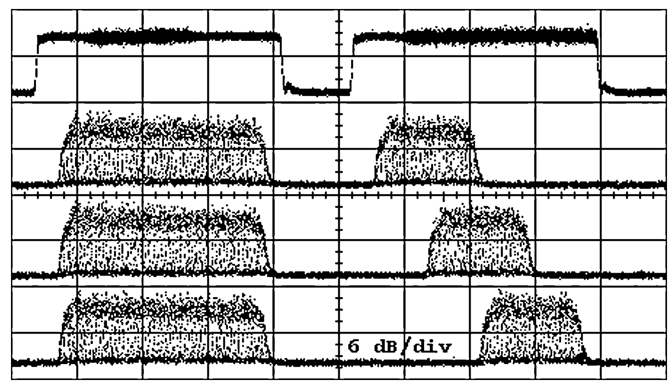

Fig. 4. Waveforms of optical headers and payloads. The first line shows the frame and header wavelengths, which delineate the packet. Subsequent lines illustrate various payload durations and offsets. The packets shown contain a variety of wavelengths, ranging from 4 to 16.

dynamically with time, as can the bandwidth demands of each network terminal. For example, for an HPC interconnection network, bandwidth demands can vary by terminal type, by the format of the algorithm, and even by the timing stage within that algorithm. In telecom routers, traffic patterns continuously vary, again leading to fluctuating bandwidth demands.

Another possible situation which is considered here is one in which the timeslot synchronization is not perfectly matched for all client terminals. It is possible that the packet payloads not be aligned perfectly with the packet slot times due to nonuniformity in the network hosts. For example, there could be clock skew between the network terminals; or terminals could be physically distant from each other, which often makes synchronization difficult. Accommodating for possible timing discrepancies in the packet payload is, therefore, an important attribute of the network architecture as well. Although some aspects of network timing and timeslot synchronization have already been studied experimentally [6], the focus of the current investigation is the integrity of the payload and data-layer transparency.

The experiments which follow demonstrate that variable data-layer service requirements can be accommodated by the physical layer in the implemented data vortex architecture [3], [4]. This feature may allow for a reduction in hardware demands, which could save cost and power, for applications that do not have continuously maximal bandwidth requirements.

III. 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 (Fig. 2). Then some of the wavelengths are selected by a series of semiconductor optical amplifiers (SOAs) to be used for a particular packet; four groups of four wavelengths each can be selected by the SOAs (Fig. 3). These 10-Gb/s nonreturn-to-zero payload wavelengths, which span the range 1530–1560 nm, are modulated together with a $2^7 - 1$ pseudorandom binary sequence and then decorrelated by approximately 450 ps/nm with 25 km of fiber. The variable-wavelength payload is amplified by a high-gain booster SOA and gated into packets by a second SOA, the timing and duration of which can also be varied. 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. The wavelengths used for both the payload and header are channels designated by the ITU WDM grid, and some adjacent channels with a spacing of just 0.8 nm (100 GHz) are included. This packet generation scheme is very similar to the ones used in [3]–[7], [9], only the setup has been modified to produce packets of variable wavelength [8] and of variable duration and offset.

The packets are extracted from one of the network output nodes 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 receiver is synchronized to the payload data, and the BER tester is gated to enable error testing only on the packet payload [4], [6].

For the experimental results discussed below, the number of wavelengths in the payload can be between 4 and 16, and the duration of the payload can range from approximately 9–19 ns, with varying timing offsets relative to the header signals (Fig. 4). All of these settings are controlled by the SOAs used to generate the optical packets. Packets remain in the system for five node

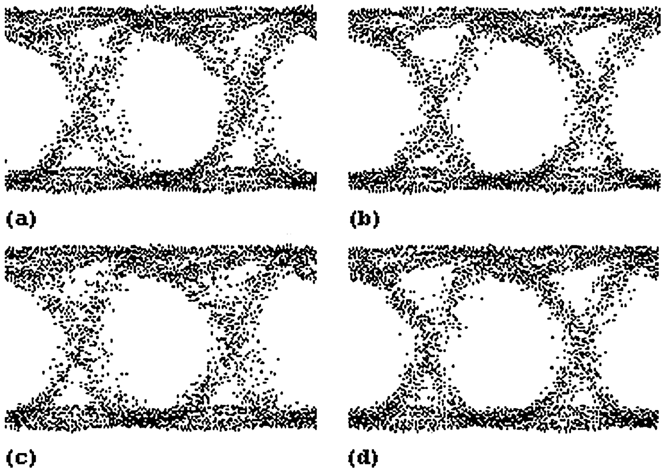

Fig. 5. Eye diagrams of output payloads for packet payloads with (a) 4, (b) 8, (c) 12, and (d) 16 wavelengths. The number of wavelengths present in a payload has a greater effect on signal integrity than the payload timing.

hops, and the network must accommodate these different packet formats simultaneously.

The results obtained in [5] indicate that the packet power incident on the implemented OPS network can vary by more than a factor of four (6.4 dB) while maintaining error-free $(< 10^{-12}\mathrm{BER})$ operation. For payloads with consistent power in each of the wavelengths, it then seems reasonable that the number of wavelengths can vary by a factor of four as well. This presumption is proven correct, as discussed below.

IV. Results

For all possible packet formats, consisting of 4, 8, 12, or 16 wavelengths and payload lengths of approximately 9 or 19 ns, BERs of 10^{-12} or better are achieved (Fig. 5). Not only do the switching nodes within the network operate transparently, without being affected by the payload format, but the receiver operates correctly for all payload formats as well. This implies that the gain and saturation conditions of the individual switching nodes are unaffected by the payload format as well. This flexibility illustrates very clearly the transparent nature of the implemented architecture and the component optical switching node design.

V. Conclusion

Packets containing payloads of variable size and format are simultaneously routed through the implemented OPS network successfully, confirming the flexibility and transparency of the network architecture. Payloads with varying numbers of wavelengths, varying durations and timing offsets, and hence varying data capacities, are generated. Within the 25.6-ns timeslot, payloads contain 4, 8, 12, or 16 wavelengths modulated at 10 Gb/s, and subtend approximately 9 or 19 ns, yielding total payload capacities of 48, 96, 144, 192, 288, or 384 bytes. All packet payloads are confirmed to route through the network path with BER values of 10^{-12} or better, without requiring reconfiguration of the network. Although only a small set of discrete packet payload sizes are used here, it is likely that a large continuum of packet sizes can be routed successfully as well. The degree of flexibility illustrated in these demonstrations further reinforces the potency of the utilized multiple-wavelength transparent switching node design and its applications to optical packet switching.

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