Cross-Layer Signal Monitoring in an Optical Packet-Switching Test-Bed via Real-Time Burst Sampling

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Abstract: **A photonic time-stretch enhanced recording oscilloscope enabling real-time burst sampling is realized within an optical switching fabric test-bed. 10-Gb/s eye diagrams are captured with the high-speed digitizer, showcasing the potential for real-time cross-layer network optimization.**

Introduction

Future network designs will require a novel architecture that can seamlessly support the ever-increasing bandwidth demands and applications of today's networks. An optical cross-layer (OCL) network communication platform is a promising approach to provide a dynamic, intelligent optical layer that interacts with higher layers, and to realize real-time bandwidth allocation with an optical-message granularity [1]. An integrated OCL design can leverage emerging physical-layer technologies and systems to allow for introspective access to the optical layer. We envision an OCL infrastructure with embedded real-time optical performance monitoring (OPM) in the physical layer providing feedback to higher routing layers [2-3]. The OCL schemes enable dynamic network routing and packet protection with rapid capacity provisioning, and a means to optimize overall performance and efficiency [4-5].

The dedicated OPM devices that assess the physical-layer performance are embedded directly within the optical network layer (Fig. 1). These systems are capable of monitoring the real-time optical-signal-to-noise-ratio (OSNR) [3] or bit-error rate (BER), which can then be utilized to reconfigure optical routing using the OCL exchange. In addition, the future optical layer should engage novel optical packet-switching (OPS) [6] fabric technologies to provide a highly programmable packet switching and routing solution. OPS will facilitate the required high-bandwidth network connections for future data-centric Internet applications, by transparently supporting broadband wavelength-striped optical messages [3] though wavelength-division multiplexing (WDM). Each wavelength channel in the multi-wavelength packet will need to scale to higher data rates. As a result, the receivers in these network links will require high-speed A/D conversion and fast digital signal processing. Thus, the bandwidth limitations of the electronic A/D converters comprise a key bottleneck in performance.

The real-time packet-level monitoring and measurement of these broadband high-speed data signals will be required for the future OCL-optimized platform. The photonic time-stretch enhanced recording (TiSER) oscilloscope [7-8] has been proposed as a promising technology to address this challenge by providing real-time digitization of high-speed signals, thereby realizing a true real-time diagnostic and performance monitoring tool for high-speed optical links. TiSER uses real-time burst sampling (RBS) to effectively slow down the signal to accommodate the digitizer's bandwidth. By embedding TiSER within an OPS fabric, we envision a dynamic system where real-time eye-diagrams can be generated, physical-layer impairments can be characterized, and rapid BER measurements can be achieved.

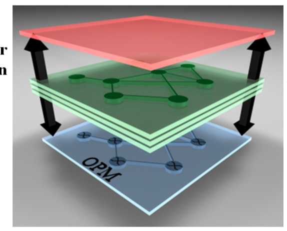

Fig. 1: OCL stack, depicting the bidirectional information flow between the application (top), network and routing (middle), and optical layers (bottom) with embedded OPM devices.

In this work, we implement the TiSER oscilloscope within a realized 4×4 OCL-enabled switching fabric test-bed [2], enabling real-time performance monitoring with a message granularity. Wavelength-striped optical packets with 8×10-Gb/s payloads are correctly routed through the test-bed, and error-free performance is achieved with BERs less than 10^{-12}. TiSER captures the 10-Gb/s eye diagrams corresponding to the error-free signals, with the future goal of rapidly extrapolating the BER for use in an OCL-optimized infrastructure.

Optical Switching Fabric Overview

The implemented 4×4 optical fabric test-bed [2-3] can provide low-latency high-bandwidth optical connections for access network edge users. The multistage network is composed of wideband 2×2 photonic switching nodes; the electronic routing control logic is distributed and provides a high level of programmability. Broadband packets are routed at each node using semiconductor optical amplifier (SOA) gates; the supported message format leverages WDM to offer a high aggregate transmission bandwidth. The wavelength-striped packet contains control information (e.g. frame, quality-of-service, address) encoded on a subset of allocated wavelength channels (single bit per channel), and the payload information is segmented and modulated simultaneously at a high data rate. The photonic switching nodes decode the control signals instantaneously upon reception of the message's leading edges using low-speed optical receivers. The node uses simple electronic control logic to process control information and to gate the SOAs based on the recovered

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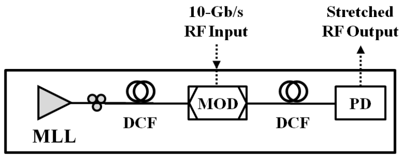

Fig. 2: Physics of the time-stretch pre-processor.

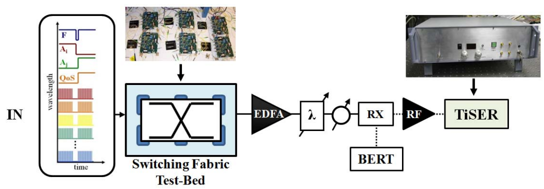

Fig. 3: Block diagram and photographs of the experimental demonstration with the optical fabric test-bed and TiSER.

headers. The SOA gates then route the optical packets to their required output port, or drop them upon contention.

TiSER Overview

The TiSER oscilloscope [7-8] uses photonic time-stretch pre-processing (Fig. 2) to perform RBS of high-speed signals. TiSER captures a burst of samples in real-time and reconstructs the eye diagram in equivalent-time mode. It enables the capture of fast non-repetitive dynamics at the modulation rate, comprising a real-time monitoring solution for high-data-rate optical links. TiSER has been shown to capture data signals up to 45 Gb/s [7]. By capturing high-speed signals using commercial slower digitizers, TiSER bridges the functionality gap between sampling oscilloscopes and real-time digitizers.

TiSER (Fig. 2) uses a mode-locked laser (MLL) that generates 36-MHz ultra-short optical pulses. A -60-ps/nm dispersion-compensating fiber (DCF) then creates chirped pulses with a sufficient time aperture to support 10-Gb/s RF data rates. A Mach-Zehnder intensity modulator encodes the 10-Gb/s data signal over the chirped pulses. Propagation through a span of -657-ps/nm DCF stretches the modulated optical pulses in time, realizing a stretch factor of 12. A photodetector (PD) receives the pulses and creates an electronic RF signal that is a stretched version of the original with reduced bandwidth. A commercial A/D digitizer is used and the eye diagram is constructed using the recorded data by removing an integral number of data periods from the stretched time scale.

Experimental Demonstration and Results

TiSER performs real-time monitoring of the optical packets propagating through the cross-layer-enabled fabric test-bed (Fig. 3). The system supports wavelength-striped optical packets with 10-Gb/s NRZ data on eight payload wavelength channels. The 100-μs duration packets are modulated at 2^{15}-1 PRBS with a single 10-Gb/s $LiNbO_3$ modulator. The electronic logic is synthesized in Xilinx complex programmable logic devices (CPLDs).

Optical packets are routed through the test-bed. To evaluate the packet quality at the input and output of the test-bed, the optical packets are transmitted to a 10-Gb/s DC-coupled p-i-n photodiode with a transimpedance and limiting amplifier pair and subsequently to the TiSER oscilloscope. Here, TiSER uses a commercially-available

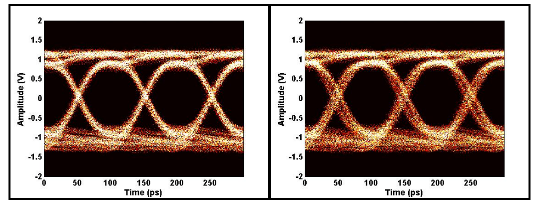

Fig. 4: 10-Gb/s TiSER-generated eye diagrams pertaining to packets at the network input (left) and output (right) (λ=1556.6 nm).

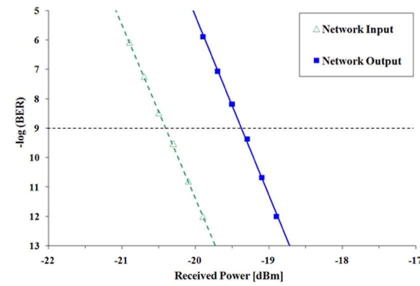

Fig. 5: BER curves (λ=1556.6 nm) for the test-bed.

electronic A/D digitizer with 2-GHz bandwidth that can capture up to 20 GSamples/s. TiSER records the data samples required to generate the eye diagrams pertaining to one 10-Gb/s channel of the packet. The TiSER-captured eye diagrams in Fig. 4 correspond to one representative error-free 10-Gb/s payload and are generated from a single packet, illustrating the message-level granularity.

We verify accurate routing of the 8×10-Gb/s wavelength-striped optical packets. The signals from the 10-Gb/s receiver are sent to a BER tester (BERT). All received packets are confirmed error-free on all eight payload wavelengths, with achieved BERs less than 10^{-12}. Fig. 5 depicts the sensitivity curves of an error-free channel, showing a power penalty less than 1 dB.

Conclusions

The TiSER oscilloscope provides a feasible means to realize the real-time message-granular monitoring of broadband data and to enable dynamic packet routing capabilities that will be required in future cross-layer networks. We demonstrate TiSER-generated 10-Gb/s eye diagrams of error-free 8×10-Gb/s optical packets propagating through an implemented OPS network test-bed. The system shows the potential of rapidly and dynamically extrapolating the messages' BER. The measurements can be used as a characterization of real-time physical-layer performance in a cross-layer-optimized platform and routing algorithms.

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