Multi-hop Optical-label Switching Using Optical 3R Regeneration

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Abstract: This paper experimentally demonstrates the multi-hop operation of an optical-label switching router with label swapping and optical 3R at each hop. A semiconductor optical amplifier based Mach-Zehnder interferometer wavelength converter performs reshaping. A Fabry-Perot filter all-optically recovers the clock from the incoming packets in burst mode. The synchronous modulation through a Mach-Zehnder modulator using the recovered clock performs retiming. The 3R regeneration maintains a good signal quality through multiple hops, which is important for scalable optical networking.

Keywords: Optical-label switching, optical label swapping, optical 3R regeneration

1. Introduction

The rapid growth of Internet constantly demands more capacity and capability. OLS is a promising technology to meet this demand by combining the advantages of the optical and electrical technologies. The optical data plane supplies abundant bandwidth, while the electrical control plane leads to flexible and sophisticated switching and network functions. As a result, OLS provides interoperability between packet, burst, and circuit switching [1, 2].

The OLS technology must be scalable for multi-hop operation to support the application in a large mesh network containing many routers [3]. Optical label swapping enables the update and regeneration of the optical label at each router hop. Optical 3R regeneration re-amplifies, reshapes, and retimes the bits in the payload to extend the reach of the optical signal without repeated high-speed O/E/O conversions. Combining these two capabilities, the OLS network will be able to support the multi-hop operation of optical packets.

It is important to study the multi-hop operation of OLS network through testbed demonstration. Previous works have demonstrated OLS with label swapping and 2R regeneration for up to 11 hops [4], and 31-hop cascaded OLS with optical 3R regeneration but no label swapping [5]. This paper experimentally demonstrates an OLS router testbed with optical label swapping and optical 3R regeneration at each hop for multi-hop operation.

2. Optical Clock Recovery with FPF

Clock recovery is an essential function in supporting 3R regeneration. OLS packet switching requires burst-mode clock recovery. The clock recovery must provide a clock with low jitter and small amplitude variation. This paper uses the FPF method with post amplitude equalization [6-8].

Figure 1 shows the simulated spectra for optical clock recovery using an FPF. The FPF has comb-shaped filter peaks. When an RZ signal passes the FPF, the clock components will remain while the data modulation is suppressed. The selection of a proper finesse value is critical to the burst-mode operation. A larger finesse value leads to lower jitter and amplitude variation in the extracted clock [6, 9], but it also results in longer lock-in time. This experiment chooses an FPF with a finesse of 100. A saturated SOA after the FPF acts as a limiting amplifier to reduce the amplitude variation [6].

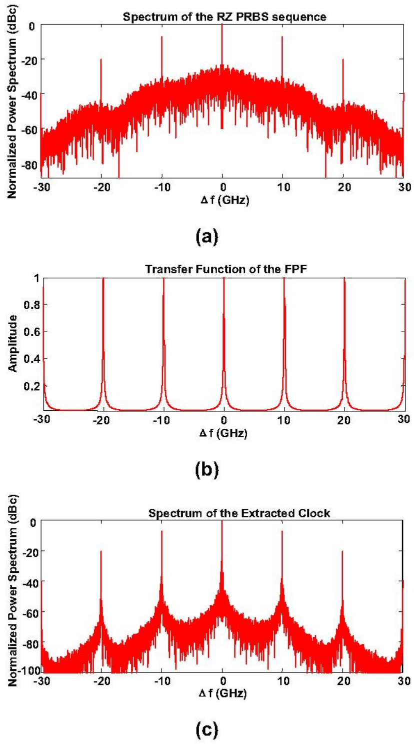

Figure 1: Simulated spectra of clock recovery using FPF. (a) Spectrum of the RZ 2^{23}-1 PRBS at 10 Gb/s. (b) Transfer function of the FPF. (c) Spectrum of the extracted clock. The free spectrum range of the FPF is 10 GHz; the finesse is 100. Δf = 0 represents the optical carrier frequency.

3. Experimental Description

Figure 2 illustrates a multi-hop OLS network. Packets travel from the legacy network to the OLS network through an ingress edge router, which performs packet aggregation and label attachments. At each intermediate router, the label enters the electrical control plane through O/E conversion, while the payload stays in the optical domain, travelling through the all-optical switch. Before leaving the router, the payload may acquire an updated optical label.

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After several hops, at the egress edge router, the OLS packets change back to the legacy format.

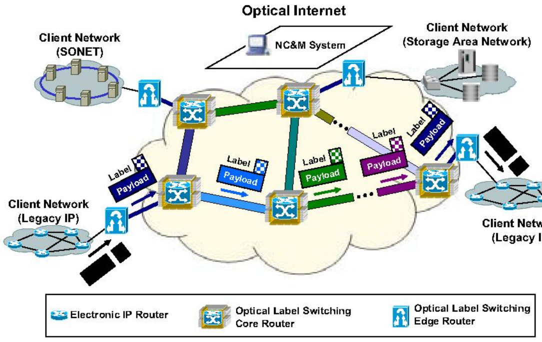

Figure 2: A multi-hop OLS network.

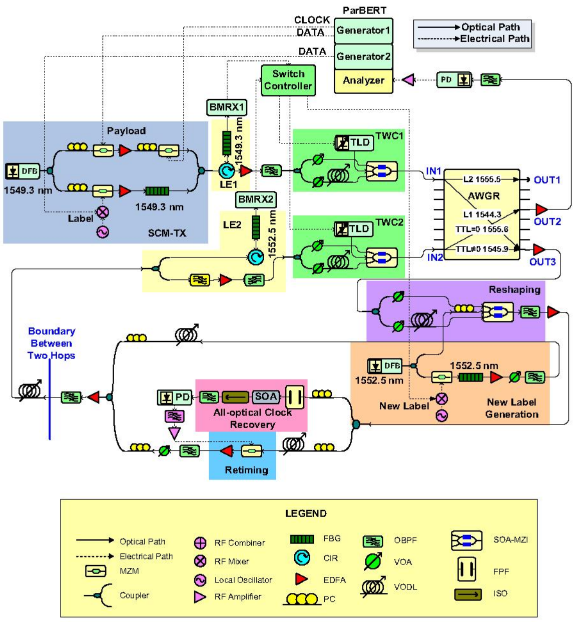

Figure 3: Simplified experimental setup. The text in the AWGR indicates the condition and the wavelength in nm for the switching.

Figure 3 shows the simplified experimental setup. One OLS router testbed emulates the multi-hop network by switching the packets repeatedly through itself until the packets have travelled a predesigned number of hops, after which the packets exit the router for measurements. In this demonstration, a "hop" refers to passing either TWC once.

In the setup, an SCM-TX generates a continuous optical packet sequence with 2.0-μs packets and 100-ns guard times. Two MZMs in tandem produce the 10-Gb/s RZ payload. The 155-Mb/s NRZ label, mixed with the 14-GHz subcarrier, transforms to the optical label through another MZM. A coupler combines the payload and label to form an OLS packet. When the packet enters the router, the LE separates the label and the payload using an FBG with a FWHM bandwidth of 0.16 nm [10]. The BMRX receives the label, based on which the switch controller makes the switching decision. Instructed by the switch controller, TWC1 duplicates the payload onto a corresponding wavelength that directs the payload from port IN1 to a desired output port of the AWGR. One out of the consecutive *N* packets possesses a label with destination "0000". This packet, named P1, will travel to OUT3 and continue coming back to the router for a total of *N* times. The other *N*-1 packets possessing labels with destination "1111" and named P2, will go to OUT1 when P1 is travelling repeatedly through the router.

After the AWGR, P1 passes the 3R regeneration blocks. The reshaping block cleans up the amplitude-domain noise on the '0' and '1' levels through wavelength conversion in an SOA-MZI [11]. The retiming block reduces jitter and limits RZ pulse expansion through synchronous modulation in an MZM driven by a recovered clock [12]. The 10-90% rise time of the clock profile after the SOA is approximately 3 ns, indicating that the clock recovery method works in burst-mode.

Before P1 exits the router, a new label generation block generates the new optical subcarrier label from the electrical signal sourced from the switch controller [4]. Because the same DFB laser provides the light for the new label generation and the reshaping, the label and payload are aligned in wavelength, and can be combined by a coupler. The PCs before the coupler adjust the label and payload into orthogonal polarization states to reduce crosstalk. When P1 comes back to the router, LE2 separates the payload and the label again. Since repeated narrow-bandwidth filtering distorts the RZ pulses significantly, LE2 uses a slightly wider (0.2 nm) grating filter for the payload path. Each time when P1 passes the router, the switch controller reduces the TTL field in the label by 1 to generate the new label. When TTL is still larger than 0, the switch controller sends P1 to OUT3. When TTL decreases to 0, the switch controller switches P1 to OUT2.

4. Experimental Results and Discussion

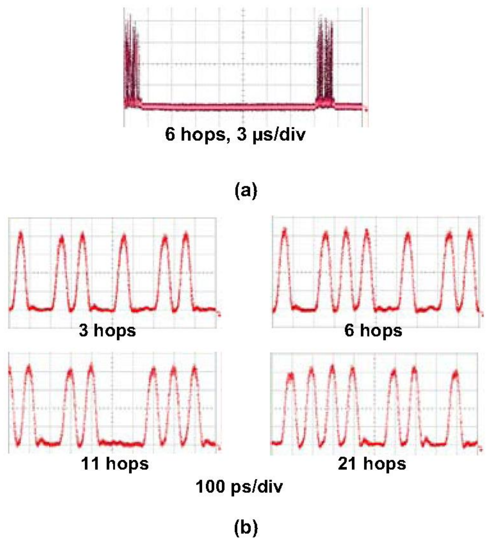

Figure 4: Oscilloscope traces observed at OUT2. (a) Packet sequence for 6 hops. (b) Bit pattern for 3, 6, 11, and 21 hops.

Figure 4 shows the oscilloscope traces of the final outputs observed at OUT2. Figure 4(a) shows the output packets for 6 hops, indicating that the switching operation is successful. Figure 4(b) shows the bit patterns for 3, 6, 11, and 21 hops. The RZ bits are clean in both the amplitude domain and time domain through the hops.

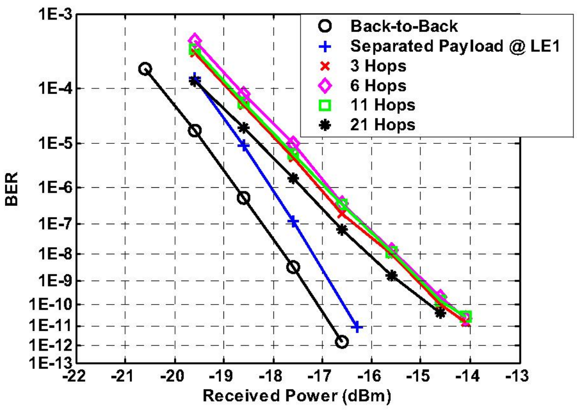

Figure 5: BER measurement results for OUT2.

Figure 5 shows the BER measurement results. The payload in a packet contains PRBS 2^{31}-1 data. There are a 24-bit preamble and a 16-bit suffix which are excluded from the BER measurement. The preamble contains the sequence "111111111111111101010101" to accelerate the rise of the recovered clock profile while avoiding pattern effects caused by the long "1"s. The suffix contains all "1"s to prolong the recovered clock. All BER curves can reach below 10^{-10}. At BER=10^{-9}, the power penalty to the payload from the first label swapping is 0.57 dB. The 3-hop result adds additional 1.80 dB penalty. But after 3 hops, all BER curves almost overlap each other. The small negative power penalty for 21-hop curve may have arisen from the long-term drift of the setup. The BER results demonstrate that the 3R regeneration maintains signal quality through multiple hops after a small initial penalty.

5. Conclusion

This paper experimentally demonstrated the multi-hop operation of an OLS router with optical subcarrier label swapping and optical 3R regeneration at each hop. The optical 3R regeneration scheme using SOA-MZI wavelength converter, burst-mode all-optical clock recovery by FPF, and synchronous modulation maintains a good signal quality for up to 21 hops. The BER performance stabilizes after 3 hops. The demonstrated optical label swapping and optical 3R regeneration schemes are suitable for scalable OLS network.

6. Aknowledgment

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8. Glossary

AWGR: Arrayed waveguide grating router.

BER: Bit-error rate.

BERT: Bit-error rate tester.

BMRX: Burst-mode receiver.

CIR: Circulator.

DFB: Distributed feedback.

EDFA: Erbium-doped fiber amplifier.

FBG: Fiber Bragg grating.

FPF: Fabry-Perot filter.

FWHM: Full-width-half-magnitude.

ISO: Isolator.

LE: Label extractor.

MZM: Mach-Zehnder modulator.

NRZ: Non-return-to-zero.

OBPF: Optical bandpass filter.

OLS: Optical-label switching.

PC: Polarization controller.

PD: Photodetector.

PRBS: Pseudo-random bit sequence.

RZ: Return-to-zero.

SCM-TX: Sub-carrier multiplexing transmitter.

SOA: Semiconductor optical amplifier.

SOA-MZI: SOA based Mach-Zehnder interferometer wavelength converter.

TLD: Tunable laser diode.

TTL: Time-to-live.

TWC: Tunable wavelength converter.

VOA: Variable optical attenuator.

VODL: Variable optical delay line.