

A scalable optical packet switch with label processing for DPSK and OFDM data packets

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Abstract: We present a scalable and low latency optical packet switch for DPSK and OFDM packets. Results show error-free operation of 1x64 optical packet switch for 12x10 Gb/s DPSK packets and 12x40Gb/s OFDM packet.

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1. Introduction

The exponential growth of data Internet traffic will require high capacity networks capable of efficiently routing various types of data format packets. Optical packet switching networks are expected to provide the required capacity and flexibility for high-speed networks. Meanwhile, high spectral efficient modulation formats such as differential phase shift keying (DPSK), differential quadrature phase shift keying (DQPSK) and orthogonal frequency division multiplexing (OFDM) are candidates for data signals at bit-rates > 100 Gb/s. They require smaller bandwidth for transmission a given data rate, and are more robust to dispersion and nonlinear effects in the optical communication system. As a result, it is important that optical packet switches (OPS) should be able to handle transparently data packets with variable data-formats. Moreover, OPS should be capable to control a large number of ports, operate at low power and introduce low latency.

In our previous work, exploiting the parallelism in the photonic domain, we have demonstrated a scalable, low latency OPS employing in-band labeling technique and error free operation with low power penalty for 160 Gb/s RZ-OOK was reported [1,2]. Here, we extend the concept of the OPS to demonstrate transparent switching of multiple modulation formats, such as DPSK and OFDM. We demonstrate parallel processing of 6 in-band labels which allows for addressing $2^6 = 64$ output ports. We also present results showing error-free operation for 12 x 10 Gb/s DPSK multi-colored packets and 12 x 40 Gb/s OFDM multi-wavelength packets with low penalty.

2. Experimental set-up

The experimental set-up is shown in Figure 1. At the transmitter side, we generate packets with two types of modulation formats. First, we generate 12 x 10 Gb/s DPSK multi-wavelength payload by modulating 12 continuous wave (cw) - lasers with wavelengths from 1543.67 nm to 1548.45 nm by using a LiNbO₃ phase modulator. The channel wavelengths are spaced by 50 GHz. Second, we generate 12 x 40 Gb/s OFDM multi-wavelength payload by modulating 12 cw-lasers with wavelength also from 1543.67 nm to 1548.45 nm by using 10-GHz LiNbO₃ amplitude modulator. The channel wavelengths spaced by 50 GHz are chosen such that the wavelengths of the cw-labels are located at a zero of the spectra of the multi-wavelength packets (see Figure 2a-b). A similar strategy is chosen for the OFDM payload (see Figure 2c-d). Here, we use discrete multitone modulation (DMT), which is the baseband version of OFDM, with up to 64-state quadrature amplitude modulation (64-QAM). To optimize the bandwidth utilization, we use Chow's rate-adaptive bit-loading algorithm [3,4] to maximize the achievable bit rate. Thus, we are able to transmit more than 40 Gb/s data traffic in less than 10 GHz bandwidth. In the experiment, a computer is used to emulate the digital DMT modulator and the data traffic is then generated by an arbitrary waveform generator

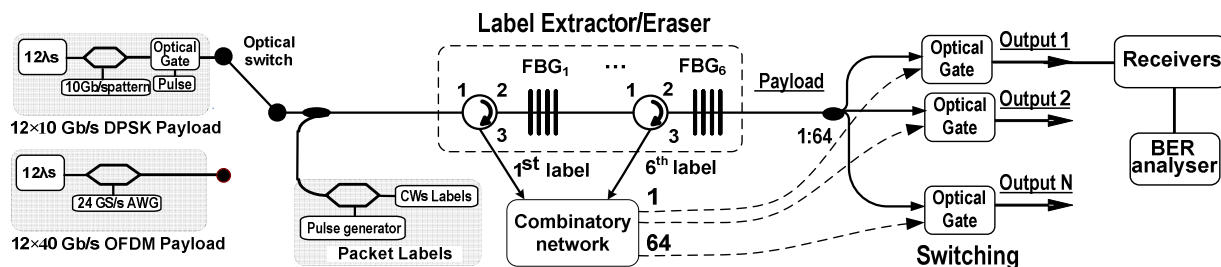


Figure 1: Experimental set-up. Two types of modulation formats are generated and processed by the optical packet switch.

(AWG) running at 24 GSamples/s. By using an optical gate, multi-wavelength DPSK and OFDM data packets with duration of 3.6ns and 2.8 ns of guard time were generated. The length of payload is limited by the pattern generator and does not form a fundamental restriction. An optical switch is used to choose between two types of format.

The address information of the packets is encoded using in-band labels with the same duration as the packet payload. Allocation of the label within the 12 x 10 GB/s DPSK and 12 x 40 GB/s OFDM is illustrated in Figs. 2a and 2c (6 labels at wavelengths $L_1=1543.88$ nm, $L_2=1544.36$ nm, $L_3=1545.16$ nm, $L_4=1546.92$ nm, $L_5=1547.72$ nm, $L_6=1548.2$ nm). The wavelengths of the labels are located at the zero's of the spectra of the multi-wavelength payloads. The in-band labelling has two advantages: firstly N labels allow for encoding 2^N addresses which makes that a large number of ports can be addressed within the limited payload bandwidth. Secondly, the parallel and asynchronous operation of the label processing makes high speed clock recovery redundant. This is essential for reducing latency and power consumption. The labels are then coupled to the payloads.

The data packets are fed into the OPS consisting of a label extractor/eraser, a combinatory network, and transparent optical gates. The label extractor separates the labels and the payload. The label extractor consists of a cascade of narrow-bandwidth fiber Bragg Gratings (FBGs) and optical circulators. The FBGs are centered around the central wavelengths of the labels. The FBGs have a Gaussian profile with 98% of reflectivity and a -3 dB bandwidth of 6 GHz. This is essential to avoid distortions in the packet payload. Figures 2b and 2d show the payloads after the labels extraction. Afterwards the payload is broadcasted to the optical gates. The labels output the label extractor in parallel and are opto-electronic converted before being fed into a combinatory network. The combinatory network operates asynchronously. The combination of the asynchronous combinatory network and the parallel processing of the optical label makes complicated packet based clock-recovery and electrical serial-to-parallel conversion redundant. The combinatory network can be scaled to a larger number of labels without increasing the latency. For 6 optical labels, the combinatory network provides 64 distinct outputs, which act as control signals for driving 64 optical gates (output ports). The optical gates are transparent switches that support any data format and data-rate.

At the output of the switch, the DPSK payload is decoded by the receiver and analyzed by the bit-error rate tester. The OFDM payload is detected by a 10 GHz photo-detector (PD). The received signal is electrically amplified and sent to a real-time oscilloscope running at a sampling rate of 50 GSamples/s. The final demodulation and evaluation is done offline by computer.

3. Results

Firstly, we investigate dynamic operation of the switch for 12 x 10 Gb/s DPSK data packets. In the experiment we investigated the behavior of a 1x64 OPS by using only two optical gates and an 18 dB attenuator to account for the 1:64 splitting losses. Using two optical gates is sufficient to evaluate the cross-talk between the output ports as well as the switching dynamics. The right panel of Figures 2 shows the time evolution of the switching for 12 x 10 Gb/s DPSK data packets. Fig. 2e shows the separated payload after label extraction. Fig. 2f shows the control signal output from combinatory network. Figs. 2g-h show the switched packet at switch 1 and switch 2, respectively. The switched packet was detected and BER was measured. The results of the measurements are shown in the left panel of Fig. 3. Error-free operation was obtained with 1.1 dB of power penalty compared to the back-to-back payload.

Next, we investigate the performance for 12 x 40 GB/s OFDM data packet. In the present experiment, 512 subcarriers are available for the DMT transmission, ranging from 0 to 12 GHz. The left panel of figure 4 shows the results from Chow's bit-loading algorithm. Different numbers of bits per subcarrier are allocated according to the

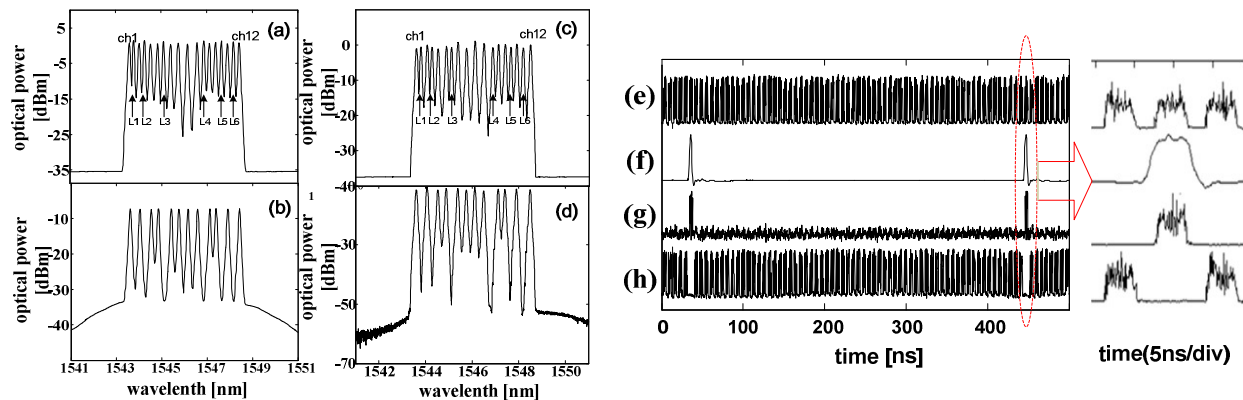


Figure 2. Spectra of the packet before and after the label extractor for a-b) 12x10 Gb/s DPSK; c-d) 12x40 Gb/s OFDM. Measured traces. e) payload after label extraction; f) Switching control generated by the combinatory network; g-h) Switched payload at output 1 and output 2 of OPS

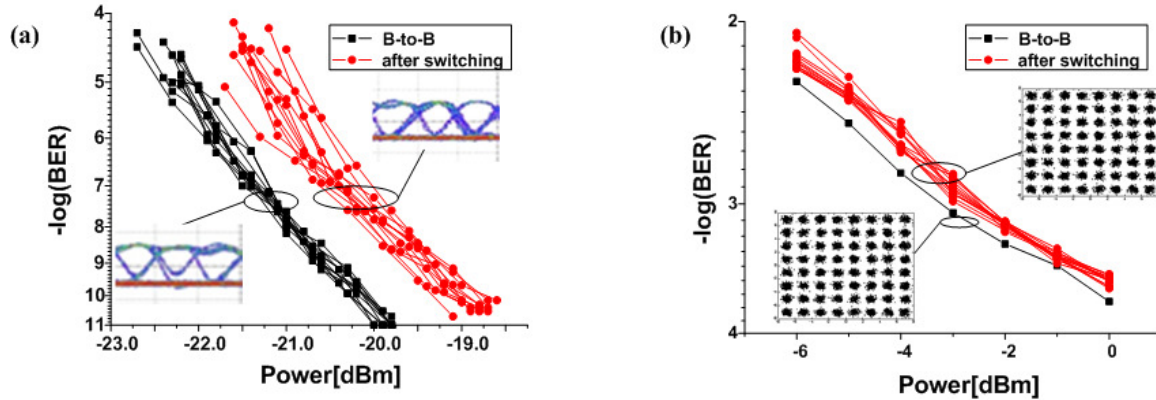


Figure 3: a) BER results and eye-diagram of 12x10 Gb/s DPSK; b) BER results and constellation diagrams of 12 x 40 GB/s OFDM

corresponding signal-to-noise ratio. Some of them allocated 6 bits of information at maximum (i.e. 64-QAM). Using DMT with bit-loading, finally we are able to achieve 40.3 Gb/s bit rate.

In right panel of figure 4, we present the electrical spectra of the signal. It is shown (curve b) that the 3-dB bandwidth of the transmission system is only around 6 GHz and the available bandwidth is not more than 12 GHz. The curve (a) in the figure is the spectrum without data modulation, which indicates the noise floor of the system. Fig. 3b shows the BER curves as a function of the received optical power. Due to the lack of a packet based BER evaluation software, the BER curves are measured under static operation by using a fixed labels that open the optical gate 1. The data stream after the gate is detected and evaluates off-line via a computer. We also get error-free operation with power penalty of 0.5dB before the label extraction, and a power penalty of 0.9 dB after the optical gate (including 18 dB of splitting loss to emulate the 1:64 splitter). We also present in figure 3b the constellation of the demodulated 25-30th sub-carriers (64 QAM) before and after the OPS.

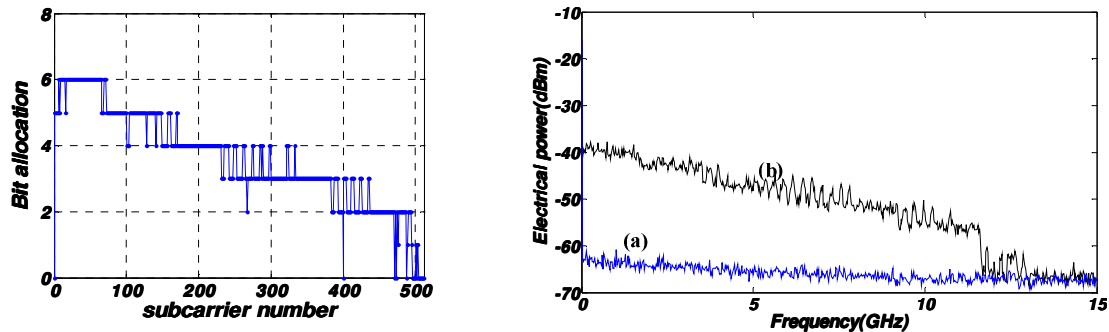


Figure 4 Left: Bit allocation map for 40 Gb/s bit rate; Right: Electrical spectrum of the signal (a) without modulation, (b) after modulation.

4. Discussions and conclusions

We have demonstrated a packet switch that can transparently process multiple data-format packets with high spectral efficiency. The data packets contain in-band labels that are processed by narrow band pass filters and asynchronous electronics. The 1x64 OPS utilizes an asynchronous and scalable optical label processor for in-band labeling. The label processor employs parallel all-optical label processing in combination with an asynchronous combinatorial network. This results in a latency lower than 3 ns. The dynamic switching results show error-free operation with 1.1 dB of power penalty for the 12 x 10 GB/s DPSK, and error-free operation with 0.9 dB of power penalty for 12 x 40 GB/s OFDM.

Acknowledgements

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5. References

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